Neuroscience: Canadian 1st Edition

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Unit 4 – Emergent Topics in Neuroscience

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UNIT 1 – NEUROSCIENCE: THE BASICS

1.1 The Cellular Levels of Organization

Introduction

Fluorescence-stained Cell Undergoing Mitosis

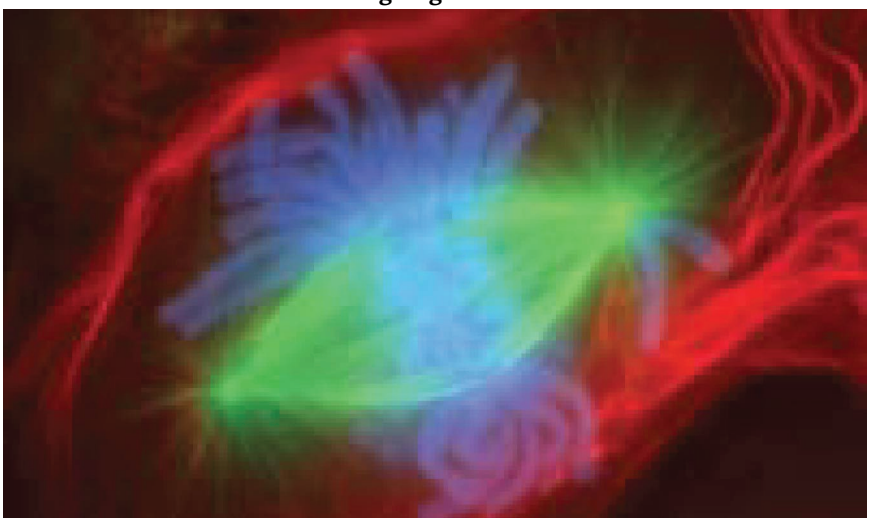


Figure 1. *A lung cell from a newt, commonly studied for its similarity to human lung cells, is stained with fluorescent dyes. The green stain reveals mitotic spindles, red is the cell membrane and part of the cytoplasm, and the structures that appear light blue are chromosomes. This cell is in anaphase of mitosis. (credit: "Mortadelo2005"/Wikimedia Commons)*

After studying this chapter, you will be able to:

- Describe the structure and function of the cell membrane, including its regulation of materials into and out of the cell
- Describe the functions of the various cytoplasmic organelles
- Explain the structure and contents of the nucleus, as well as the process of DNA replication
- Explain the process by which a cell builds proteins using the DNA code
- List the stages of the cell cycle in order, including the steps of cell division in somatic cells
- Discuss how a cell differentiates and becomes more specialized
- List the morphological and physiological characteristics of some representative cell types in the human body

You developed from a single fertilized egg cell into the complex organism containing trillions of cells that you see when you look in a mirror. During this developmental process, early, undifferentiated cells differentiate and become specialized in their structure and function. These different cell types form specialized tissues that work

in concert to perform all of the functions necessary for the living organism. Cellular and developmental biologists study how the continued division of a single cell leads to such complexity and differentiation.

Consider the difference between a structural cell in the skin and a nerve cell. A structural skin cell may be shaped like a flat plate (squamous) and live only for a short time before it is shed and replaced. Packed tightly into rows and sheets, the squamous skin cells provide a protective barrier for the cells and tissues that lie beneath. A nerve cell, on the other hand, may be shaped something like a star, sending out long processes up to a meter in length and may live for the entire lifetime of the organism. With their long winding appendages, nerve cells can communicate with one another and with other types of body cells and send rapid signals that inform the organism about its environment and allow it to interact with that environment. These differences illustrate one very important theme that is consistent at all organizational levels of biology: the form of a structure is optimally suited to perform particular functions assigned to that structure. Keep this theme in mind as you tour the inside of a cell and are introduced to the various types of cells in the body.

A primary responsibility of each cell is to contribute to homeostasis. Homeostasis is a term used in biology that refers to a dynamic state of balance within parameters that are compatible with life. For example, living cells require a water-based environment to survive in, and there are various physical (anatomical) and physiological mechanisms that keep all of the trillions of living cells in the human body moist. This is one aspect of homeostasis. When a particular parameter, such as blood pressure or blood oxygen content, moves far enough *out* of homeostasis (generally becoming too high or too low), illness or disease—and sometimes death—inevitably results.

The concept of a cell started with microscopic observations of dead cork tissue by scientist Robert Hooke in 1665. Without realizing their function or importance, Hook coined the term "cell" based on the resemblance of the small subdivisions in the cork to the rooms that monks inhabited, called cells. About ten years later, Antonie van Leeuwenhoek became the first person to observe living and moving cells under a microscope. In the century that followed, the theory that cells represented the basic unit of life would develop. These tiny fluid-filled sacs house components responsible for the thousands of biochemical reactions necessary for an organism to grow and survive. In this chapter, you will learn about the major components and functions of a prototypical, generalized cell and discover some of the different types of cells in the human body.

The Cell Membrane

By the end of this section, you will be able to:

- Describe the molecular components that make up the cell membrane
- Explain the major features and properties of the cell membrane
- Differentiate between materials that can and cannot diffuse through the lipid bilayer
- Compare and contrast different types of passive transport with active transport, providing examples of each

Despite differences in structure and function, all living cells in multicellular organisms have a surrounding cell

membrane. As the outer layer of your skin separates your body from its environment, the cell membrane (also known as the plasma membrane) separates the inner contents of a cell from its exterior environment. This cell membrane provides a protective barrier around the cell and regulates which materials can pass in or out.

Structure and Composition of the Cell Membrane

The **cell membrane** is an extremely pliable structure composed primarily of back-to-back phospholipids (a "bilayer"). Cholesterol is also present, which contributes to the fluidity of the membrane, and there are various proteins embedded within the membrane that have a variety of functions.

A single phospholipid molecule has a phosphate group on one end, called the "head," and two side-by-side chains of fatty acids that make up the lipid tails (Figure 1. Phospholipid Structure). The phosphate group is negatively charged, making the head polar and hydrophilic—or "water loving." A **hydrophilic** molecule (or region of a molecule) is one that is attracted to water. The phosphate heads are thus attracted to the water molecules of both the extracellular and intracellular environments. The lipid tails, on the other hand, are uncharged, or nonpolar, and are hydrophobic—or "water fearing." A **hydrophobic** molecule (or region of a molecule) repels and is repelled by water. Some lipid tails consist of saturated fatty acids and some contain unsaturated fatty acids. This combination adds to the fluidity of the tails that are constantly in motion. Phospholipids are thus amphipathic molecules. An **amphipathic** molecule is one that contains both a hydrophilic and a hydrophobic region. In fact, soap works to remove oil and grease stains because it has amphipathic properties. The hydrophilic portion can dissolve in water while the hydrophobic portion can trap grease in micelles that then can be washed away.

Phospholipid Structure

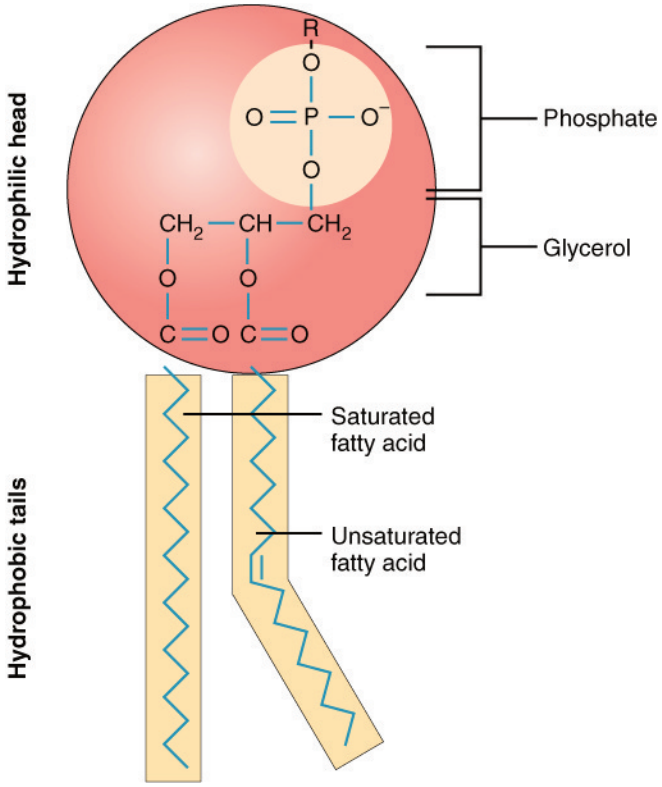


Figure 1. *A phospholipid molecule consists of a polar phosphate "head," which is hydrophilic and a non-polar lipid*

"tail," which is hydrophobic. Unsaturated fatty acids result in kinks in the hydrophobic tails.

The cell membrane consists of two adjacent layers of phospholipids. The lipid tails of one layer face the lipid tails of the other layer, meeting at the interface of the two layers. The phospholipid heads face outward, one layer exposed to the interior of the cell and one layer exposed to the exterior (Figure 2. Phospholipid Bilayer). Because the phosphate groups are polar and hydrophilic, they are attracted to water in the intracellular fluid. **Intracellular fluid (ICF)** is the fluid interior of the cell. The phosphate groups are also attracted to the extracellular fluid. **Extracellular fluid (ECF)** is the fluid environment outside the enclosure of the cell membrane. **Interstitial fluid (IF)** is the term given to extracellular fluid not contained within blood vessels. Because the lipid tails are hydrophobic, they meet in the inner region of the membrane, excluding watery intracellular and extracellular fluid from this space. The cell membrane has many proteins, as well as other lipids (such as cholesterol), that are associated with the phospholipid bilayer. An important feature of the membrane is that it remains fluid; the lipids and proteins in the cell membrane are not rigidly locked in place.

Phospolipid Bilayer

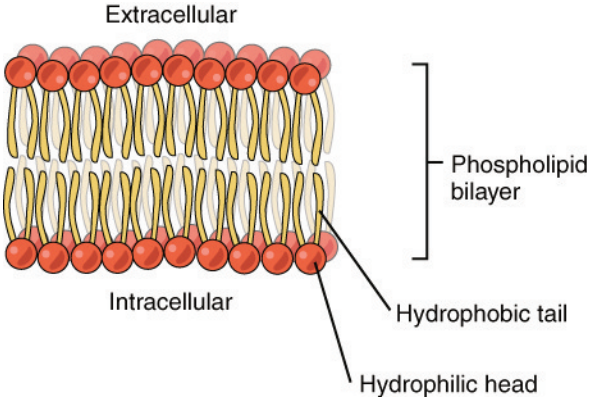


Figure 2. *The phospholipid bilayer consists of two adjacent sheets of phospholipids, arranged tail to tail. The hydrophobic tails associate with one another, forming the interior of the membrane. The polar heads contact the fluid inside and outside of the cell.*

Membrane Proteins

The lipid bilayer forms the basis of the cell membrane, but it is peppered throughout with various proteins. Two different types of proteins that are commonly associated with the cell membrane are the integral proteins and peripheral protein (Figure 3. Cell Membrane). As its name suggests, **an integral protein** is a protein that is embedded in the membrane. A **channel protein** is an example of an integral protein that selectively allows particular materials, such as certain ions, to pass into or out of the cell.

Cell Membrane

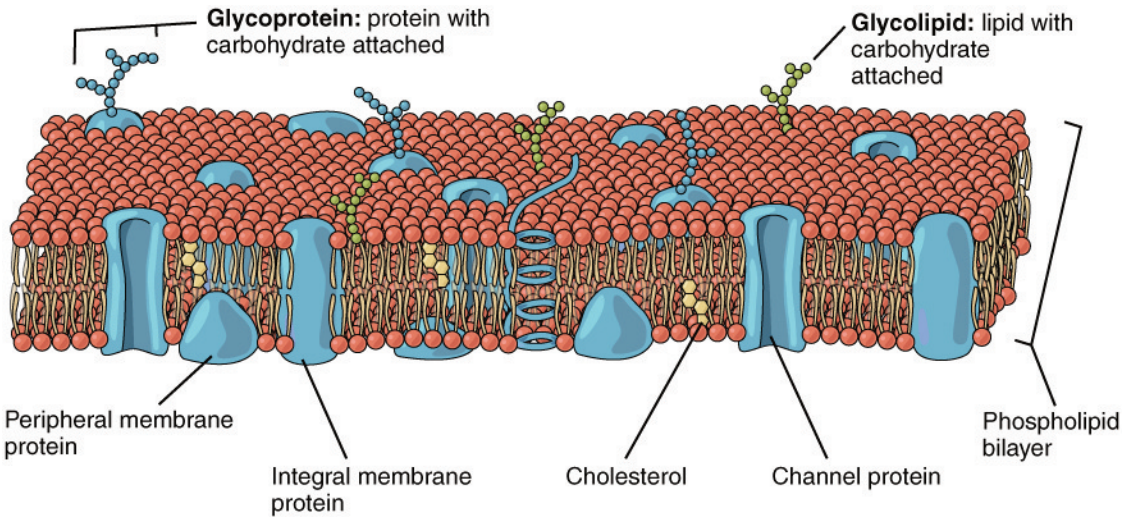


Figure 3. The cell membrane of the cell is a phospholipid bilayer containing many different molecular components, including proteins and cholesterol, some with carbohydrate groups attached.

Another important group of integral proteins are cell recognition proteins, which serve to mark a cell's identity so that it can be recognized by other cells. A **receptor** is a type of recognition protein that can selectively bind a specific molecule outside the cell, and this binding induces a chemical reaction within the cell. A **ligand** is the specific molecule that binds to and activates a receptor. Some integral proteins serve dual roles as both a receptor and an ion channel. One example of a receptor-ligand interaction is the receptors on nerve cells that bind neurotransmitters, such as dopamine. When a dopamine molecule binds to a dopamine receptor protein, a channel within the transmembrane protein opens to allow certain ions to flow into the cell.

Some integral membrane proteins are glycoproteins. A **glycoprotein** is a protein that has carbohydrate molecules attached, which extend into the extracellular matrix. The attached carbohydrate tags on glycoproteins aid in cell recognition. The carbohydrates that extend from membrane proteins and even from some membrane lipids collectively form the glycocalyx. The **glycocalyx** is a fuzzy-appearing coating around the cell formed from glycoproteins and other carbohydrates attached to the cell membrane. The glycocalyx can have various roles. For example, it may have molecules that allow the cell to bind to another cell, it may contain receptors for hormones, or it might have enzymes to break down nutrients. The glycocalyces found in a person's body are products of that person's genetic makeup. They give each of the individual's trillions of cells the "identity" of belonging in the person's body. This identity is the primary way that a person's immune defense cells "know" not to attack the person's own body cells, but it also is the reason organs donated by another person might be rejected.

Peripheral proteins are typically found on the inner or outer surface of the lipid bilayer but can also be attached to the internal or external surface of an integral protein. These proteins typically perform a specific function for the cell. Some peripheral proteins on the surface of intestinal cells, for example, act as digestive enzymes to break down nutrients to sizes that can pass through the cells and into the bloodstream.

Transport across the Cell Membrane

One of the great wonders of the cell membrane is its ability to regulate the concentration of substances inside the cell. These substances include ions such as Ca^{++}, Na^{+}, K^{+}, and Cl^{-}; nutrients including sugars, fatty acids, and amino acids; and waste products, particularly carbon dioxide (CO_2), which must leave the cell.

The membrane's lipid bilayer structure provides the first level of control. The phospholipids are tightly packed together, and the membrane has a hydrophobic interior. This structure causes the membrane to be **selectively permeable**. A membrane that has selective permeability allows only substances meeting certain criteria to pass through it unaided. In the case of the cell membrane, only relatively small, nonpolar materials can move through the lipid bilayer (remember, the lipid tails of the membrane are nonpolar). Some examples of these are other lipids, oxygen and carbon dioxide gases, and alcohol. However, water-soluble materials—like glucose, amino acids, and electrolytes—need some assistance to cross the membrane because they are repelled by the hydrophobic tails of the phospholipid bilayer. All substances that move through the membrane do so by one of two general methods, which are categorized based on whether or not energy is required. **Passive transport** is the movement of substances across the membrane without the expenditure of cellular energy. In contrast, **active transport** is the movement of substances across the membrane using energy from adenosine triphosphate (ATP).

Passive Transport

In order to understand *how* substances move passively across a cell membrane, it is necessary to understand concentration gradients and diffusion. A **concentration gradient** is the difference in concentration of a substance across a space. Molecules (or ions) will spread/diffuse from where they are more concentrated to where they are less concentrated until they are equally distributed in that space. (When molecules move in this way, they are said to move *down* their concentration gradient.) **Diffusion** is the movement of particles from an area of higher concentration to an area of lower concentration. A couple of common examples will help to illustrate this concept. Imagine being inside a closed bathroom. If a bottle of perfume were sprayed, the scent molecules would naturally diffuse from the spot where they left the bottle to all corners of the bathroom, and this diffusion would go on until no more concentration gradient remains. Another example is a spoonful of sugar placed in a cup of tea. Eventually the sugar will diffuse throughout the tea until no concentration gradient remains. In both cases, if the room is warmer or the tea hotter, diffusion occurs even faster as the molecules are bumping into each other and spreading out faster than at cooler temperatures. Having an internal body temperature around 98.6° F thus also aids in diffusion of particles within the body.

> Visit this link to see diffusion and how it is propelled by the kinetic energy of molecules in solution. How does temperature affect diffusion rate, and why?

Whenever a substance exists in greater concentration on one side of a semipermeable membrane, such as the cell membranes, any substance that can move down its concentration gradient across the membrane will do so. Consider substances that can easily diffuse through the lipid bilayer of the cell membrane, such as the gases oxygen (O_2) and CO_2. O_2 generally diffuses into cells because it is more concentrated outside of them, and CO_2 typically diffuses out of cells because it is more concentrated inside of them. Neither of these examples requires any energy on the part of the cell, and therefore they use passive transport to move across the membrane.

Before moving on, you need to review the gases that can diffuse across a cell membrane. Because cells rapidly use up oxygen during metabolism, there is typically a lower concentration of O_2 inside the cell than outside. As a result, oxygen will diffuse from the interstitial fluid directly through the lipid bilayer of the membrane and

into the cytoplasm within the cell. On the other hand, because cells produce CO_2 as a byproduct of metabolism, CO_2 concentrations rise within the cytoplasm; therefore, CO_2 will move from the cell through the lipid bilayer and into the interstitial fluid, where its concentration is lower. This mechanism of molecules moving across a cell membrane from the side where they are more concentrated to the side where they are less concentrated is a form of passive transport called simple diffusion (Figure 4. Simple Diffusion across the Cell (Plasma) Membrane).

Simple Diffusion across the Cell (Plasma) Membrane

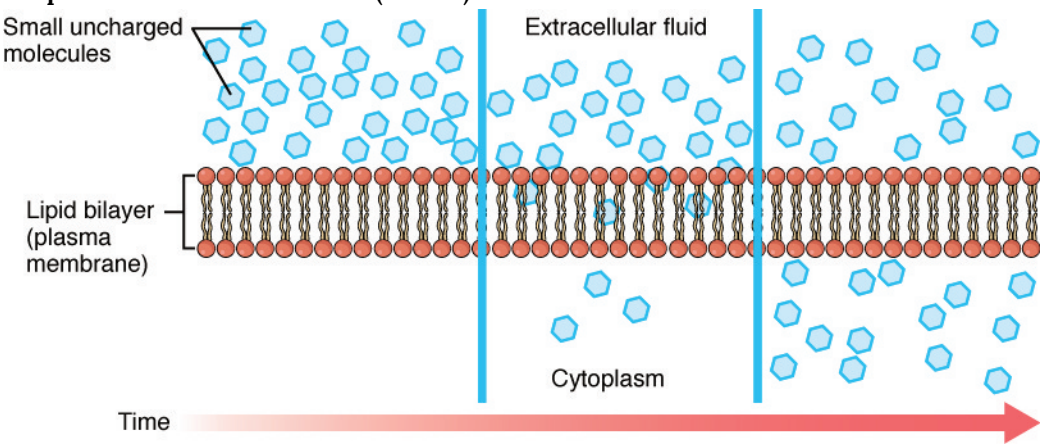


Figure 4. *The structure of the lipid bilayer allows small, uncharged substances such as oxygen and carbon dioxide, and hydrophobic molecules such as lipids, to pass through the cell membrane, down their concentration gradient, by simple diffusion.*

Large polar or ionic molecules, which are hydrophilic, cannot easily cross the phospholipid bilayer. Very small polar molecules, such as water, can cross via simple diffusion due to their small size. Charged atoms or molecules of any size cannot cross the cell membrane via simple diffusion as the charges are repelled by the hydrophobic tails in the interior of the phospholipid bilayer. Solutes dissolved in water on either side of the cell membrane will tend to diffuse down their concentration gradients, but because most substances cannot pass freely through the lipid bilayer of the cell membrane, their movement is restricted to protein channels and specialized transport mechanisms in the membrane. **Facilitated diffusion** is the diffusion process used for those substances that cannot cross the lipid bilayer due to their size, charge, and/or polarity (Figure 5. Facilitated Diffusion). A common example of facilitated diffusion is the movement of glucose into the cell, where it is used to make ATP. Although glucose can be more concentrated outside of a cell, it cannot cross the lipid bilayer via simple diffusion because it is both large and polar. To resolve this, a specialized carrier protein called the glucose transporter will transfer glucose molecules into the cell to facilitate its inward diffusion.

Facilitated Diffusion

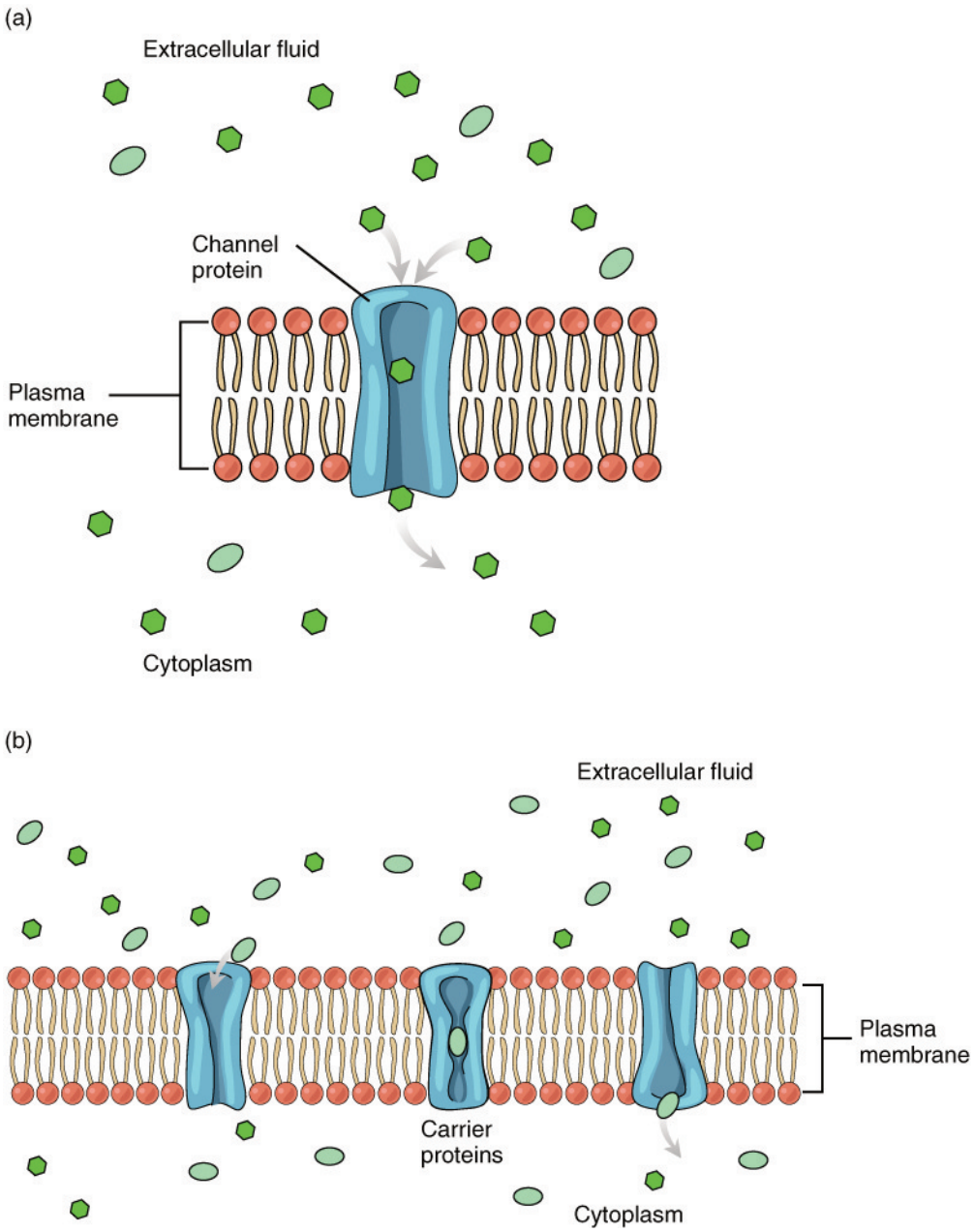


Figure 5. *(a) Facilitated diffusion of substances crossing the cell (plasma) membrane takes place with the help of proteins such as channel proteins and carrier proteins. Channel proteins are less selective than carrier proteins, and usually mildly discriminate between their cargo based on size and charge. (b) Carrier proteins are more selective, often only allowing one particular type of molecule to cross.*

As an example, even though sodium ions (Na^+) are highly concentrated outside of cells, these electrolytes are charged and cannot pass through the nonpolar lipid bilayer of the membrane. Their diffusion is facilitated by membrane proteins that form sodium channels (or "pores"), so that Na^+ ions can move down their concentration gradient from outside the cells to inside the cells. There are many other solutes that must undergo facilitated diffusion to move into a cell, such as amino acids, or to move out of a cell, such as wastes. Because facilitated diffusion is a passive process, it does not require energy expenditure by the cell.

Water also can move freely across the cell membrane of all cells, either through protein channels or by slipping

between the lipid tails of the membrane itself. **Osmosis** is the diffusion of water through a semipermeable membrane (Figure 6. Osmosis).

Osmosis

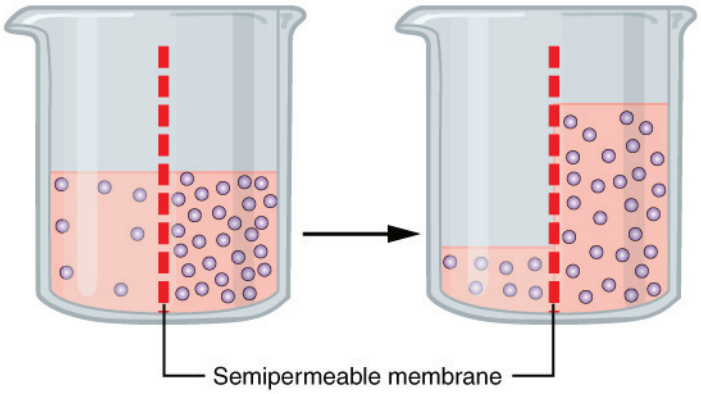


Figure 6. *Osmosis is the diffusion of water through a semipermeable membrane down its concentration gradient. If a membrane is permeable to water, though not to a solute, water will equalize its own concentration by diffusing to the side of lower water concentration (and thus the side of higher solute concentration). In the beaker on the left, the solution on the right side of the membrane is hypertonic.*

The movement of water molecules is not itself regulated by cells, so it is important that cells are exposed to an environment in which the concentration of solutes outside of the cells (in the extracellular fluid) is equal to the concentration of solutes inside the cells (in the cytoplasm). Two solutions that have the same concentration of solutes are said to be **isotonic** (equal tension). When cells and their extracellular environments are isotonic, the concentration of water molecules is the same outside and inside the cells, and the cells maintain their normal shape (and function).

Osmosis occurs when there is an imbalance of solutes outside of a cell versus inside the cell. A solution that has a higher concentration of solutes than another solution is said to be **hypertonic**, and water molecules tend to diffuse into a hypertonic solution (Figure 7. Concentration of Solutions). Cells in a hypertonic solution will shrivel as water leaves the cell via osmosis. In contrast, a solution that has a lower concentration of solutes than another solution is said to be **hypotonic**, and water molecules tend to diffuse out of a hypotonic solution. Cells in a hypotonic solution will take on too much water and swell, with the risk of eventually bursting. A critical aspect of homeostasis in living things is to create an internal environment in which all of the body's cells are in an isotonic solution. Various organ systems, particularly the kidneys, work to maintain this homeostasis.

Concentration of Solutions

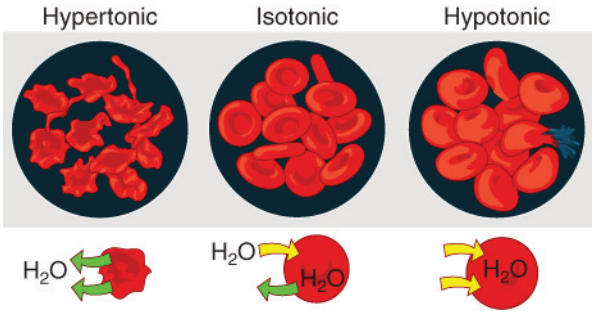


Figure 7. *A hypertonic solution has a solute concentration higher than another solution. An isotonic solution has a solute concentration equal to another solution. A hypotonic solution has a solute concentration lower than another solution.*

Another mechanism besides diffusion to passively transport materials between compartments is filtration. Unlike diffusion of a substance from where it is more concentrated to less concentrated, filtration uses a hydrostatic pressure gradient that pushes the fluid—and the solutes within it—from a higher pressure area to a lower pressure area. Filtration is an extremely important process in the body. For example, the circulatory system uses filtration to move plasma and substances across the endothelial lining of capillaries and into surrounding tissues, supplying cells with the nutrients. Filtration pressure in the kidneys provides the mechanism to remove wastes from the bloodstream.

Active Transport

For all of the transport methods described above, the cell expends no energy. Membrane proteins that aid in the passive transport of substances do so without the use of ATP. During active transport, ATP is required to move a substance across a membrane, often with the help of protein carriers, and usually *against* its concentration gradient.

One of the most common types of active transport involves proteins that serve as pumps. The word "pump" probably conjures up thoughts of using energy to pump up the tire of a bicycle or a basketball. Similarly, energy from ATP is required for these membrane proteins to transport substances—molecules or ions—across the membrane, usually against their concentration gradients (from an area of low concentration to an area of high concentration).

The **sodium-potassium pump**, which is also called Na^+/K^+ ATPase, transports sodium out of a cell while moving potassium into the cell. The Na^+/K^+ pump is an important ion pump found in the membranes of many types of cells. These pumps are particularly abundant in nerve cells, which are constantly pumping out sodium ions and pulling in potassium ions to maintain an electrical gradient across their cell membranes. An **electrical gradient** is a difference in electrical charge across a space. In the case of nerve cells, for example, the electrical gradient exists between the inside and outside of the cell, with the inside being negatively-charged (at around -70 mV) relative to the outside. The negative electrical gradient is maintained because each Na^+/K^+ pump moves three Na^+ ions out of the cell and two K^+ ions into the cell for each ATP molecule that is used (Figure 8. Sodium-Potassium Pump). This process is so important for nerve cells that it accounts for the majority of their ATP usage.
Sodium-Potassium Pump

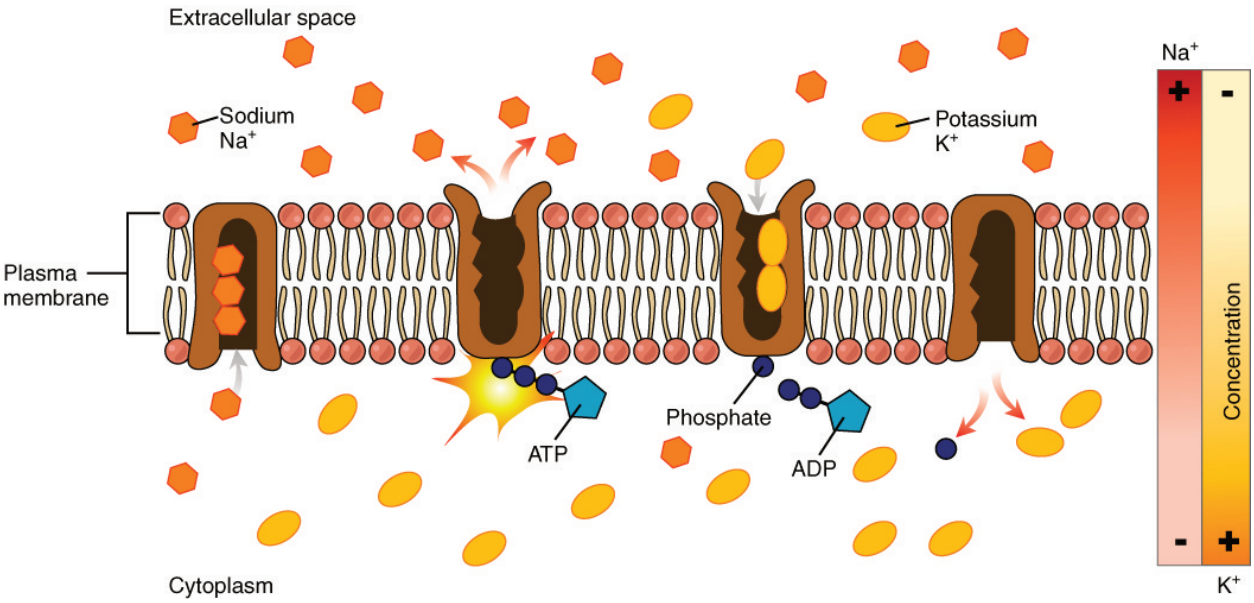


Figure 8. *The sodium-potassium pump is found in many cell (plasma) membranes. Powered by ATP, the pump moves sodium and potassium ions in opposite directions, each against its concentration gradient. In a single cycle of the pump, three sodium ions are extruded from and two potassium ions are imported into the cell.*

Active transport pumps can also work together with other active or passive transport systems to move substances across the membrane. For example, the sodium-potassium pump maintains a high concentration of sodium ions outside of the cell. Therefore, if the cell needs sodium ions, all it has to do is open a passive sodium channel, as the concentration gradient of the sodium ions will drive them to diffuse into the cell. In this way, the action of an active transport pump (the sodium-potassium pump) powers the passive transport of sodium ions by creating a concentration gradient. When active transport powers the transport of another substance in this way, it is called secondary active transport.

Symporters are secondary active transporters that move two substances in the same direction. For example, the sodium-glucose symporter uses sodium ions to "pull" glucose molecules into the cell. Because cells store glucose for energy, glucose is typically at a higher concentration inside of the cell than outside. However, due to the action of the sodium-potassium pump, sodium ions will easily diffuse into the cell when the symporter is opened. The flood of sodium ions through the symporter provides the energy that allows glucose to move through the symporter and into the cell, against its concentration gradient.

Conversely, antiporters are secondary active transport systems that transport substances in opposite directions. For example, the sodium-hydrogen ion antiporter uses the energy from the inward flood of sodium ions to move hydrogen ions (H+) out of the cell. The sodium-hydrogen antiporter is used to maintain the pH of the cell's interior.

Other forms of active transport do not involve membrane carriers. **Endocytosis** (bringing "into the cell") is the process of a cell ingesting material by enveloping it in a portion of its cell membrane, and then pinching off that portion of membrane (Figure 9. Three Forms of Endocytosis). Once pinched off, the portion of membrane and its contents becomes an independent, intracellular vesicle. A **vesicle** is a membranous sac—a spherical and hollow organelle bounded by a lipid bilayer membrane. Endocytosis often brings materials into the cell that must to be broken down or digested. **Phagocytosis** ("cell eating") is the endocytosis of large particles. Many immune cells engage in phagocytosis of invading pathogens. Like little Pac-men, their job is to patrol body tissues for unwanted matter, such as invading bacterial cells, phagocytize them, and digest them. In contrast

to phagocytosis, **pinocytosis** ("cell drinking") brings fluid containing dissolved substances into a cell through membrane vesicles.

Three Forms of Endocytosis

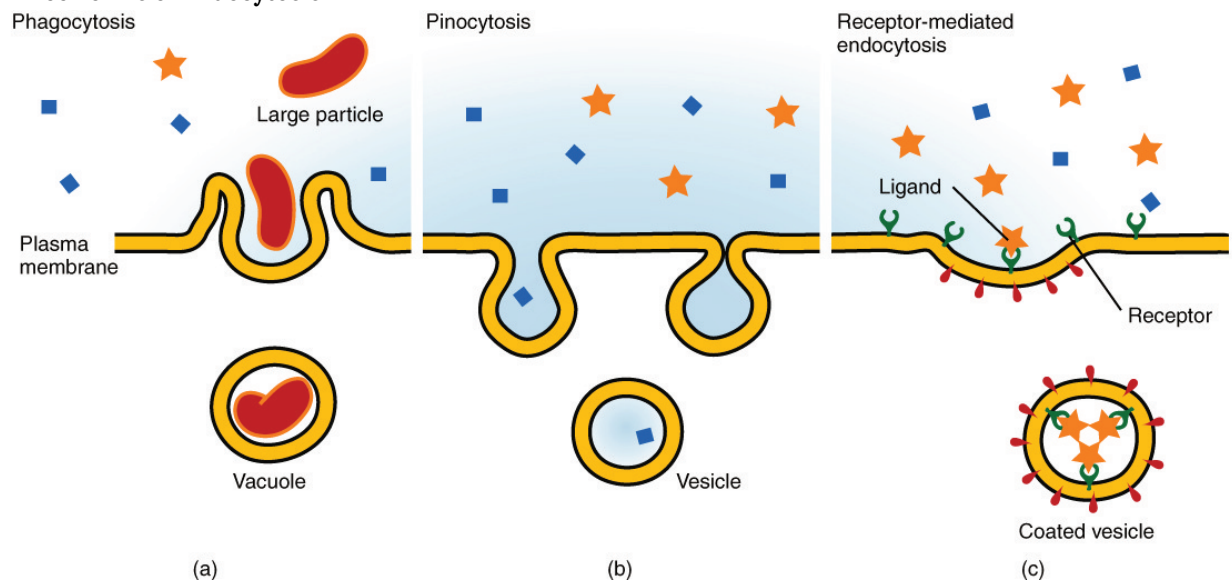


Figure 9. *Endocytosis is a form of active transport in which a cell envelopes extracellular materials using its cell membrane. (a) In phagocytosis, which is relatively nonselective, the cell takes in a large particle. (b) In pinocytosis, the cell takes in small particles in fluid. (c) In contrast, receptor-mediated endocytosis is quite selective. When external receptors bind a specific ligand, the cell responds by endocytosing the ligand.*

Phagocytosis and pinocytosis take in large portions of extracellular material, and they are typically not highly selective in the substances they bring in. Cells regulate the endocytosis of specific substances via receptor-mediated endocytosis. **Receptor-mediated endocytosis** is endocytosis by a portion of the cell membrane that contains many receptors that are specific for a certain substance. Once the surface receptors have bound sufficient amounts of the specific substance (the receptor's ligand), the cell will endocytose the part of the cell membrane containing the receptor-ligand complexes. Iron, a required component of hemoglobin, is endocytosed by red blood cells in this way. Iron is bound to a protein called transferrin in the blood. Specific transferrin receptors on red blood cell surfaces bind the iron-transferrin molecules, and the cell endocytoses the receptor-ligand complexes.

In contrast with endocytosis, **exocytosis** (taking "out of the cell") is the process of a cell exporting material using vesicular transport (Figure 10. Exocytosis). Many cells manufacture substances that must be secreted, like a factory manufacturing a product for export. These substances are typically packaged into membrane-bound vesicles within the cell. When the vesicle membrane fuses with the cell membrane, the vesicle releases it contents into the interstitial fluid. The vesicle membrane then becomes part of the cell membrane. Cells of the stomach and pancreas produce and secrete digestive enzymes through exocytosis (Figure 11. Pancreatic Cells' Enzyme Products). Endocrine cells produce and secrete hormones that are sent throughout the body, and certain immune cells produce and secrete large amounts of histamine, a chemical important for immune responses.

Exocytosis

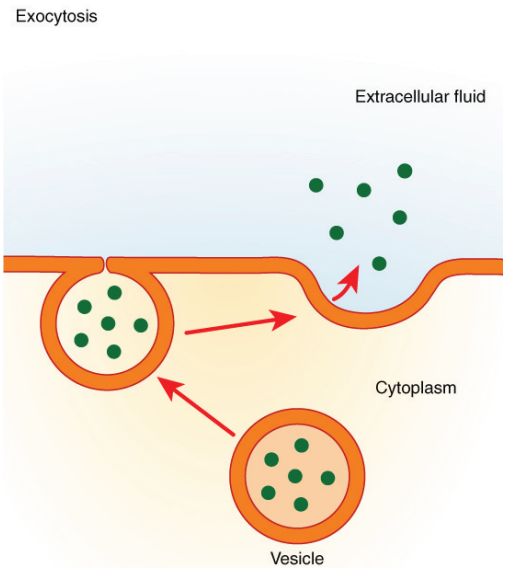


Figure 10. *Exocytosis is much like endocytosis in reverse. Material destined for export is packaged into a vesicle inside the cell. The membrane of the vesicle fuses with the cell membrane, and the contents are released into the extracellular space.*

Pancreatic Cells' Enzyme Products

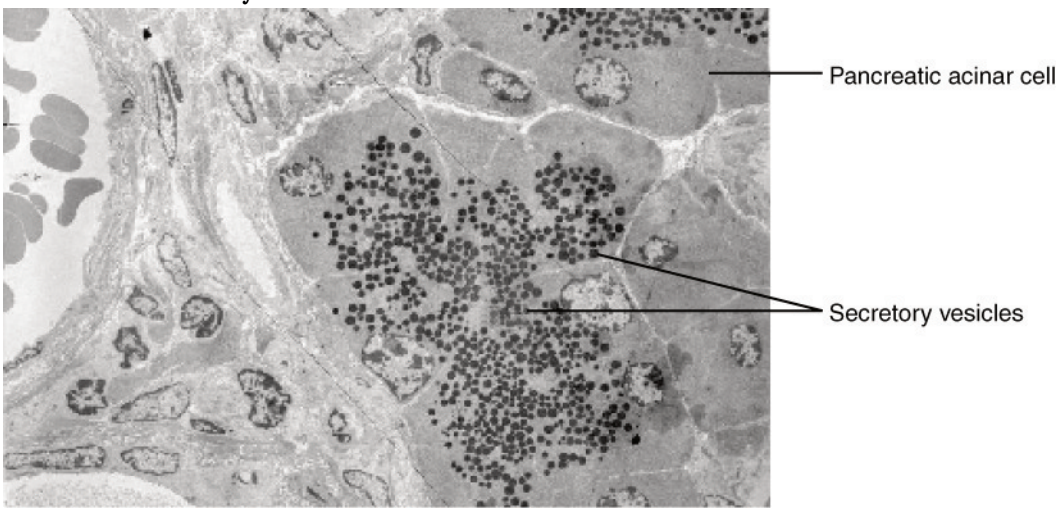


Figure 11. *The pancreatic acinar cells produce and secrete many enzymes that digest food. The tiny black granules in this electron micrograph are secretory vesicles filled with enzymes that will be exported from the cells via exocytosis. LM × 2900. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://virtualslides.med.umich.edu/Histology/EMsmallCharts/3%20Image%20Scope%20finals/226%20-%20Pancreas_001.svs/view.apml to explore the tissue sample in greater detail.

DISEASES OF THE…**Cell: Cystic Fibrosis**

Cystic fibrosis (CF) affects approximately 30,000 people in the United States, with about 1,000 new cases reported each year. The genetic disease is most well known for its damage to the lungs, causing breathing difficulties and chronic lung infections, but it also affects the liver, pancreas, and intestines. Only about 50 years ago, the prognosis for children born with CF was very grim—a life expectancy rarely over 10 years. Today, with advances in medical treatment, many CF patients live into their 30s.

The symptoms of CF result from a malfunctioning membrane ion channel called the cystic fibrosis transmembrane conductance regulator, or CFTR. In healthy people, the CFTR protein is an integral membrane protein that transports Cl^- ions out of the cell. In a person who has CF, the gene for the CFTR is mutated, thus, the cell manufactures a defective channel protein that typically is not incorporated into the membrane, but is instead degraded by the cell.

The CFTR requires ATP in order to function, making its Cl^- transport a form of active transport. This characteristic puzzled researchers for a long time because the Cl^- ions are actually flowing *down* their concentration gradient when transported out of cells. Active transport generally pumps ions *against* their concentration gradient, but the CFTR presents an exception to this rule.

In normal lung tissue, the movement of Cl^- out of the cell maintains a Cl^--rich, negatively charged environment immediately outside of the cell. This is particularly important in the epithelial lining of the respiratory system. Respiratory epithelial cells secrete mucus, which serves to trap dust, bacteria, and other debris. A cilium (plural = cilia) is one of the hair-like appendages found on certain cells. Cilia on the epithelial cells move the mucus and its trapped particles up the airways away from the lungs and toward the outside. In order to be effectively moved upward, the mucus cannot be too viscous; rather it must have a thin, watery consistency. The transport of Cl^- and the maintenance of an electronegative environment outside of the cell attract positive ions such as Na^+ to the extracellular space. The accumulation of both Cl^- and Na^+ ions in the extracellular space creates solute-rich mucus, which has a low concentration of water molecules. As a result, through osmosis, water moves from cells and extracellular matrix into the mucus, "thinning" it out. This is how, in a normal respiratory system, the mucus is kept sufficiently watered-down to be propelled out of the respiratory system.

If the CFTR channel is absent, Cl^- ions are not transported out of the cell in adequate numbers, thus preventing them from drawing positive ions. The absence of ions in the secreted mucus results in the lack of a normal water concentration gradient. Thus, there is no osmotic pressure pulling water into the mucus. The resulting mucus is thick and sticky, and the ciliated epithelia cannot effectively remove it from the respiratory system. Passageways in the lungs become blocked with mucus, along with the debris it carries. Bacterial infections occur more easily because bacterial cells are not effectively carried away from the lungs.

Chapter Review

The cell membrane provides a barrier around the cell, separating its internal components from the extracellular

environment. It is composed of a phospholipid bilayer, with hydrophobic internal lipid "tails" and hydrophilic external phosphate "heads." Various membrane proteins are scattered throughout the bilayer, both inserted within it and attached to it peripherally. The cell membrane is selectively permeable, allowing only a limited number of materials to diffuse through its lipid bilayer. All materials that cross the membrane do so using passive (non energy-requiring) or active (energy-requiring) transport processes. During passive transport, materials move by simple diffusion or by facilitated diffusion through the membrane, down their concentration gradient. Water passes through the membrane in a diffusion process called osmosis. During active transport, energy is expended to assist material movement across the membrane in a direction against their concentration gradient. Active transport may take place with the help of protein pumps or through the use of vesicles.

The Cytoplasm and Cellular Organelles

By the end of this section you will be able to:

- Describe the structure and function of the cellular organelles associated with the endomembrane system, including the endoplasmic reticulum, Golgi apparatus, and lysosomes
- Describe the structure and function of mitochondria and peroxisomes
- Explain the three components of the cytoskeleton, including their composition and functions

Now that you have learned that the cell membrane surrounds all cells, you can dive inside of a prototypical human cell to learn about its internal components and their functions. All living cells in multicellular organisms contain an internal cytoplasmic compartment, and a nucleus within the cytoplasm. **Cytosol**, the jelly-like substance within the cell, provides the fluid medium necessary for biochemical reactions. Eukaryotic cells, including all animal cells, also contain various cellular organelles. An **organelle** ("little organ") is one of several different types of membrane-enclosed bodies in the cell, each performing a unique function. Just as the various bodily organs work together in harmony to perform all of a human's functions, the many different cellular organelles work together to keep the cell healthy and performing all of its important functions. The organelles and cytosol, taken together, compose the cell's **cytoplasm**. The **nucleus** is a cell's central organelle, which contains the cell's DNA (Figure 1. Prototypical Human Cell).

Prototypical Human Cell

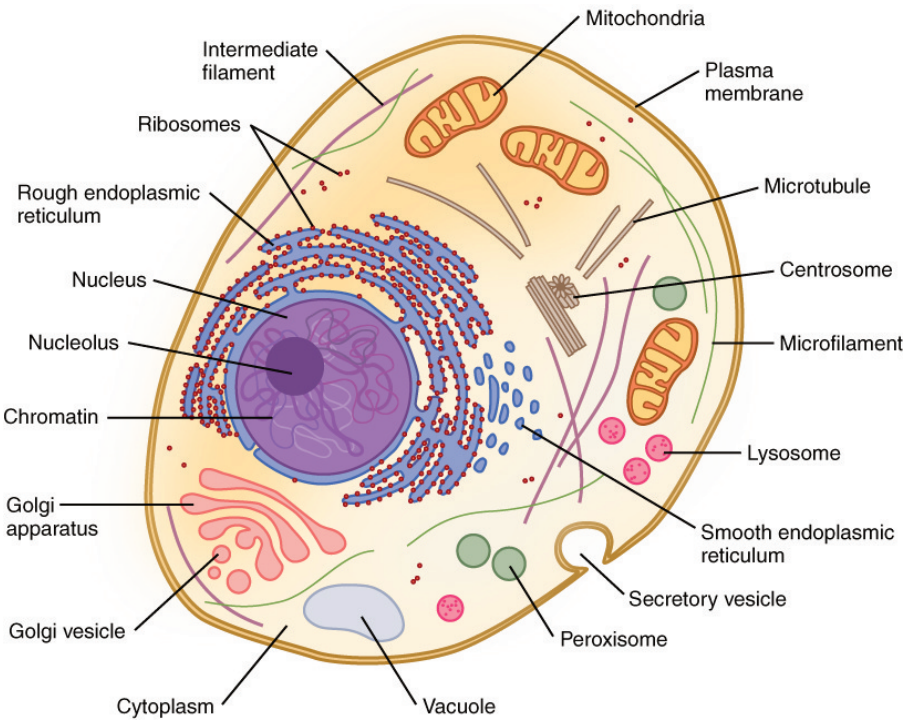


Figure 1. *While this image is not indicative of any one particular human cell, it is a prototypical example of a cell containing the primary organelles and internal structures.*

Organelles of the Endomembrane System

A set of three major organelles together form a system within the cell called the endomembrane system. These organelles work together to perform various cellular jobs, including the task of producing, packaging, and exporting certain cellular products. The organelles of the endomembrane system include the endoplasmic reticulum, Golgi apparatus, and vesicles.

Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** is a system of channels that is continuous with the nuclear membrane (or "envelope") covering the nucleus and composed of the same lipid bilayer material. The ER can be thought of as a series of winding thoroughfares similar to the waterway canals in Venice. The ER provides passages throughout much of the cell that function in transporting, synthesizing, and storing materials. The winding structure of the ER results in a large membranous surface area that supports its many functions (Figure 2. Endoplasmic Reticulum (ER)).

Endoplasmic Reticulum (ER)

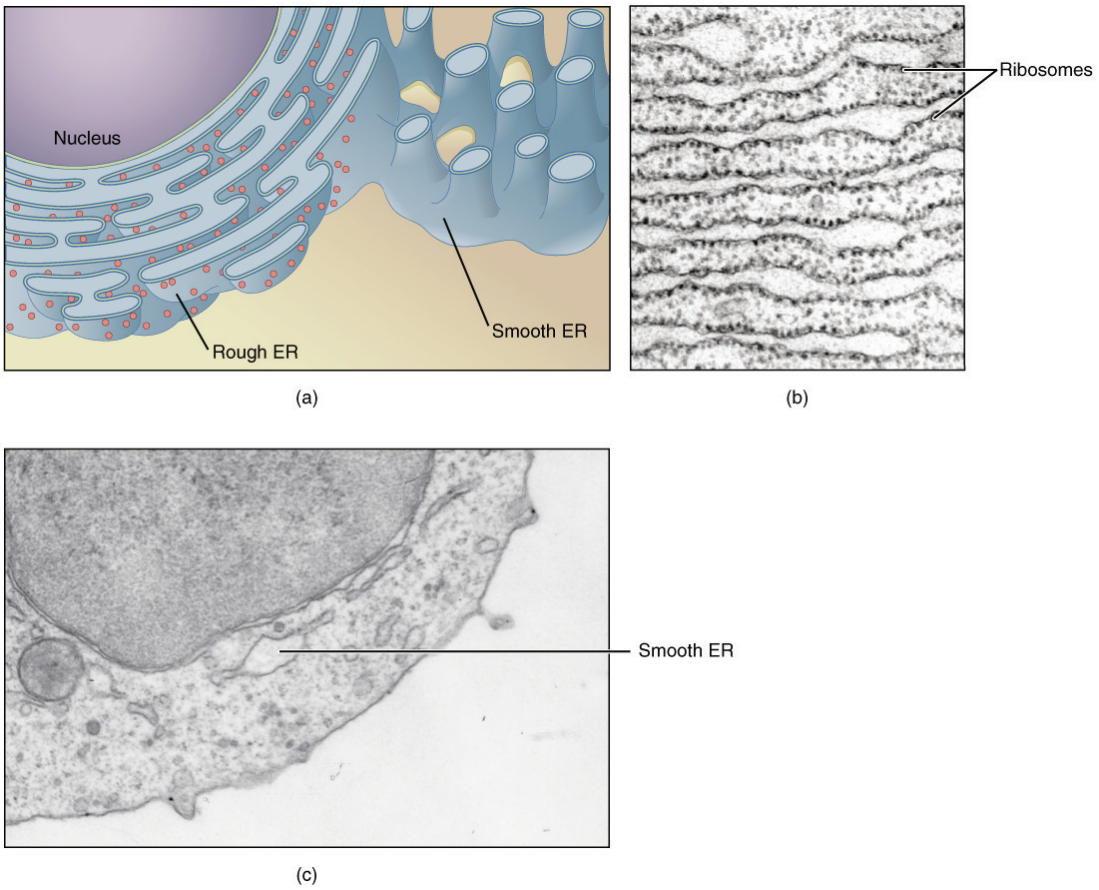


Figure 2. *(a) The ER is a winding network of thin membranous sacs found in close association with the cell nucleus. The smooth and rough endoplasmic reticula are very different in appearance and function (source: mouse tissue). (b) Rough ER is studded with numerous ribosomes, which are sites of protein synthesis (source: mouse tissue). EM × 110,000. (c) Smooth ER synthesizes phospholipids, steroid hormones, regulates the concentration of cellular* Ca^{2+}*, metabolizes some carbohydrates, and breaks down certain toxins (source: mouse tissue). EM × 110,510. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)*

Endoplasmic reticulum can exist in two forms: rough ER and smooth ER. These two types of ER perform some very different functions and can be found in very different amounts depending on the type of cell. Rough ER (RER) is so-called because its membrane is dotted with embedded granules—organelles called ribosomes, giving the RER a bumpy appearance. A **ribosome** is an organelle that serves as the site of protein synthesis. It is composed of two ribosomal RNA subunits that wrap around mRNA to start the process of translation, followed by protein synthesis. Smooth ER (SER) lacks these ribosomes.

One of the main functions of the smooth ER is in the synthesis of lipids. The smooth ER synthesizes phospholipids, the main component of biological membranes, as well as steroid hormones. For this reason, cells that produce large quantities of such hormones, such as those of the female ovaries and male testes, contain large amounts of smooth ER. In addition to lipid synthesis, the smooth ER also sequesters (i.e., stores) and regulates the concentration of cellular Ca^{2+}, a function extremely important in cells of the nervous system where Ca^{2+} is the trigger for neurotransmitter release. The smooth ER additionally metabolizes some carbohydrates and performs a detoxification role, breaking down certain toxins.

In contrast with the smooth ER, the primary job of the rough ER is the synthesis and modification of proteins destined for the cell membrane or for export from the cell. For this protein synthesis, many ribosomes attach to

the ER (giving it the studded appearance of rough ER). Typically, a protein is synthesized within the ribosome and released inside the channel of the rough ER, where sugars can be added to it (by a process called glycosylation) before it is transported within a vesicle to the next stage in the packaging and shipping process: the Golgi apparatus.

The Golgi Apparatus

The **Golgi apparatus** is responsible for sorting, modifying, and shipping off the products that come from the rough ER, much like a post-office. The Golgi apparatus looks like stacked flattened discs, almost like stacks of oddly shaped pancakes. Like the ER, these discs are membranous. The Golgi apparatus has two distinct sides, each with a different role. One side of the apparatus receives products in vesicles. These products are sorted through the apparatus, and then they are released from the opposite side after being repackaged into new vesicles. If the product is to be exported from the cell, the vesicle migrates to the cell surface and fuses to the cell membrane, and the cargo is secreted (Figure 3. Golgi Apparatus).

Golgi Apparatus

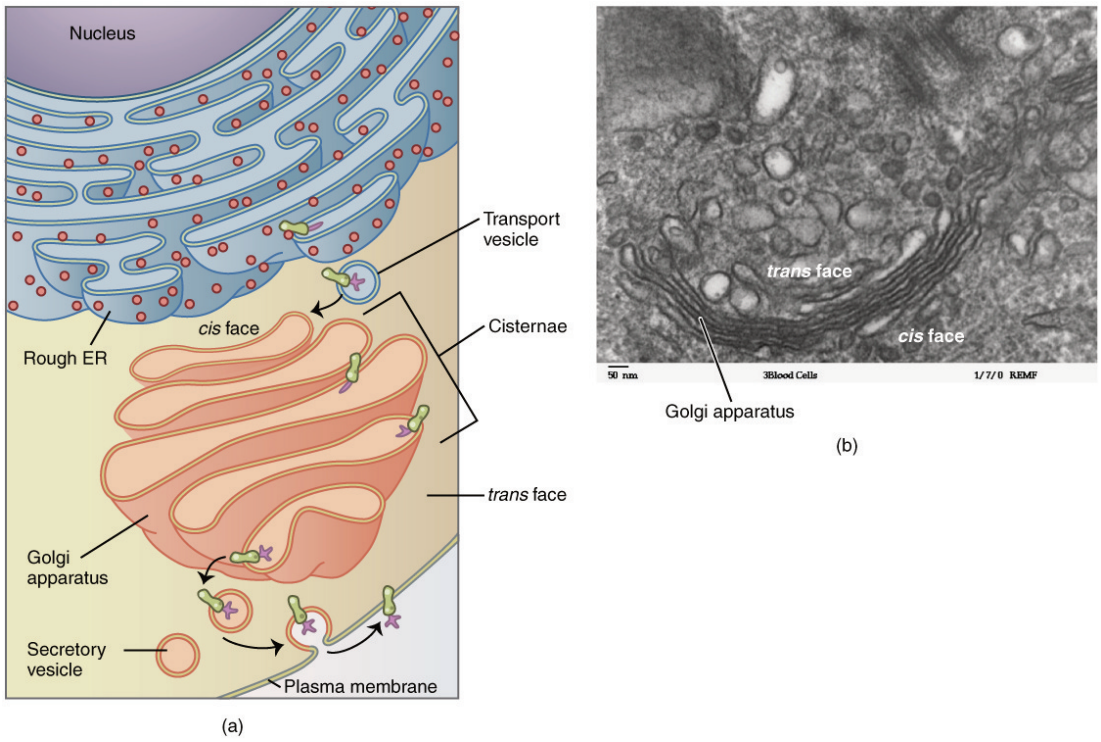


Figure 3. *(a) The Golgi apparatus manipulates products from the rough ER, and also produces new organelles called lysosomes. Proteins and other products of the ER are sent to the Golgi apparatus, which organizes, modifies, packages, and tags them. Some of these products are transported to other areas of the cell and some are exported from the cell through exocytosis. Enzymatic proteins are packaged as new lysosomes (or packaged and sent for fusion with existing lysosomes). (b) An electron micrograph of the Golgi apparatus.*

Lysosomes

Some of the protein products packaged by the Golgi include digestive enzymes that are meant to remain inside the cell for use in breaking down certain materials. The enzyme-containing vesicles released by the Golgi may form new lysosomes, or fuse with existing, lysosomes. A **lysosome** is an organelle that contains enzymes that break down and digest unneeded cellular components, such as a damaged organelle. (A lysosome is similar to a wrecking crew that takes down old and unsound buildings in a neighborhood.) **Autophagy** ("self-eating") is the process of a cell digesting its own structures. Lysosomes are also important for breaking down foreign material. For example, when certain immune defense cells (white blood cells) phagocytize bacteria, the bacterial cell is transported into a lysosome and digested by the enzymes inside. As one might imagine, such phagocytic defense cells contain large numbers of lysosomes.

Under certain circumstances, lysosomes perform a more grand and dire function. In the case of damaged or unhealthy cells, lysosomes can be triggered to open up and release their digestive enzymes into the cytoplasm of the cell, killing the cell. This "self-destruct" mechanism is called **autolysis**, and makes the process of cell death controlled (a mechanism called "apoptosis").

> Watch this video to learn about the endomembrane system, which includes the rough and smooth ER and the Golgi body as well as lysosomes and vesicles. What is the primary role of the endomembrane system?

Organelles for Energy Production and Detoxification

In addition to the jobs performed by the endomembrane system, the cell has many other important functions. Just as you must consume nutrients to provide yourself with energy, so must each of your cells take in nutrients, some of which convert to chemical energy that can be used to power biochemical reactions. Another important function of the cell is detoxification. Humans take in all sorts of toxins from the environment and also produce harmful chemicals as byproducts of cellular processes. Cells called hepatocytes in the liver detoxify many of these toxins.

Mitochondria

A **mitochondrion** (plural = mitochondria) is a membranous, bean-shaped organelle that is the "energy transformer" of the cell. Mitochondria consist of an outer lipid bilayer membrane as well as an additional inner lipid bilayer membrane (Figure 4. Mitochondrion). The inner membrane is highly folded into winding structures with a great deal of surface area, called cristae. It is along this inner membrane that a series of proteins, enzymes, and other molecules perform the biochemical reactions of cellular respiration. These reactions convert energy stored in nutrient molecules (such as glucose) into adenosine triphosphate (ATP), which provides usable cellular energy to the cell. Cells use ATP constantly, and so the mitochondria are constantly at work. Oxygen molecules

are required during cellular respiration, which is why you must constantly breathe it in. One of the organ systems in the body that uses huge amounts of ATP is the muscular system because ATP is required to sustain muscle contraction. As a result, muscle cells are packed full of mitochondria. Nerve cells also need large quantities of ATP to run their sodium-potassium pumps. Therefore, an individual neuron will be loaded with over a thousand mitochondria. On the other hand, a bone cell, which is not nearly as metabolically-active, might only have a couple hundred mitochondria.

Mitochondrion

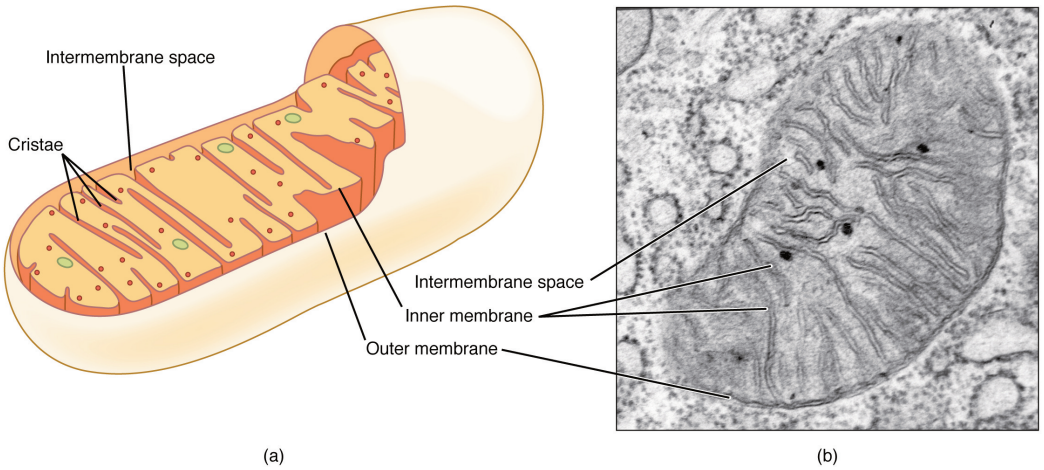


Figure 4. *The mitochondria are the energy-conversion factories of the cell. (a) A mitochondrion is composed of two separate lipid bilayer membranes. Along the inner membrane are various molecules that work together to produce ATP, the cell's major energy currency. (b) An electron micrograph of mitochondria. EM × 236,000. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

Peroxisomes

Like lysosomes, a **peroxisome** is a membrane-bound cellular organelle that contains mostly enzymes (Figure 5. Peroxisome). Peroxisomes perform a couple of different functions, including lipid metabolism and chemical detoxification. In contrast to the digestive enzymes found in lysosomes, the enzymes within peroxisomes serve to transfer hydrogen atoms from various molecules to oxygen, producing hydrogen peroxide (H_2O_2). In this way, peroxisomes neutralize poisons such as alcohol. In order to appreciate the importance of peroxisomes, it is necessary to understand the concept of reactive oxygen species.

Peroxisome

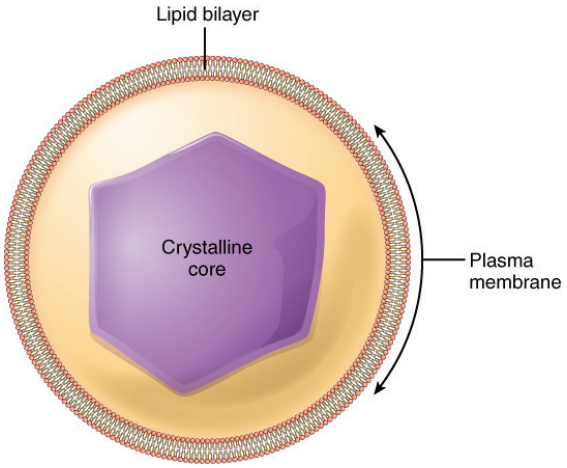


Figure 5. *Peroxisomes are membrane-bound organelles that contain an abundance of enzymes for detoxifying harmful substances and lipid metabolism.*

Reactive oxygen species (ROS) such as peroxides and free radicals are the highly reactive products of many normal cellular processes, including the mitochondrial reactions that produce ATP and oxygen metabolism. Examples of ROS include the hydroxyl radical OH, H_2O_2, and superoxide $O_2^-O_2^-$. Some ROS are important for certain cellular functions, such as cell signaling processes and immune responses against foreign substances. Free radicals are reactive because they contain free unpaired electrons; they can easily oxidize other molecules throughout the cell, causing cellular damage and even cell death. Free radicals are thought to play a role in many destructive processes in the body, from cancer to coronary artery disease.

Peroxisomes, on the other hand, oversee reactions that neutralize free radicals. Peroxisomes produce large amounts of the toxic H_2O_2 in the process, but peroxisomes contain enzymes that convert H_2O_2 into water and oxygen. These byproducts are safely released into the cytoplasm. Like miniature sewage treatment plants, peroxisomes neutralize harmful toxins so that they do not wreak havoc in the cells. The liver is the organ primarily responsible for detoxifying the blood before it travels throughout the body, and liver cells contain an exceptionally high number of peroxisomes.

Defense mechanisms such as detoxification within the peroxisome and certain cellular antioxidants serve to neutralize many of these molecules. Some vitamins and other substances, found primarily in fruits and vegetables, have antioxidant properties. Antioxidants work by being oxidized themselves, halting the destructive reaction cascades initiated by the free radicals. Sometimes though, ROS accumulate beyond the capacity of such defenses.

Oxidative stress is the term used to describe damage to cellular components caused by ROS. Due to their characteristic unpaired electrons, ROS can set off chain reactions where they remove electrons from other molecules, which then become oxidized and reactive, and do the same to other molecules, causing a chain reaction. ROS can cause permanent damage to cellular lipids, proteins, carbohydrates, and nucleic acids. Damaged DNA can lead to genetic mutations and even cancer. A **mutation** is a change in the nucleotide sequence in a gene within a cell's DNA, potentially altering the protein coded by that gene. Other diseases believed to be triggered or exacerbated by ROS include Alzheimer's disease, cardiovascular diseases, diabetes, Parkinson's disease, arthritis, Huntington's disease, and schizophrenia, among many others. It is noteworthy that these diseases are largely age-related. Many scientists believe that oxidative stress is a major contributor to the aging process.

AGING AND THE…**Cell: The Free Radical Theory**

The free radical theory on aging was originally proposed in the 1950s, and still remains under debate. Generally speaking, the free radical theory of aging suggests that accumulated cellular damage from oxidative stress contributes to the physiological and anatomical effects of aging. There are two significantly different versions of this theory: one states that the aging process itself is a result of oxidative damage, and the other states that oxidative damage causes age-related disease and disorders. The latter version of the theory is more widely accepted than the former. However, many lines of evidence suggest that oxidative damage does contribute to the aging process. Research has shown that reducing oxidative damage can result in a longer lifespan in certain organisms such as yeast, worms, and fruit flies. Conversely, increasing oxidative damage can shorten the lifespan of mice and worms. Interestingly, a manipulation called calorie-restriction (moderately restricting the caloric intake) has been shown to increase life span in some laboratory animals. It is believed that this increase is at least in part due to a reduction of oxidative stress. However, a long-term study of primates with calorie-restriction showed no increase in their lifespan. A great deal of additional research will be required to better understand the link between reactive oxygen species and aging.

The Cytoskeleton

Much like the bony skeleton structurally supports the human body, the cytoskeleton helps the cells to maintain their structural integrity. The **cytoskeleton** is a group of fibrous proteins that provide structural support for cells, but this is only one of the functions of the cytoskeleton. Cytoskeletal components are also critical for cell motility, cell reproduction, and transportation of substances within the cell.

The cytoskeleton forms a complex thread-like network throughout the cell consisting of three different kinds of protein-based filaments: microfilaments, intermediate filaments, and microtubules (Figure 6. The Three Components of the Cytoskeleton). The thickest of the three is the **microtubule**, a structural filament composed of subunits of a protein called tubulin. Microtubules maintain cell shape and structure, help resist compression of the cell, and play a role in positioning the organelles within the cell. Microtubules also make up two types of cellular appendages important for motion: cilia and flagella. **Cilia** are found on many cells of the body, including the epithelial cells that line the airways of the respiratory system. Cilia move rhythmically; they beat constantly, moving waste materials such as dust, mucus, and bacteria upward through the airways, away from the lungs and toward the mouth. Beating cilia on cells in the female fallopian tubes move egg cells from the ovary towards the uterus. A **flagellum** (plural = flagella) is an appendage larger than a cilium and specialized for cell locomotion. The only flagellated cell in humans is the sperm cell that must propel itself towards female egg cells.

The Three Components of the Cytoskeleton

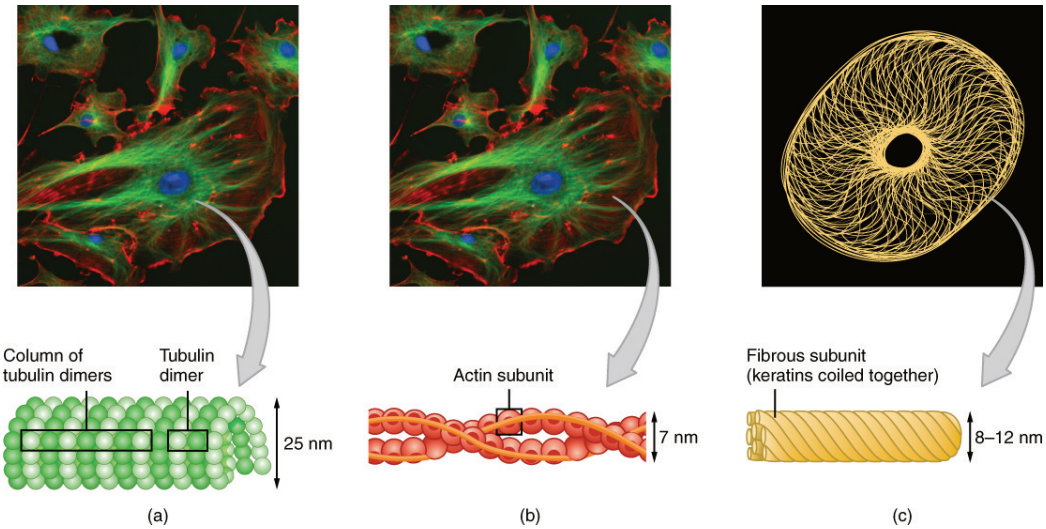


Figure 6. *The cytoskeleton consists of (a) microtubules, (b) microfilaments, and (c) intermediate filaments. The cytoskeleton plays an important role in maintaining cell shape and structure, promoting cellular movement, and aiding cell division.*

A very important function of microtubules is to set the paths (somewhat like railroad tracks) along which the genetic material can be pulled (a process requiring ATP) during cell division, so that each new daughter cell receives the appropriate set of chromosomes. Two short, identical microtubule structures called centrioles are found near the nucleus of cells. A **centriole** can serve as the cellular origin point for microtubules extending outward as cilia or flagella or can assist with the separation of DNA during cell division. Microtubules grow out from the centrioles by adding more tubulin subunits, like adding additional links to a chain.

In contrast with microtubules, the **microfilament** is a thinner type of cytoskeletal filament (see Figure 6. The Three Components of the Cytoskeleton (b)). Actin, a protein that forms chains, is the primary component of these microfilaments. Actin fibers, twisted chains of actin filaments, constitute a large component of muscle tissue and, along with the protein myosin, are responsible for muscle contraction. Like microtubules, actin filaments are long chains of single subunits (called actin subunits). In muscle cells, these long actin strands, called thin filaments, are "pulled" by thick filaments of the myosin protein to contract the cell.

Actin also has an important role during cell division. When a cell is about to split in half during cell division, actin filaments work with myosin to create a cleavage furrow that eventually splits the cell down the middle, forming two new cells from the original cell.

The final cytoskeletal filament is the intermediate filament. As its name would suggest, an **intermediate filament** is a filament intermediate in thickness between the microtubules and microfilaments (see Figure 6. The Three Components of the Cytoskeleton (c)). Intermediate filaments are made up of long fibrous subunits of a protein called keratin that are wound together like the threads that compose a rope. Intermediate filaments, in concert with the microtubules, are important for maintaining cell shape and structure. Unlike the microtubules, which resist compression, intermediate filaments resist tension—the forces that pull apart cells. There are many cases in which cells are prone to tension, such as when epithelial cells of the skin are compressed, tugging them in different directions. Intermediate filaments help anchor organelles together within a cell and also link cells to other cells by forming special cell-to-cell junctions.

Chapter Review

The internal environmental of a living cell is made up of a fluid, jelly-like substance called cytosol, which consists mainly of water, but also contains various dissolved nutrients and other molecules. The cell contains an array of cellular organelles, each one performing a unique function and helping to maintain the health and activity of the cell. The cytosol and organelles together compose the cell's cytoplasm. Most organelles are surrounded by a lipid membrane similar to the cell membrane of the cell. The endoplasmic reticulum (ER), Golgi apparatus, and lysosomes share a functional connectivity and are collectively referred to as the endomembrane system. There are two types of ER: smooth and rough. While the smooth ER performs many functions, including lipid synthesis and ion storage, the rough ER is mainly responsible for protein synthesis using its associated ribosomes. The rough ER sends newly made proteins to the Golgi apparatus where they are modified and packaged for delivery to various locations within or outside of the cell. Some of these protein products are enzymes destined to break down unwanted material and are packaged as lysosomes for use inside the cell.

Cells also contain mitochondria and peroxisomes, which are the organelles responsible for producing the cell's energy supply and detoxifying certain chemicals, respectively. Biochemical reactions within mitochondria transform energy-carrying molecules into the usable form of cellular energy known as ATP. Peroxisomes contain enzymes that transform harmful substances such as free radicals into oxygen and water. Cells also contain a miniaturized "skeleton" of protein filaments that extend throughout its interior. Three different kinds of filaments compose this cytoskeleton (in order of increasing thickness): microfilaments, intermediate filaments, and microtubules. Each cytoskeletal component performs unique functions as well as provides a supportive framework for the cell.

The Nucleus and DNA Replication

By the end of this section you will be able to:

- Describe the structure and features of the nuclear membrane
- List the contents of the nucleus
- Explain the organization of the DNA molecule within the nucleus
- Describe the process of DNA replication

The nucleus is the largest and most prominent of a cell's organelles (Figure 1. The Nucleus). The nucleus is generally considered the control center of the cell because it stores all of the genetic instructions for manufacturing proteins. Interestingly, some cells in the body, such as muscle cells, contain more than one nucleus (Figure 3. Red Blood Cell Extruding Its Nucleus), which is known as multinucleated. Other cells, such as mammalian red blood cells (RBCs), do not contain nuclei at all. RBCs eject their nuclei as they mature, making space for the large numbers of hemoglobin molecules that carry oxygen throughout the body (Figure 3. Red

Blood Cell Extruding Its Nucleus). Without nuclei, the life span of RBCs is short, and so the body must produce new ones constantly.

The Nucleus

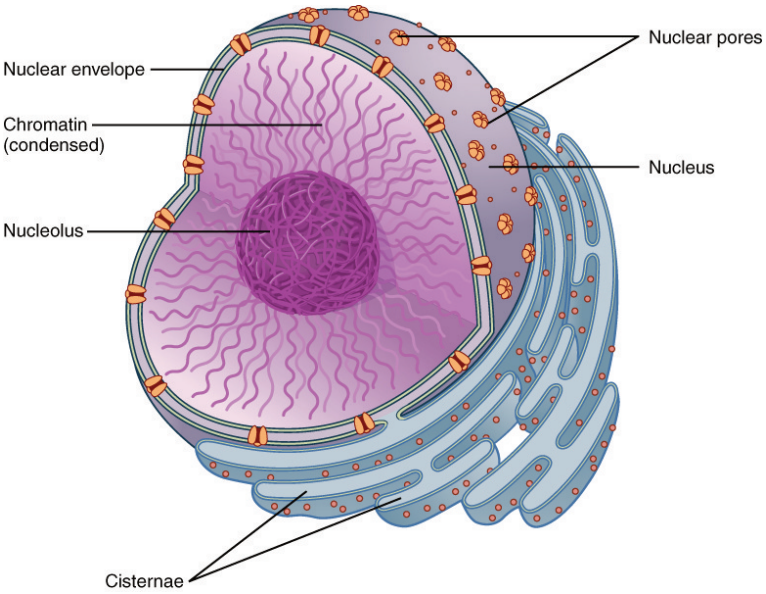


Figure 1. *The nucleus is the control center of the cell. The nucleus of living cells contains the genetic material that determines the entire structure and function of that cell.*

Multinucleate Muscle Cell

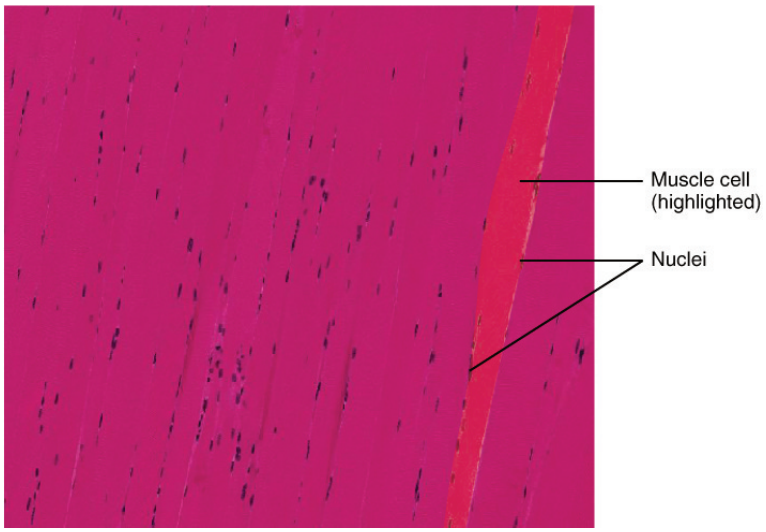


Figure 2. *Unlike cardiac muscle cells and smooth muscle cells, which have a single nucleus, a skeletal muscle cell contains many nuclei, and is referred to as "multinucleated." These muscle cells are long and fibrous (often referred to as muscle fibers). During development, many smaller cells fuse to form a mature muscle fiber. The nuclei of the fused cells are conserved in the mature cell, thus imparting a multinucleate characteristic to mature muscle cells. LM × 104.3. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://141.214.65.171/Histology/Basic%20Tissues/

Muscle/058thin_HISTO_83X.svs/view.apml to explore the tissue sample in greater detail.

Red Blood Cell Extruding Its Nucleus

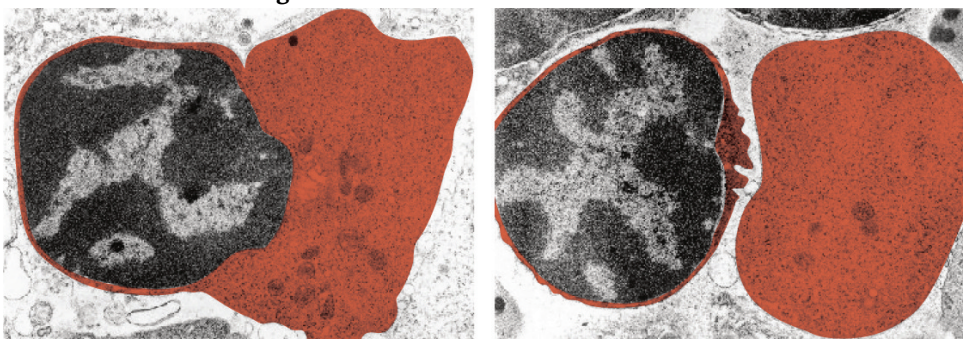


Figure 3. *Mature red blood cells lack a nucleus. As they mature, erythroblasts extrude their nucleus, making room for more hemoglobin. The two panels here show an erythroblast before and after ejecting its nucleus, respectively. (credit: modification of micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://virtualslides.med.umich.edu/Histology/EMsmallCharts/3%20Image%20Scope%20finals/139%20-%20Erythroblast_001.svs/view.apml to explore the tissue sample in greater detail.

Inside the nucleus lies the blueprint that dictates everything a cell will do and all of the products it will make. This information is stored within DNA. The nucleus sends "commands" to the cell via molecular messengers that translate the information from DNA. Each cell in your body (with the exception of germ cells) contains the complete set of your DNA. When a cell divides, the DNA must be duplicated so that the each new cell receives a full complement of DNA. The following section will explore the structure of the nucleus and its contents, as well as the process of DNA replication.

Organization of the Nucleus and Its DNA

Like most other cellular organelles, the nucleus is surrounded by a membrane called the **nuclear envelope**. This membranous covering consists of two adjacent lipid bilayers with a thin fluid space in between them. Spanning these two bilayers are nuclear pores. A **nuclear pore** is a tiny passageway for the passage of proteins, RNA, and solutes between the nucleus and the cytoplasm. Proteins called pore complexes lining the nuclear pores regulate the passage of materials into and out of the nucleus.

Inside the nuclear envelope is a gel-like nucleoplasm with solutes that include the building blocks of nucleic acids. There also can be a dark-staining mass often visible under a simple light microscope, called a **nucleolus** (plural = nucleoli). The nucleolus is a region of the nucleus that is responsible for manufacturing the

RNA necessary for construction of ribosomes. Once synthesized, newly made ribosomal subunits exit the cell's nucleus through the nuclear pores.

The genetic instructions that are used to build and maintain an organism are arranged in an orderly manner in strands of DNA. Within the nucleus are threads of **chromatin** composed of DNA and associated proteins (Figure 4. DNA Macrostructure). Along the chromatin threads, the DNA is wrapped around a set of **histone** proteins. A **nucleosome** is a single, wrapped DNA-histone complex. Multiple nucleosomes along the entire molecule of DNA appear like a beaded necklace, in which the string is the DNA and the beads are the associated histones. When a cell is in the process of division, the chromatin condenses into chromosomes, so that the DNA can be safely transported to the "daughter cells." The **chromosome** is composed of DNA and proteins; it is the condensed form of chromatin. It is estimated that humans have almost 22,000 genes distributed on 46 chromosomes.

DNA Macrostructure

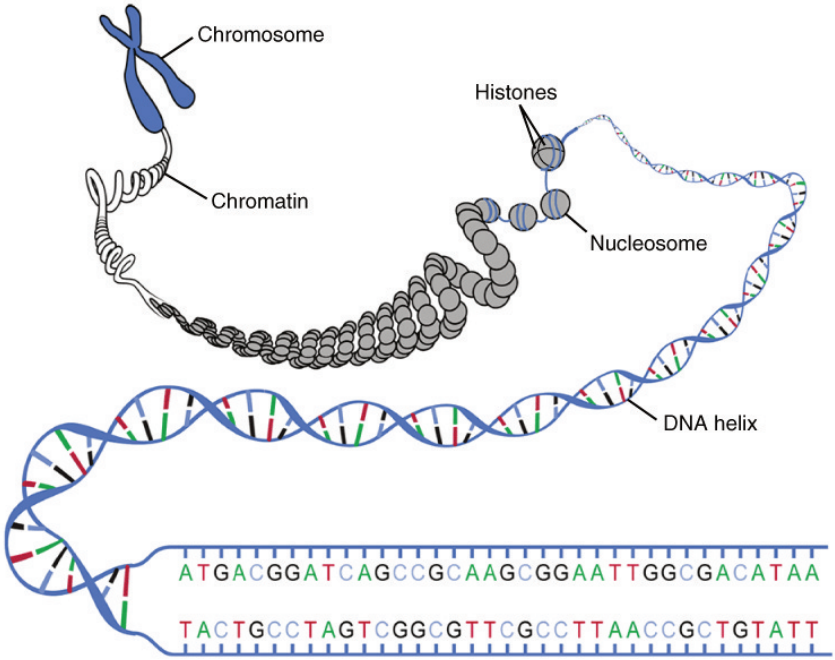


Figure 4. Strands of DNA are wrapped around supporting histones. These proteins are increasingly bundled and condensed into chromatin, which is packed tightly into chromosomes when the cell is ready to divide.

DNA Replication

In order for an organism to grow, develop, and maintain its health, cells must reproduce themselves by dividing to produce two new daughter cells, each with the full complement of DNA as found in the original cell. Billions of new cells are produced in an adult human every day. Only very few cell types in the body do not divide, including nerve cells, skeletal muscle fibers, and cardiac muscle cells. The division time of different cell types varies. Epithelial cells of the skin and gastrointestinal lining, for instance, divide very frequently to replace those that are constantly being rubbed off of the surface by friction.

A DNA molecule is made of two strands that "complement" each other in the sense that the molecules that compose the strands fit together and bind to each other, creating a double-stranded molecule that looks much like a long, twisted ladder. Each side rail of the DNA ladder is composed of alternating sugar and

phosphate groups (Figure 5. Molecular Structure of DNA). The two sides of the ladder are not identical, but are complementary. These two backbones are bonded to each other across pairs of protruding bases, each bonded pair forming one "rung," or cross member. The four DNA bases are adenine (A), thymine (T), cytosine (C), and guanine (G). Because of their shape and charge, the two bases that compose a pair always bond together. Adenine always binds with thymine, and cytosine always binds with guanine. The particular sequence of bases along the DNA molecule determines the genetic code. Therefore, if the two complementary strands of DNA were pulled apart, you could infer the order of the bases in one strand from the bases in the other, complementary strand. For example, if one strand has a region with the sequence AGTGCCT, then the sequence of the complementary strand would be TCACGGA.

Molecular Structure of DNA

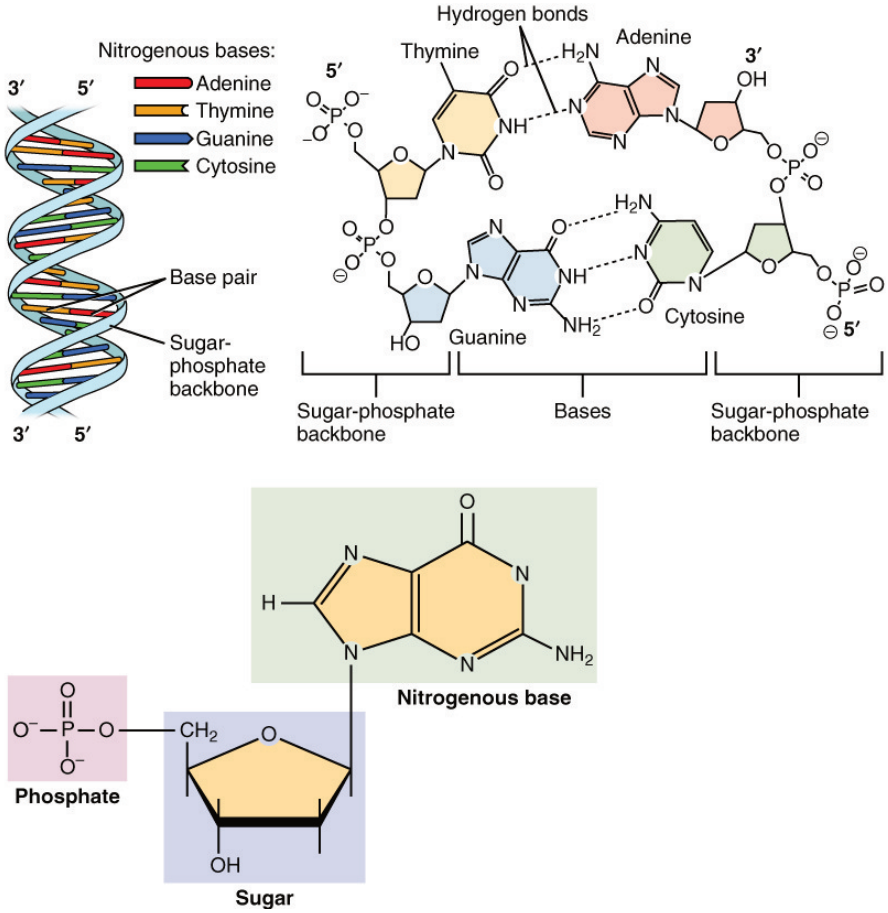


Figure 5. *The DNA double helix is composed of two complementary strands. The strands are bonded together via their nitrogenous base pairs using hydrogen bonds.*

DNA replication is the copying of DNA that occurs before cell division can take place. After a great deal of debate and experimentation, the general method of DNA replication was deduced in 1958 by two scientists in California, Matthew Meselson and Franklin Stahl. This method is illustrated in Figure 6. (DNA Replication) and described below.

DNA Replication

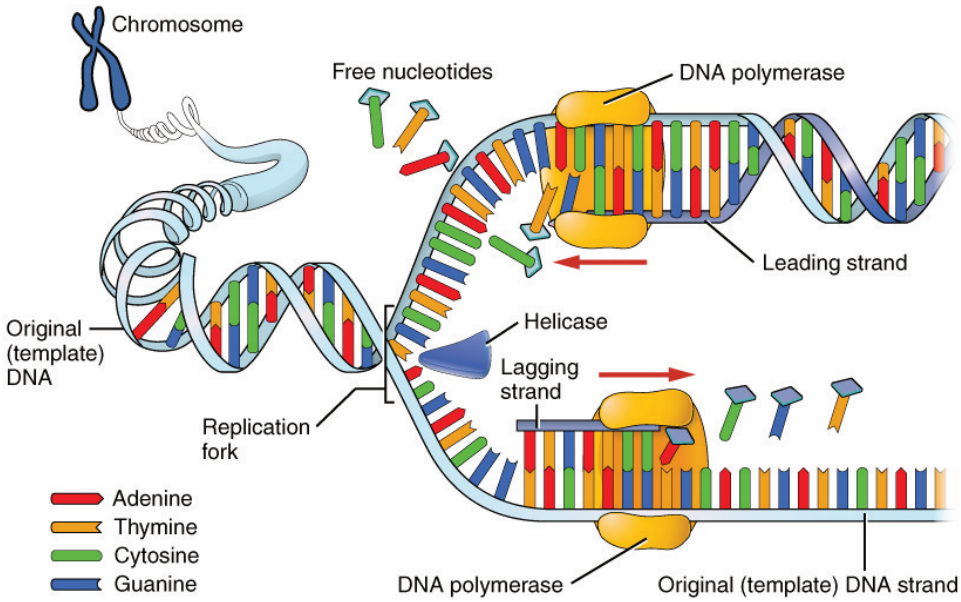


Figure 6. *DNA replication faithfully duplicates the entire genome of the cell. During DNA replication, a number of different enzymes work together to pull apart the two strands so each strand can be used as a template to synthesize new complementary strands. The two new daughter DNA molecules each contain one pre-existing strand and one newly synthesized strand. Thus, DNA replication is said to be "semiconservative."*

Stage 1: Initiation. The two complementary strands are separated, much like unzipping a zipper. Special enzymes, including **helicase**, untwist and separate the two strands of DNA.

Stage 2: Elongation. Each strand becomes a template along which a new complementary strand is built. **DNA polymerase** brings in the correct bases to complement the template strand, synthesizing a new strand base by base. A DNA polymerase is an enzyme that adds free nucleotides to the end of a chain of DNA, making a new double strand. This growing strand continues to be built until it has fully complemented the template strand.

Stage 3: Termination. Once the two original strands are bound to their own, finished, complementary strands, DNA replication is stopped and the two new identical DNA molecules are complete.

Each new DNA molecule contains one strand from the original molecule and one newly synthesized strand. The term for this mode of replication is "semiconservative," because half of the original DNA molecule is conserved in each new DNA molecule. This process continues until the cell's entire **genome**, the entire complement of an organism's DNA, is replicated. As you might imagine, it is very important that DNA replication take place precisely so that new cells in the body contain the exact same genetic material as their parent cells. Mistakes made during DNA replication, such as the accidental addition of an inappropriate nucleotide, have the potential to render a gene dysfunctional or useless. Fortunately, there are mechanisms in place to minimize such mistakes. A DNA proofreading process enlists the help of special enzymes that scan the newly synthesized molecule for mistakes and corrects them. Once the process of DNA replication is complete, the cell is ready to divide. You will explore the process of cell division later in the chapter.

Watch this video to learn about DNA replication. DNA replication proceeds simultaneously at several sites on the same molecule. What separates the base pair at the start of DNA replication?

Chapter Review

The nucleus is the command center of the cell, containing the genetic instructions for all of the materials a cell will make (and thus all of its functions it can perform). The nucleus is encased within a membrane of two interconnected lipid bilayers, side-by-side. This nuclear envelope is studded with protein-lined pores that allow materials to be trafficked into and out of the nucleus. The nucleus contains one or more nucleoli, which serve as sites for ribosome synthesis. The nucleus houses the genetic material of the cell: DNA. DNA is normally found as a loosely contained structure called chromatin within the nucleus, where it is wound up and associated with a variety of histone proteins. When a cell is about to divide, the chromatin coils tightly and condenses to form chromosomes.

There is a pool of cells constantly dividing within your body. The result is billions of new cells being created each day. Before any cell is ready to divide, it must replicate its DNA so that each new daughter cell will receive an exact copy of the organism's genome. A variety of enzymes are enlisted during DNA replication. These enzymes unwind the DNA molecule, separate the two strands, and assist with the building of complementary strands along each parent strand. The original DNA strands serve as templates from which the nucleotide sequence of the new strands are determined and synthesized. When replication is completed, two identical DNA molecules exist. Each one contains one original strand and one newly synthesized complementary strand.

Protein Synthesis

By the end of this section you will be able to:

- Explain how the genetic code stored within DNA determines the protein that will form
- Describe the process of transcription
- Describe the process of translation
- Discuss the function of ribosomes

It was mentioned earlier that DNA provides a "blueprint" for the cell structure and physiology. This refers to the fact that DNA contains the information necessary for the cell to build one very important type of molecule: the protein. Most structural components of the cell are made up, at least in part, by proteins and virtually all the functions that a cell carries out are completed with the help of proteins. One of the most important

classes of proteins is enzymes, which help speed up necessary biochemical reactions that take place inside the cell. Some of these critical biochemical reactions include building larger molecules from smaller components (such as occurs during DNA replication or synthesis of microtubules) and breaking down larger molecules into smaller components (such as when harvesting chemical energy from nutrient molecules). Whatever the cellular process may be, it is almost sure to involve proteins. Just as the cell's genome describes its full complement of DNA, a cell's **proteome** is its full complement of proteins. Protein synthesis begins with genes. A **gene** is a functional segment of DNA that provides the genetic information necessary to build a protein. Each particular gene provides the code necessary to construct a particular protein. **Gene expression**, which transforms the information coded in a gene to a final gene product, ultimately dictates the structure and function of a cell by determining which proteins are made.

The interpretation of genes works in the following way. Recall that proteins are polymers, or chains, of many amino acid building blocks. The sequence of bases in a gene (that is, its sequence of A, T, C, G nucleotides) translates to an amino acid sequence. A **triplet** is a section of three DNA bases in a row that codes for a specific amino acid. Similar to the way in which the three-letter code *d-o-g* signals the image of a dog, the three-letter DNA base code signals the use of a particular amino acid. For example, the DNA triplet CAC (cytosine, adenine, and cytosine) specifies the amino acid valine. Therefore, a gene, which is composed of multiple triplets in a unique sequence, provides the code to build an entire protein, with multiple amino acids in the proper sequence (Figure 1. The Genetic Code). The mechanism by which cells turn the DNA code into a protein product is a two-step process, with an RNA molecule as the intermediate.

The Genetic Code

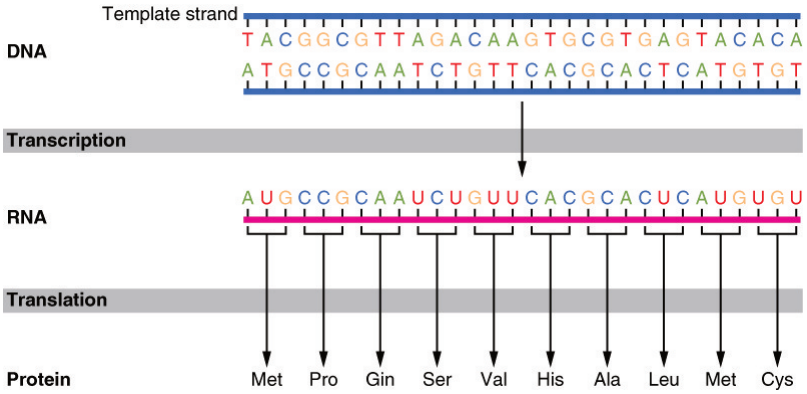


Figure 1. *DNA holds all of the genetic information necessary to build a cell's proteins. The nucleotide sequence of a gene is ultimately translated into an amino acid sequence of the gene's corresponding protein.*

From DNA to RNA: Transcription

DNA is housed within the nucleus, and protein synthesis takes place in the cytoplasm, thus there must be some sort of intermediate messenger that leaves the nucleus and manages protein synthesis. This intermediate messenger is **messenger RNA (mRNA)**, a single-stranded nucleic acid that carries a copy of the genetic code for a single gene out of the nucleus and into the cytoplasm where it is used to produce proteins.

There are several different types of RNA, each having different functions in the cell. The structure of RNA is similar to DNA with a few small exceptions. For one thing, unlike DNA, most types of RNA, including mRNA, are single-stranded and contain no complementary strand. Second, the ribose sugar in RNA contains an additional

oxygen atom compared with DNA. Finally, instead of the base thymine, RNA contains the base uracil. This means that adenine will always pair up with uracil during the protein synthesis process.

Gene expression begins with the process called **transcription**, which is the synthesis of a strand of mRNA that is complementary to the gene of interest. This process is called transcription because the mRNA is like a transcript, or copy, of the gene's DNA code. Transcription begins in a fashion somewhat like DNA replication, in that a region of DNA unwinds and the two strands separate, however, only that small portion of the DNA will be split apart. The triplets within the gene on this section of the DNA molecule are used as the template to transcribe the complementary strand of RNA (Figure 2. Transcription: from DNA to mRNA). A **codon** is a three-base sequence of mRNA, so-called because they directly encode amino acids. Like DNA replication, there are three stages to transcription: initiation, elongation, and termination.

Transcription: from DNA to mRNA

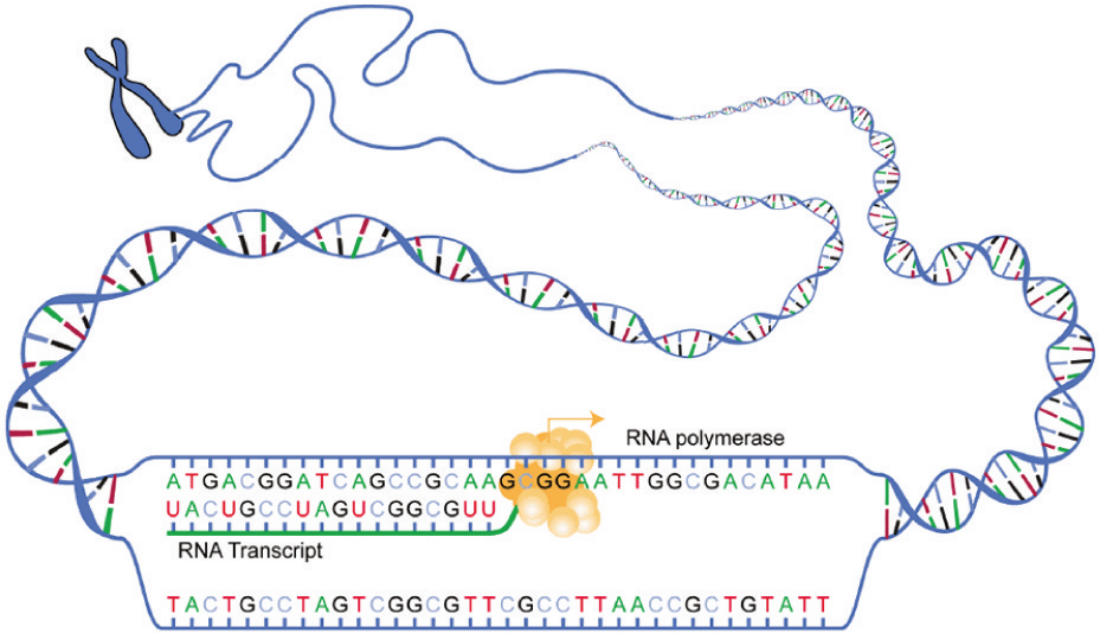


Figure 2. *In the first of the two stages of making protein from DNA, a gene on the DNA molecule is transcribed into a complementary mRNA molecule.*

Stage 1: Initiation. A region at the beginning of the gene called a **promoter**—a particular sequence of nucleotides—triggers the start of transcription.

Stage 2: Elongation. Transcription starts when RNA polymerase unwinds the DNA segment. One strand, referred to as the coding strand, becomes the template with the genes to be coded. The polymerase then aligns the correct nucleic acid (A, C, G, or U) with its complementary base on the coding strand of DNA. **RNA polymerase** is an enzyme that adds new nucleotides to a growing strand of RNA. This process builds a strand of mRNA.

Stage 3: Termination. When the polymerase has reached the end of the gene, one of three specific triplets (UAA, UAG, or UGA) codes a "stop" signal, which triggers the enzymes to terminate transcription and release the mRNA transcript.

Before the mRNA molecule leaves the nucleus and proceeds to protein synthesis, it is modified in a number of ways. For this reason, it is often called a pre-mRNA at this stage. For example, your DNA, and thus complementary mRNA, contains long regions called non-coding regions that do not code for amino acids. Their function is still a mystery, but the process called **splicing** removes these non-coding regions from the pre-mRNA transcript (Figure 3. Splicing DNA). A **spliceosome**—a structure composed of various proteins and other molecules—attaches to the mRNA and "splices" or cuts out the non-coding regions. The removed segment of the transcript is called an **intron**. The remaining exons are pasted together. An **exon** is a segment of RNA that remains after splicing. Interestingly, some introns that are removed from mRNA are not always non-coding. When different coding regions of mRNA are spliced out, different variations of the protein will eventually result, with differences in structure and function. This process results in a much larger variety of possible proteins and protein functions. When the mRNA transcript is ready, it travels out of the nucleus and into the cytoplasm.

Splicing DNA

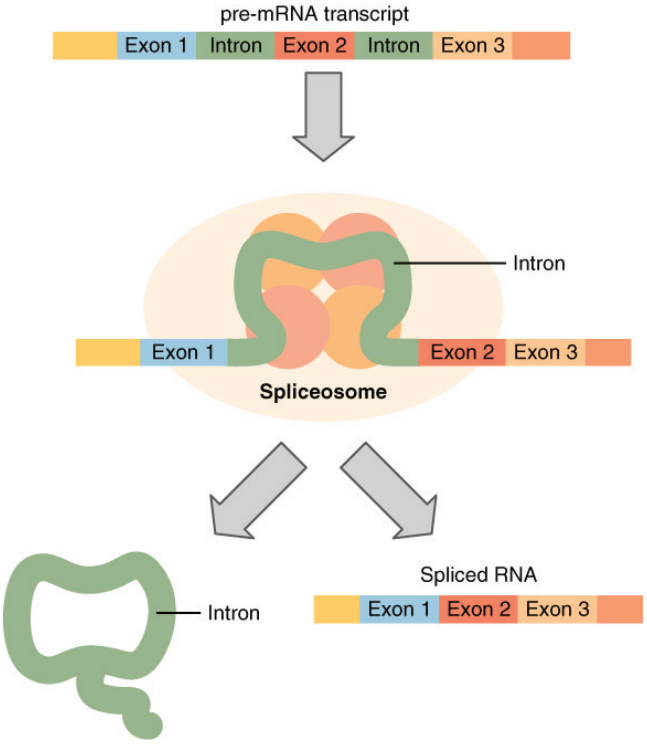


Figure 3. *In the nucleus, a structure called a spliceosome cuts out introns (noncoding regions) within a pre-mRNA transcript and reconnects the exons.*

From RNA to Protein: Translation

Like translating a book from one language into another, the codons on a strand of mRNA must be translated into the amino acid alphabet of proteins. **Translation** is the process of synthesizing a chain of amino acids called a **polypeptide**. Translation requires two major aids: first, a "translator," the molecule that will conduct the translation, and second, a substrate on which the mRNA strand is translated into a new protein, like the translator's "desk." Both of these requirements are fulfilled by other types of RNA. The substrate on which translation takes place is the ribosome.

Remember that many of a cell's ribosomes are found associated with the rough ER, and carry out the synthesis

of proteins destined for the Golgi apparatus. **Ribosomal RNA (rRNA)** is a type of RNA that, together with proteins, composes the structure of the ribosome. Ribosomes exist in the cytoplasm as two distinct components, a small and a large subunit. When an mRNA molecule is ready to be translated, the two subunits come together and attach to the mRNA. The ribosome provides a substrate for translation, bringing together and aligning the mRNA molecule with the molecular "translators" that must decipher its code.

The other major requirement for protein synthesis is the translator molecules that physically "read" the mRNA codons. **Transfer RNA (tRNA)** is a type of RNA that ferries the appropriate corresponding amino acids to the ribosome, and attaches each new amino acid to the last, building the polypeptide chain one-by-one. Thus tRNA transfers specific amino acids from the cytoplasm to a growing polypeptide. The tRNA molecules must be able to recognize the codons on mRNA and match them with the correct amino acid. The tRNA is modified for this function. On one end of its structure is a binding site for a specific amino acid. On the other end is a base sequence that matches the codon specifying its particular amino acid. This sequence of three bases on the tRNA molecule is called an **anticodon**. For example, a tRNA responsible for shuttling the amino acid glycine contains a binding site for glycine on one end. On the other end it contains an anticodon that complements the glycine codon (GGA is a codon for glycine, and so the tRNAs anticodon would read CCU). Equipped with its particular cargo and matching anticodon, a tRNA molecule can read its recognized mRNA codon and bring the corresponding amino acid to the growing chain (Figure 4. Translation from RNA to Protein).

Translation from RNA to Protein

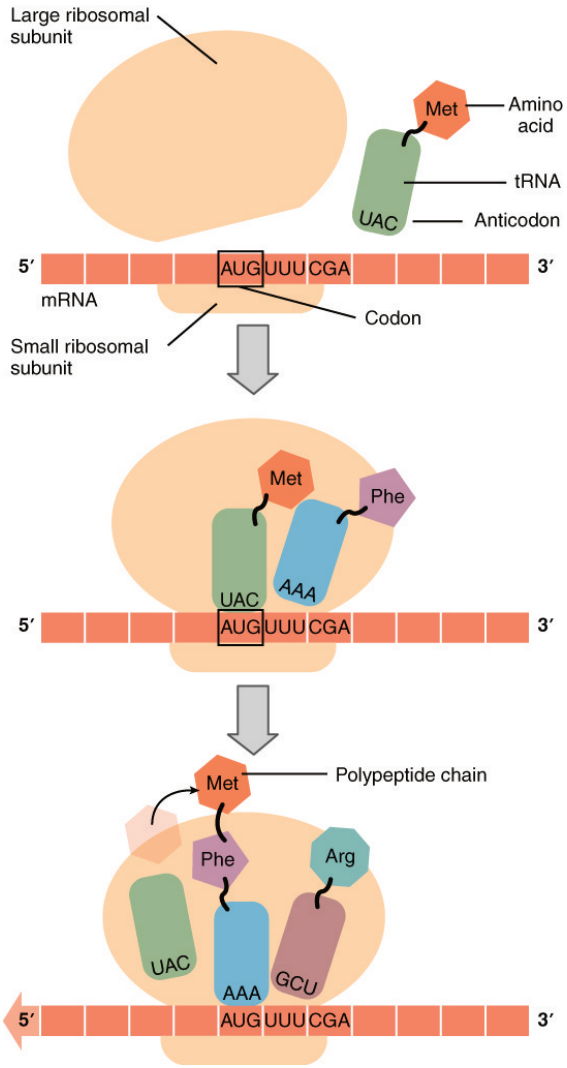


Figure 4. *During translation, the mRNA transcript is "read" by a functional complex consisting of the ribosome and tRNA molecules. tRNAs bring the appropriate amino acids in sequence to the growing polypeptide chain by matching their anti-codons with codons on the mRNA strand.*

Much like the processes of DNA replication and transcription, translation consists of three main stages: initiation, elongation, and termination. Initiation takes place with the binding of a ribosome to an mRNA transcript. The elongation stage involves the recognition of a tRNA anticodon with the next mRNA codon in the sequence. Once the anticodon and codon sequences are bound (remember, they are complementary base pairs), the tRNA presents its amino acid cargo and the growing polypeptide strand is attached to this next amino acid. This attachment takes place with the assistance of various enzymes and requires energy. The tRNA molecule then releases the mRNA strand, the mRNA strand shifts one codon over in the ribosome, and the next appropriate tRNA arrives with its matching anticodon. This process continues until the final codon on the mRNA is reached which provides a "stop" message that signals termination of translation and triggers the release of the complete, newly synthesized protein. Thus, a gene within the DNA molecule is transcribed into mRNA, which is then translated into a protein product (Figure 5. From DNA to Protein: Transcription through Translation).

From DNA to Protein: Transcription through Translation

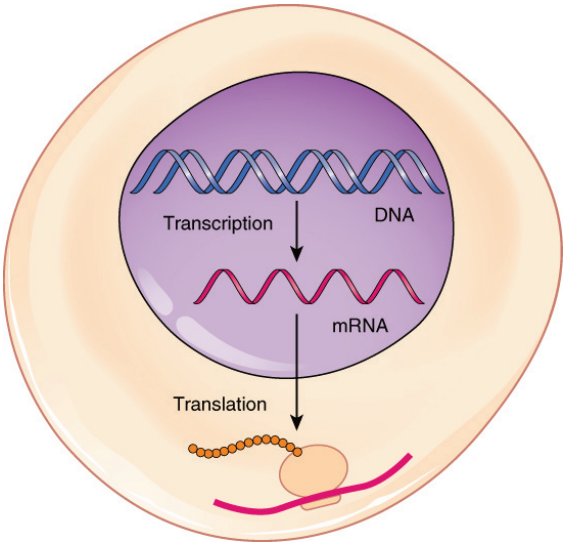


Figure 5. *Transcription within the cell nucleus produces an mRNA molecule, which is modified and then sent into the cytoplasm for translation. The transcript is decoded into a protein with the help of a ribosome and tRNA molecules.*

Commonly, an mRNA transcription will be translated simultaneously by several adjacent ribosomes. This increases the efficiency of protein synthesis. A single ribosome might translate an mRNA molecule in approximately one minute; so multiple ribosomes aboard a single transcript could produce multiple times the number of the same protein in the same minute. A **polyribosome** is a string of ribosomes translating a single mRNA strand.

Watch this video to learn about ribosomes. The ribosome binds to the mRNA molecule to start translation of its code into a protein. What happens to the small and large ribosomal subunits at the end of translation?

Chapter Review

DNA stores the information necessary for instructing the cell to perform all of its functions. Cells use the genetic code stored within DNA to build proteins, which ultimately determine the structure and function of the cell. This genetic code lies in the particular sequence of nucleotides that make up each gene along the DNA molecule. To "read" this code, the cell must perform two sequential steps. In the first step, transcription, the DNA code is converted into a RNA code. A molecule of messenger RNA that is complementary to a specific gene is synthesized in a process similar to DNA replication. The molecule of mRNA provides the code to synthesize a protein. In the process of translation, the mRNA attaches to a ribosome. Next, tRNA molecules shuttle the appropriate amino acids to the ribosome, one-by-one, coded by sequential triplet codons on the mRNA, until the protein is fully synthesized. When completed, the mRNA detaches from the ribosome, and the protein is released. Typically, multiple ribosomes attach to a single mRNA molecule at once such that multiple proteins can be manufactured from the mRNA concurrently.

Cell Growth and Division

By the end of this section you will be able to:

- Describe the stages of the cell cycle
- Discuss how the cell cycle is regulated
- Describe the implications of losing control over the cell cycle
- Describe the stages of mitosis and cytokinesis, in order

So far in this chapter, you have read numerous times of the importance and prevalence of cell division. While there are a few cells in the body that do not undergo cell division (such as gametes, red blood cells, most neurons, and some muscle cells), most somatic cells divide regularly. A **somatic cell** is a general term for a body cell, and all human cells, except for the cells that produce eggs and sperm (which are referred to as germ cells), are somatic cells. Somatic cells contain *two* copies of each of their chromosomes (one copy received from each parent). A **homologous** pair of chromosomes is the two copies of a single chromosome found in each somatic cell. The human is a **diploid** organism, having 23 homologous pairs of chromosomes in each of the somatic cells. The condition of having pairs of chromosomes is known as diploidy.

Cells in the body replace themselves over the lifetime of a person. For example, the cells lining the gastrointestinal tract must be frequently replaced when constantly "worn off" by the movement of food through the gut. But what triggers a cell to divide, and how does it prepare for and complete cell division? The **cell cycle** is the sequence of events in the life of the cell from the moment it is created at the end of a previous cycle of cell division until it then divides itself, generating two new cells.

The Cell Cycle

One "turn" or cycle of the cell cycle consists of two general phases: interphase, followed by mitosis and cytokinesis. **Interphase** is the period of the cell cycle during which the cell is not dividing. The majority of cells are in interphase most of the time. **Mitosis** is the division of genetic material, during which the cell nucleus breaks down and two new, fully functional, nuclei are formed. **Cytokinesis** divides the cytoplasm into two distinctive cells.

Interphase

A cell grows and carries out all normal metabolic functions and processes in a period called G_1 (Figure 1. Cell Cycle). **G_1 phase** (gap 1 phase) is the first gap, or growth phase in the cell cycle. For cells that will divide again, G_1 is followed by replication of the DNA, during the S phase. The **S phase** (synthesis phase) is period during which a cell replicates its DNA.

Cell Cycle

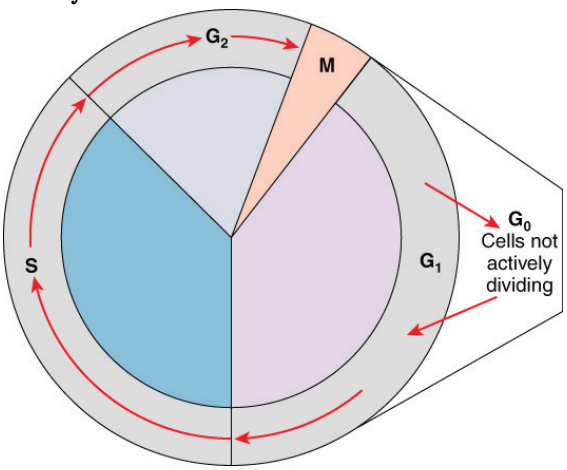


Figure 1. *The two major phases of the cell cycle include mitosis (cell division), and interphase, when the cell grows and performs all of its normal functions. Interphase is further subdivided into* G_1*,* S*, and* G_2 *phases.*

After the synthesis phase, the cell proceeds through the G_2 phase. The **G_2 phase** is a second gap phase, during which the cell continues to grow and makes the necessary preparations for mitosis. Between G_1, S, and G_2 phases, cells will vary the most in their duration of the G1 phase. It is here that a cell might spend a couple of hours, or many days. The S phase typically lasts between 8-10 hours and the G_2 phase approximately 5 hours. In contrast to these phases, the **G_0 phase** is a resting phase of the cell cycle. Cells that have temporarily stopped dividing and are resting (a common condition) and cells that have permanently ceased dividing (like nerve cells) are said to be in G_0.

The Structure of Chromosomes

Billions of cells in the human body divide every day. During the synthesis phase (S, for DNA synthesis) of interphase, the amount of DNA within the cell precisely doubles. Therefore, after DNA replication but before cell division, each cell actually contains *two* copies of each chromosome. Each copy of the chromosome is referred to as a **sister chromatid** and is physically bound to the other copy. The **centromere** is the structure that attaches one sister chromatid to another. Because a human cell has 46 chromosomes, during this phase, there are 92 chromatids (46 × 2) in the cell. Make sure not to confuse the concept of a pair of chromatids (one chromosome and its exact copy attached during mitosis) and a homologous pair of chromosomes (two paired chromosomes which were inherited separately, one from each parent) (Figure 2. A Homologous Pair of Chromosomes with their Attached Sister Chromatids).

A Homologous Pair of Chromosomes with their Attached Sister Chromatids

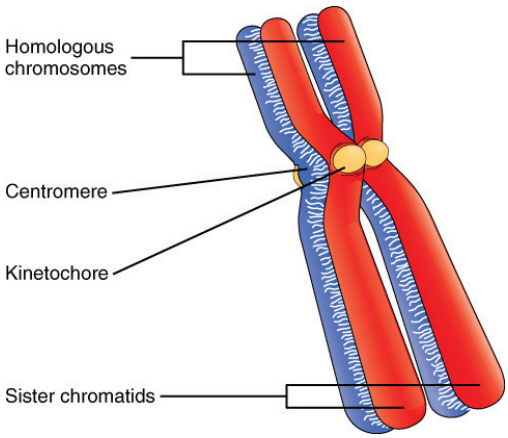


Figure 2. *The red and blue colors correspond to a homologous pair of chromosomes. Each member of the pair was separately inherited from one parent. Each chromosome in the homologous pair is also bound to an identical sister chromatid, which is produced by DNA replication, and results in the familiar "X" shape.*

Mitosis and Cytokinesis

The **mitotic phase** of the cell typically takes between 1 and 2 hours. During this phase, a cell undergoes two major processes. First, it completes mitosis, during which the contents of the nucleus are equitably pulled apart and distributed between its two halves. Cytokinesis then occurs, dividing the cytoplasm and cell body into two new cells. Mitosis is divided into four major stages that take place after interphase (Figure 3. Cell Division: Mitosis Followed by Cytokinesis) and in the following order: prophase, metaphase, anaphase, and telophase. The process is then followed by cytokinesis.

Cell Division: Mitosis Followed by Cytokinesis

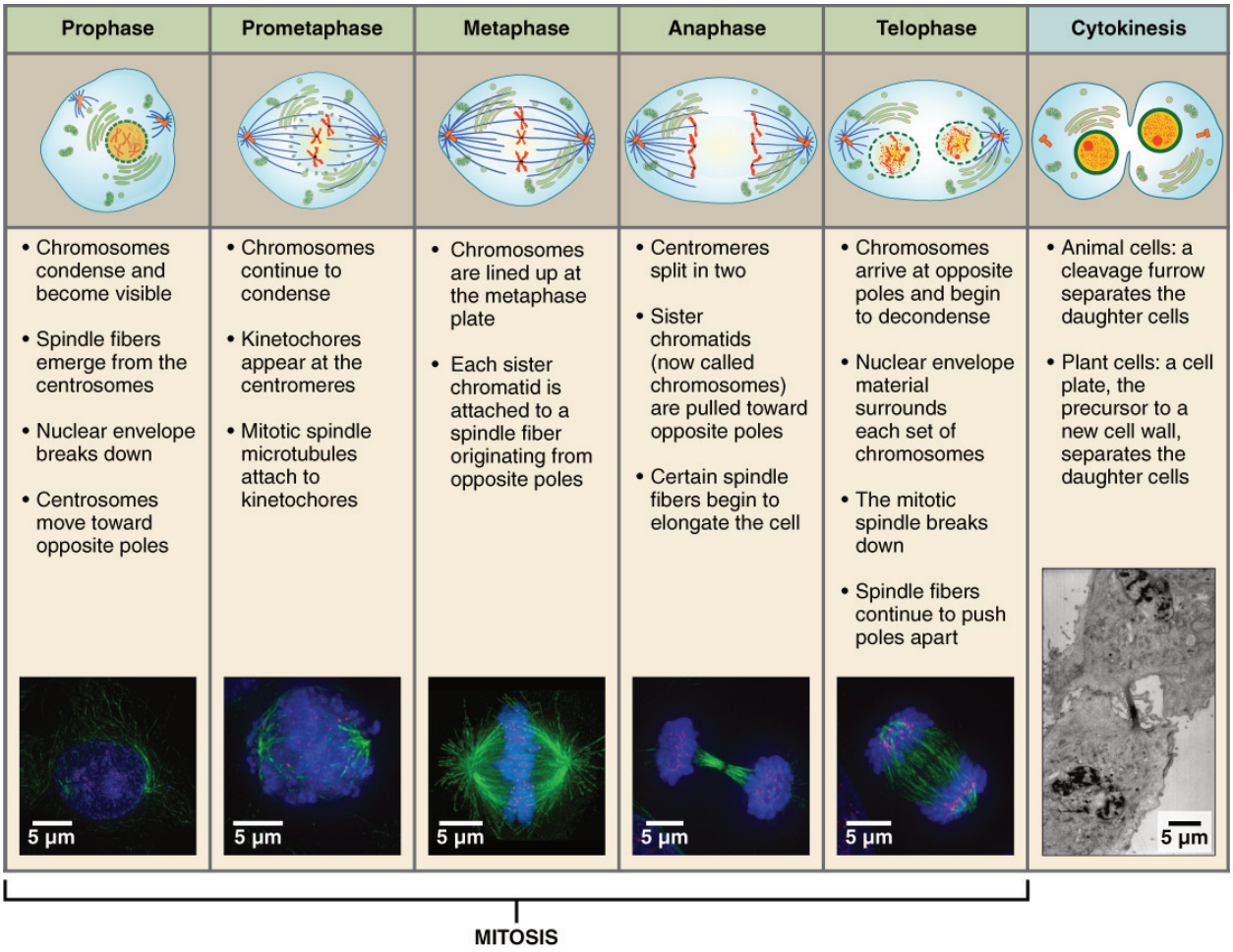


Figure 3. *The stages of cell division oversee the separation of identical genetic material into two new nuclei, followed by the division of the cytoplasm.*

Prophase is the first phase of mitosis, during which the loosely packed chromatin coils and condenses into visible chromosomes. During prophase, each chromosome becomes visible with its identical partner attached, forming the familiar X-shape of sister chromatids. The nucleolus disappears early during this phase, and the nuclear envelope also disintegrates.

A major occurrence during prophase concerns a very important structure that contains the origin site for microtubule growth. Recall the cellular structures called centrioles that serve as origin points from which microtubules extend. These tiny structures also play a very important role during mitosis. A **centrosome** is a pair of centrioles together. The cell contains two centrosomes side-by-side, which begin to move apart during prophase. As the centrosomes migrate to two different sides of the cell, microtubules begin to extend from each like long fingers from two hands extending toward each other. The **mitotic spindle** is the structure composed of the centrosomes and their emerging microtubules.

Near the end of prophase there is an invasion of the nuclear area by microtubules from the mitotic spindle. The nuclear membrane has disintegrated, and the microtubules attach themselves to the centromeres that adjoin pairs of sister chromatids. The **kinetochore** is a protein structure on the centromere that is the point of attachment between the mitotic spindle and the sister chromatids. This stage is referred to as late prophase or "prometaphase" to indicate the transition between prophase and metaphase.

Metaphase is the second stage of mitosis. During this stage, the sister chromatids, with their attached

microtubules, line up along a linear plane in the middle of the cell. A metaphase plate forms between the centrosomes that are now located at either end of the cell. The **metaphase plate** is the name for the plane through the center of the spindle on which the sister chromatids are positioned. The microtubules are now poised to pull apart the sister chromatids and bring one from each pair to each side of the cell.

Anaphase is the third stage of mitosis. Anaphase takes place over a few minutes, when the pairs of sister chromatids are separated from one another, forming individual chromosomes once again. These chromosomes are pulled to opposite ends of the cell by their kinetochores, as the microtubules shorten. Each end of the cell receives one partner from each pair of sister chromatids, ensuring that the two new daughter cells will contain identical genetic material.

Telophase is the final stage of mitosis. Telophase is characterized by the formation of two new daughter nuclei at either end of the dividing cell. These newly formed nuclei surround the genetic material, which uncoils such that the chromosomes return to loosely packed chromatin. Nucleoli also reappear within the new nuclei, and the mitotic spindle breaks apart, each new cell receiving its own complement of DNA, organelles, membranes, and centrioles. At this point, the cell is already beginning to split in half as cytokinesis begins.

The **cleavage furrow** is a contractile band made up of microfilaments that forms around the midline of the cell during cytokinesis. (Recall that microfilaments consist of actin.) This contractile band squeezes the two cells apart until they finally separate. Two new cells are now formed. One of these cells (the "stem cell") enters its own cell cycle; able to grow and divide again at some future time. The other cell transforms into the functional cell of the tissue, typically replacing an "old" cell there.

Imagine a cell that completed mitosis but never underwent cytokinesis. In some cases, a cell may divide its genetic material and grow in size, but fail to undergo cytokinesis. This results in larger cells with more than one nucleus. Usually this is an unwanted aberration and can be a sign of cancerous cells.

Cell Cycle Control

A very elaborate and precise system of regulation controls direct the way cells proceed from one phase to the next in the cell cycle and begin mitosis. The control system involves molecules within the cell as well as external triggers. These internal and external control triggers provide "stop" and "advance" signals for the cell. Precise regulation of the cell cycle is critical for maintaining the health of an organism, and loss of cell cycle control can lead to cancer.

Mechanisms of Cell Cycle Control

As the cell proceeds through its cycle, each phase involves certain processes that must be completed before the cell should advance to the next phase. A **checkpoint** is a point in the cell cycle at which the cycle can be signaled to move forward or stopped. At each of these checkpoints, different varieties of molecules provide the stop or go signals, depending on certain conditions within the cell. A **cyclin** is one of the primary classes of cell cycle control molecules (Figure 4. Control of the Cell Cycle). A **cyclin-dependent kinase (CDK)** is one of a group of molecules that work together with cyclins to determine progression past cell checkpoints. By interacting with many additional molecules, these triggers push the cell cycle forward unless prevented from doing so by "stop" signals, if for some reason the cell is not ready. At the G_1 checkpoint, the cell must be ready for DNA synthesis to occur. At the G_2checkpoint the cell must be fully prepared for mitosis. Even during mitosis, a crucial stop

and go checkpoint in metaphase ensures that the cell is fully prepared to complete cell division. The metaphase checkpoint ensures that all sister chromatids are properly attached to their respective microtubules and lined up at the metaphase plate before the signal is given to separate them during anaphase.

Control of the Cell Cycle

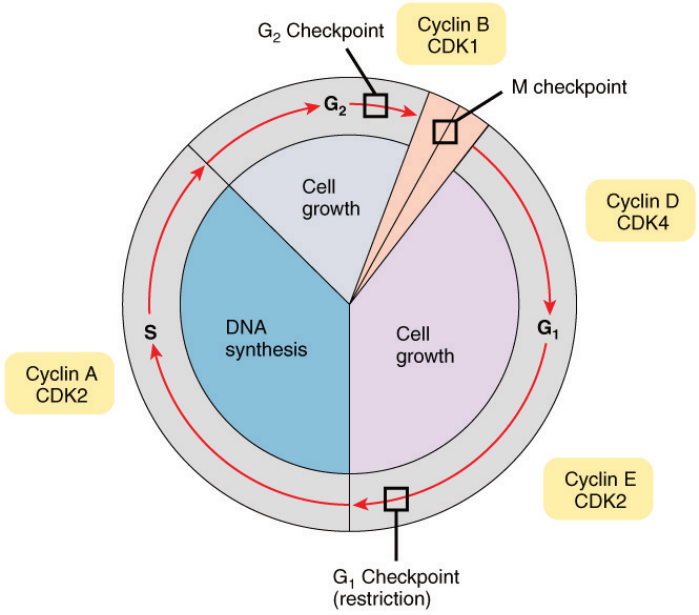


Figure 4. *Cells proceed through the cell cycle under the control of a variety of molecules, such as cyclins and cyclin-dependent kinases. These control molecules determine whether or not the cell is prepared to move into the following stage.*

The Cell Cycle Out of Control: Implications

Most people understand that cancer or tumors are caused by abnormal cells that multiply continuously. If the abnormal cells continue to divide unstopped, they can damage the tissues around them, spread to other parts of the body, and eventually result in death. In healthy cells, the tight regulation mechanisms of the cell cycle prevent this from happening, while failures of cell cycle control can cause unwanted and excessive cell division. Failures of control may be caused by inherited genetic abnormalities that compromise the function of certain "stop" and "go" signals. Environmental insult that damages DNA can also cause dysfunction in those signals. Often, a combination of both genetic predisposition and environmental factors lead to cancer.

The process of a cell escaping its normal control system and becoming cancerous may actually happen throughout the body quite frequently. Fortunately, certain cells of the immune system are capable of recognizing cells that have become cancerous and destroying them. However, in certain cases the cancerous cells remain undetected and continue to proliferate. If the resulting tumor does not pose a threat to surrounding tissues, it is said to be benign and can usually be easily removed. If capable of damage, the tumor is considered malignant and the patient is diagnosed with cancer.

HOMEOSTATIC IMBALANCES

Cancer Arises from Homeostatic Imbalances Cancer is an extremely complex condition, capable of arising from a wide variety of genetic and environmental causes. Typically, mutations or aberrations in a cell's DNA that compromise normal cell cycle control systems lead to cancerous tumors. Cell cycle control is an example of a homeostatic mechanism that maintains proper cell function and health. While progressing through the phases of the cell cycle, a large variety of intracellular molecules provide stop and go signals to regulate movement forward to the next phase. These signals are maintained in an intricate balance so that the cell only proceeds to the next phase when it is ready. This homeostatic control of the cell cycle can be thought of like a car's cruise control. Cruise control will continually apply just the right amount of acceleration to maintain a desired speed, unless the driver hits the brakes, in which case the car will slow down. Similarly, the cell includes molecular messengers, such as cyclins, that push the cell forward in its cycle.

In addition to cyclins, a class of proteins that are encoded by genes called proto-oncogenes provide important signals that regulate the cell cycle and move it forward. Examples of proto-oncogene products include cell-surface receptors for growth factors, or cell-signaling molecules, two classes of molecules that can promote DNA replication and cell division. In contrast, a second class of genes known as tumor suppressor genes sends stop signals during a cell cycle. For example, certain protein products of tumor suppressor genes signal potential problems with the DNA and thus stop the cell from dividing, while other proteins signal the cell to die if it is damaged beyond repair. Some tumor suppressor proteins also signal a sufficient surrounding cellular density, which indicates that the cell need not presently divide. The latter function is uniquely important in preventing tumor growth: normal cells exhibit a phenomenon called "contact inhibition;" thus, extensive cellular contact with neighboring cells causes a signal that stops further cell division.

These two contrasting classes of genes, proto-oncogenes and tumor suppressor genes, are like the accelerator and brake pedal of the cell's own "cruise control system," respectively. Under normal conditions, these stop and go signals are maintained in a homeostatic balance. Generally speaking, there are two ways that the cell's cruise control can lose control: a malfunctioning (overactive) accelerator, or a malfunctioning (underactive) brake. When compromised through a mutation, or otherwise altered, proto-oncogenes can be converted to oncogenes, which produce oncoproteins that push a cell forward in its cycle and stimulate cell division even when it is undesirable to do so. For example, a cell that should be programmed to self-destruct (a process called apoptosis) due to extensive DNA damage might instead be triggered to proliferate by an oncoprotein. On the other hand, a dysfunctional tumor suppressor gene may fail to provide the cell with a necessary stop signal, also resulting in unwanted cell division and proliferation.

A delicate homeostatic balance between the many proto-oncogenes and tumor suppressor genes delicately controls the cell cycle and ensures that only healthy cells replicate. Therefore, a disruption of this homeostatic balance can cause aberrant cell division and cancerous growths.

Visit this link to learn about mitosis. Mitosis results in two identical diploid cells. What structures

forms during prophase?

Chapter Review

The life of cell consists of stages that make up the cell cycle. After a cell is born, it passes through an interphase before it is ready to replicate itself and produce daughter cells. This interphase includes two gap phases (G_1 and G_2), as well as an S phase, during which its DNA is replicated in preparation for cell division. The cell cycle is under precise regulation by chemical messengers both inside and outside the cell that provide "stop" and "go" signals for movement from one phase to the next. Failures of these signals can result in cells that continue to divide uncontrollably, which can lead to cancer.

Once a cell has completed interphase and is ready for cell division, it proceeds through four separate stages of mitosis (prophase, metaphase, anaphase, and telophase). Telophase is followed by the division of the cytoplasm (cytokinesis), which generates two daughter cells. This process takes place in all normally dividing cells of the body except for the germ cells that produce eggs and sperm.

Cellular Differentiation

By the end of this section you will be able to:

- Discuss how the generalized cells of a developing embryo or the stem cells of an adult organism become differentiated into specialized cells
- Distinguish between the categories of stem cells

How does a complex organism such as a human develop from a single cell—a fertilized egg—into the vast array of cell types such as nerve cells, muscle cells, and epithelial cells that characterize the adult? Throughout development and adulthood, the process of cellular differentiation leads cells to assume their final morphology and physiology. Differentiation is the process by which unspecialized cells become specialized to carry out distinct functions.

Stem Cells

A **stem cell** is an unspecialized cell that can divide without limit as needed and can, under specific conditions,

differentiate into specialized cells. Stem cells are divided into several categories according to their potential to differentiate.

The first embryonic cells that arise from the division of the zygote are the ultimate stem cells; these stems cells are described as **totipotent** because they have the potential to differentiate into any of the cells needed to enable an organism to grow and develop.

The embryonic cells that develop from totipotent stem cells and are precursors to the fundamental tissue layers of the embryo are classified as pluripotent. A **pluripotent** stem cell is one that has the potential to differentiate into any type of human tissue but cannot support the full development of an organism. These cells then become slightly more specialized, and are referred to as multipotent cells.

A **multipotent** stem cell has the potential to differentiate into different types of cells within a given cell lineage or small number of lineages, such as a red blood cell or white blood cell.

Finally, multipotent cells can become further specialized oligopotent cells. An **oligopotent** stem cell is limited to becoming one of a few different cell types. In contrast, a **unipotent** cell is fully specialized and can only reproduce to generate more of its own specific cell type.

Stem cells are unique in that they can also continually divide and regenerate new stem cells instead of further specializing. There are different stem cells present at different stages of a human's life. They include the embryonic stem cells of the embryo, fetal stem cells of the fetus, and adult stem cells in the adult. One type of adult stem cell is the epithelial stem cell, which gives rise to the keratinocytes in the multiple layers of epithelial cells in the epidermis of skin. Adult bone marrow has three distinct types of stem cells: hematopoietic stem cells, which give rise to red blood cells, white blood cells, and platelets (Figure 1. Hematopoiesis); endothelial stem cells, which give rise to the endothelial cell types that line blood and lymph vessels; and mesenchymal stem cells, which give rise to the different types of muscle cells.

Hematopoiesis

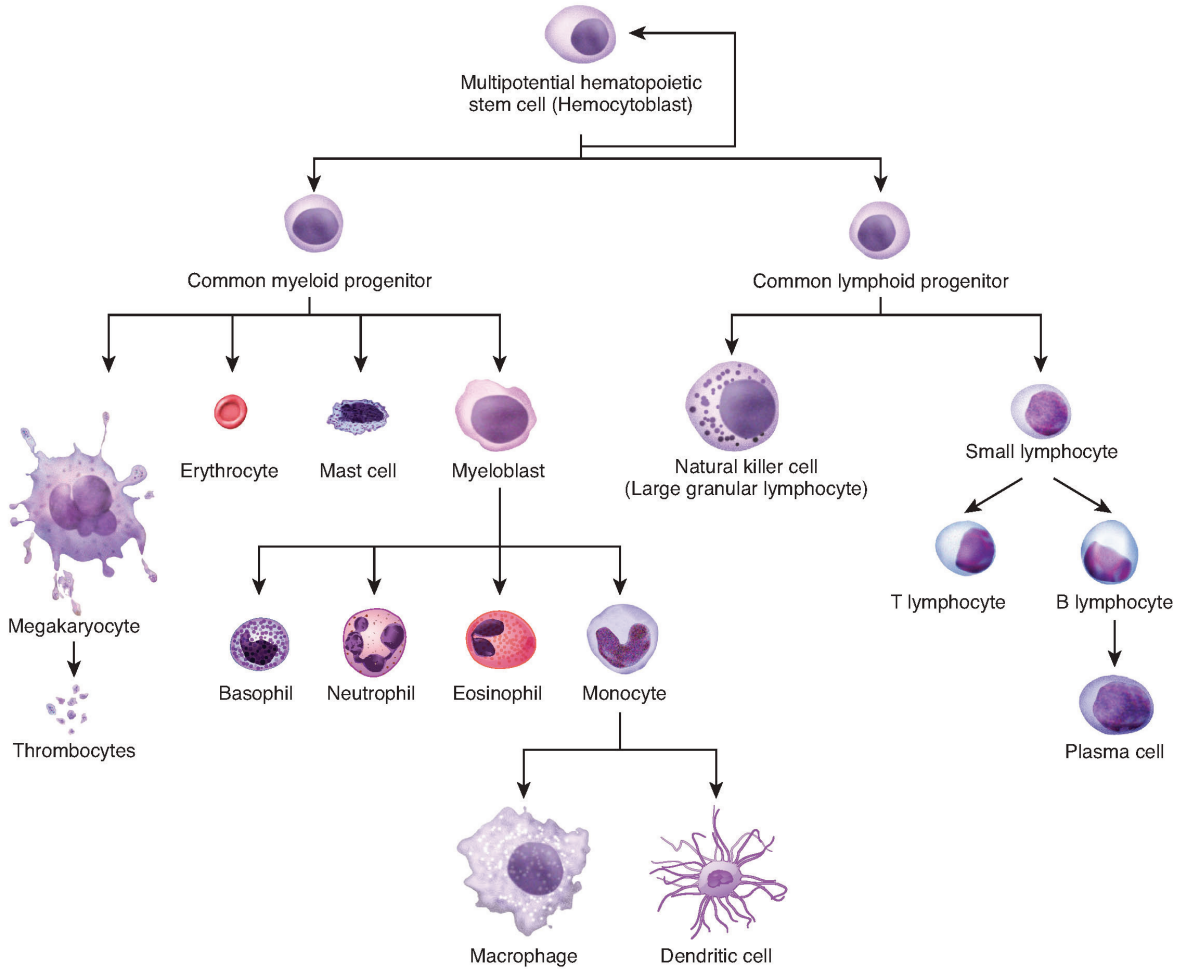


Figure 1. *The process of hematopoiesis involves the differentiation of multipotent cells into blood and immune cells. The multipotent hematopoietic stem cells give rise to many different cell types, including the cells of the immune system and red blood cells.*

Differentiation

When a cell differentiates (becomes more specialized), it may undertake major changes in its size, shape, metabolic activity, and overall function. Because all cells in the body, beginning with the fertilized egg, contain the same DNA, how do the different cell types come to be so different? The answer is analogous to a movie script. The different actors in a movie all read from the same script, however, they are each only reading their own part of the script. Similarly, all cells contain the same full complement of DNA, but each type of cell only "reads" the portions of DNA that are relevant to its own function. In biology, this is referred to as the unique genetic expression of each cell.

In order for a cell to differentiate into its specialized form and function, it need only manipulate those genes (and thus those proteins) that will be expressed, and not those that will remain silent. The primary mechanism by which genes are turned "on" or "off" is through transcription factors. A transcription factor is one of a class

of proteins that bind to specific genes on the DNA molecule and either promote or inhibit their transcription (Figure 2. Transcription Factors Regulate Gene Expression).

Transcription Factors Regulate Gene Expression

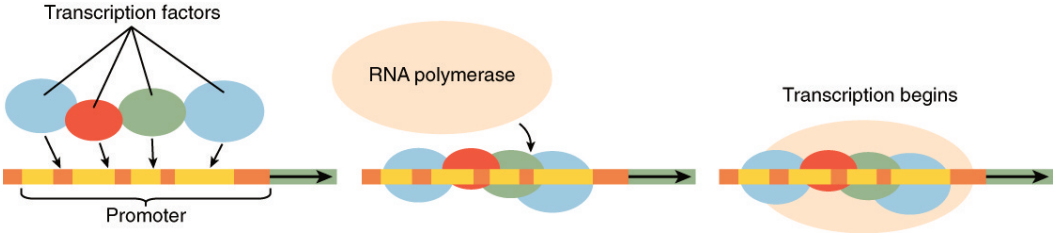


Figure 2. *While each body cell contains the organism's entire genome, different cells regulate gene expression with the use of various transcription factors. Transcription factors are proteins that affect the binding of RNA polymerase to a particular gene on the DNA molecule.*

EVERYDAY CONNECTION

Stem Cell Research Stem cell research aims to find ways to use stem cells to regenerate and repair cellular damage. Over time, most adult cells undergo the wear and tear of aging and lose their ability to divide and repair themselves. Stem cells do not display a particular morphology or function. Adult stem cells, which exist as a small subset of cells in most tissues, keep dividing and can differentiate into a number of specialized cells generally formed by that tissue. These cells enable the body to renew and repair body tissues.

The mechanisms that induce a non-differentiated cell to become a specialized cell are poorly understood. In a laboratory setting, it is possible to induce stem cells to differentiate into specialized cells by changing the physical and chemical conditions of growth. Several sources of stem cells are used experimentally and are classified according to their origin and potential for differentiation. Human embryonic stem cells (hESCs) are extracted from embryos and are pluripotent. The adult stem cells that are present in many organs and differentiated tissues, such as bone marrow and skin, are multipotent, being limited in differentiation to the types of cells found in those tissues. The stem cells isolated from umbilical cord blood are also multipotent, as are cells from deciduous teeth (baby teeth). Researchers have recently developed induced pluripotent stem cells (iPSCs) from mouse and human adult stem cells. These cells are genetically reprogrammed multipotent adult cells that function like embryonic stem cells; they are capable of generating cells characteristic of all three germ layers.

Because of their capacity to divide and differentiate into specialized cells, stem cells offer a potential treatment for diseases such as diabetes and heart disease (Figure 3. Stem Cells). Cell-based therapy refers to treatment in which stem cells induced to differentiate in a growth dish are injected into a patient to repair damaged or destroyed cells or tissues. Many obstacles must be overcome for the application of cell-based therapy. Although embryonic stem cells have a nearly unlimited range of differentiation potential, they are seen as foreign by the patient's immune system and may trigger rejection. Also, the destruction of embryos to isolate embryonic stem cells raises considerable ethical and legal questions.

Stem Cells

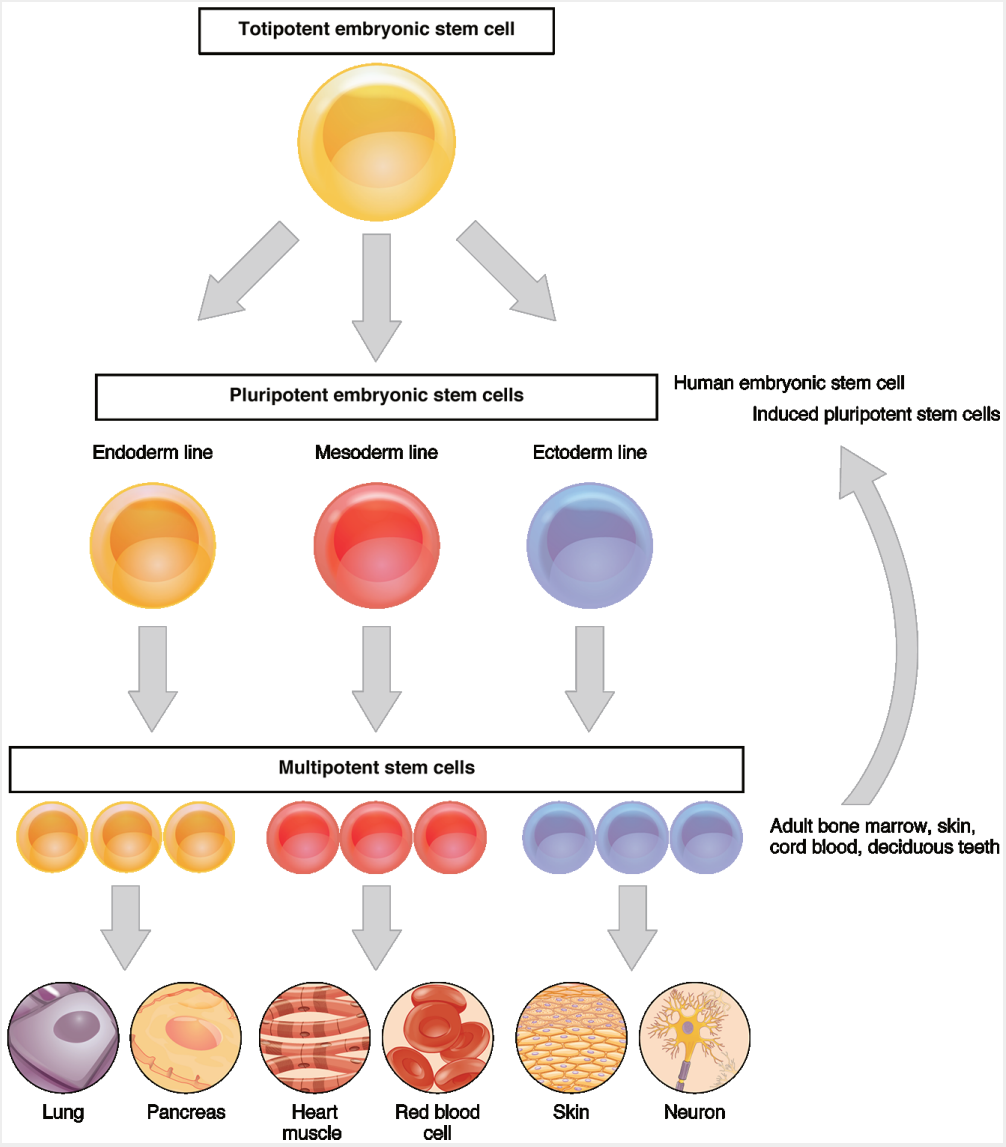


Figure 3. *The capacity of stem cells to differentiate into specialized cells make them potentially valuable in therapeutic applications designed to replace damaged cells of different body tissues.*

In contrast, adult stem cells isolated from a patient are not seen as foreign by the body, but they have a limited range of differentiation. Some individuals bank the cord blood or deciduous teeth of their child, storing away those sources of stem cells for future use, should their child need it. Induced pluripotent stem cells are considered a promising advance in the field because using them avoids the legal, ethical, and immunological pitfalls of embryonic stem cells.

Chapter Review

One of the major areas of research in biology is that of how cells specialize to assume their unique structures and functions, since all cells essentially originate from a single fertilized egg. Cell differentiation is the process of cells becoming specialized as they body develops. A stem cell is an unspecialized cell that can divide without limit as needed and can, under specific conditions, differentiate into specialized cells. Stem cells are divided into several categories according to their potential to differentiate. While all somatic cells contain the exact same genome, different cell types only express some of those genes at any given time. These differences in gene expression ultimately dictate a cell's unique morphological and physiological characteristics. The primary mechanism that determines which genes will be expressed and which ones will not is through the use of different transcription factor proteins, which bind to DNA and promote or hinder the transcription of different genes. Through the action of these transcription factors, cells specialize into one of hundreds of different cell types in the human body.

License

1.2 The Nervous System and Nervous Tissue

Introduction

Robotic Arms Playing Foosball

Figure 1. *As the neural circuitry of the nervous system has become more fully understood and robotics more sophisticated, it is now possible to integrate technology with the body and restore abilities following traumatic events. At some point in the future, will this type of technology lead to the ability to augment our nervous systems? (credit: U.S. Army/Wikimedia Commons)*

After studying this chapter, you will be able to:

- Name the major divisions of the nervous system, both anatomical and functional
- Describe the functional and structural differences between gray matter and white matter structures
- Name the parts of the multipolar neuron in order of polarity
- List the types of glial cells and assign each to the proper division of the nervous system, along with their function(s)

- Distinguish the major functions of the nervous system: sensation, integration, and response
- Describe the components of the membrane that establish the resting membrane potential
- Describe the changes that occur to the membrane that result in the action potential
- Explain the differences between types of graded potentials
- Categorize the major neurotransmitters by chemical type and effect

The nervous system is a very complex organ system. In Peter D. Kramer's book *Listening to Prozac*, a pharmaceutical researcher is quoted as saying, "If the human brain were simple enough for us to understand, we would be too simple to understand it" (1994). That quote is from the early 1990s; in the two decades since, progress has continued at an amazing rate within the scientific disciplines of neuroscience. It is an interesting conundrum to consider that the complexity of the nervous system may be too complex for it (that is, for us) to completely unravel. But our current level of understanding is probably nowhere close to that limit.

One easy way to begin to understand the structure of the nervous system is to start with the large divisions and work through to a more in-depth understanding. In other chapters, the finer details of the nervous system will be explained, but first looking at an overview of the system will allow you to begin to understand how its parts work together. The focus of this chapter is on nervous (neural) tissue, both its structure and its function. But before you learn about that, you will see a big picture of the system—actually, a few big pictures.

Basic Structure and Function of the Nervous System

By the end of this section, you will be able to:

- Identify the anatomical and functional divisions of the nervous system
- Relate the functional and structural differences between gray matter and white matter structures of the nervous system to the structure of neurons
- List the basic functions of the nervous system

The picture you have in your mind of the nervous system probably includes the **brain**, the nervous tissue contained within the cranium, and the **spinal cord**, the extension of nervous tissue within the vertebral column. That suggests it is made of two organs—and you may not even think of the spinal cord as an organ—but the nervous system is a very complex structure. Within the brain, many different and separate regions are responsible for many different and separate functions. It is as if the nervous system is composed of many organs that all look similar and can only be differentiated using tools such as the microscope or electrophysiology. In comparison, it is easy to see that the stomach is different than the esophagus or the liver, so you can imagine the digestive system as a collection of specific organs.

The Central and Peripheral Nervous Systems

The nervous system can be divided into two major regions: the central and peripheral nervous systems. The **central nervous system (CNS)** is the brain and spinal cord, and the **peripheral nervous system (PNS)** is everything else (Figure 1. Central and Peripheral Nervous System). The brain is contained within the cranial cavity of the skull, and the spinal cord is contained within the vertebral cavity of the vertebral column. It is a bit of an oversimplification to say that the CNS is what is inside these two cavities and the peripheral nervous system is outside of them, but that is one way to start to think about it. In actuality, there are some elements of the peripheral nervous system that are within the cranial or vertebral cavities. The peripheral nervous system is so named because it is on the periphery—meaning beyond the brain and spinal cord. Depending on different aspects of the nervous system, the dividing line between central and peripheral is not necessarily universal.

Central and Peripheral Nervous System

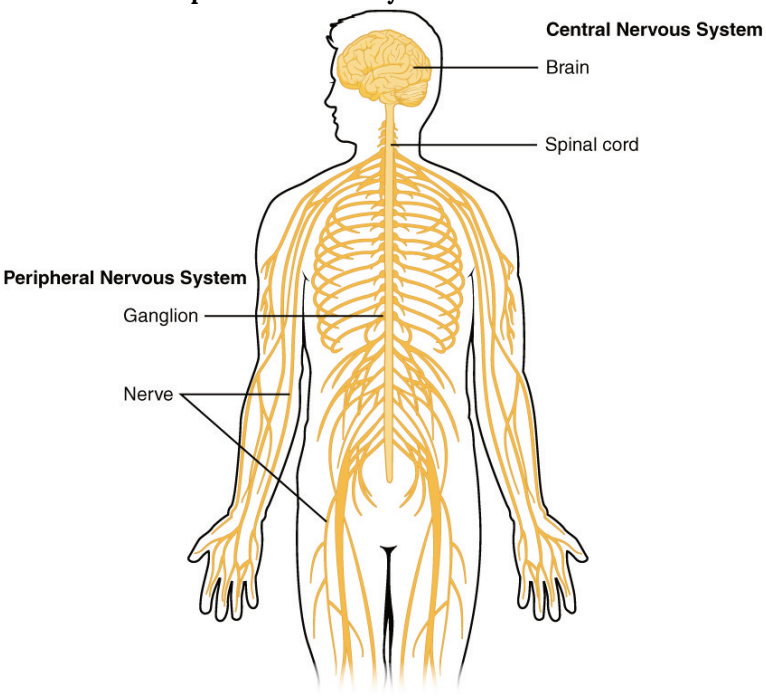


Figure 1. *The structures of the PNS are referred to as ganglia and nerves, which can be seen as distinct structures. The equivalent structures in the CNS are not obvious from this overall perspective and are best examined in prepared tissue under the microscope.*

Nervous tissue, present in both the CNS and PNS, contains two basic types of cells: neurons and glial cells. A **glial cell** is one of a variety of cells that provide a framework of tissue that supports the neurons and their activities. The **neuron** is the more functionally important of the two, in terms of the communicative function of the nervous system. To describe the functional divisions of the nervous system, it is important to understand the structure of a neuron. Neurons are cells and therefore have a **soma**, or cell body, but they also have extensions of the cell; each extension is generally referred to as a **process**. There is one important process that every neuron has called an **axon**, which is the fiber that connects a neuron with its target. Another type of process that branches off from the soma is the **dendrite**. Dendrites are responsible for receiving most of the input from other neurons. Looking at nervous tissue, there are regions that predominantly contain cell bodies and regions that are largely composed of just axons. These two regions within nervous system structures are often referred to as **gray**

matter (the regions with many cell bodies and dendrites) or **white matter** (the regions with many axons). Figure 2. (Gray Matter and White Matter) demonstrates the appearance of these regions in the brain and spinal cord. The colors ascribed to these regions are what would be seen in "fresh," or unstained, nervous tissue. Gray matter is not necessarily gray. It can be pinkish because of blood content, or even slightly tan, depending on how long the tissue has been preserved. But white matter is white because axons are insulated by a lipid-rich substance called **myelin**. Lipids can appear as white ("fatty") material, much like the fat on a raw piece of chicken or beef. Actually, gray matter may have that color ascribed to it because next to the white matter, it is just darker—hence, gray.

The distinction between gray matter and white matter is most often applied to central nervous tissue, which has large regions that can be seen with the unaided eye. When looking at peripheral structures, often a microscope is used and the tissue is stained with artificial colors. That is not to say that central nervous tissue cannot be stained and viewed under a microscope, but unstained tissue is most likely from the CNS—for example, a frontal section of the brain or cross section of the spinal cord.

Gray Matter and White Matter

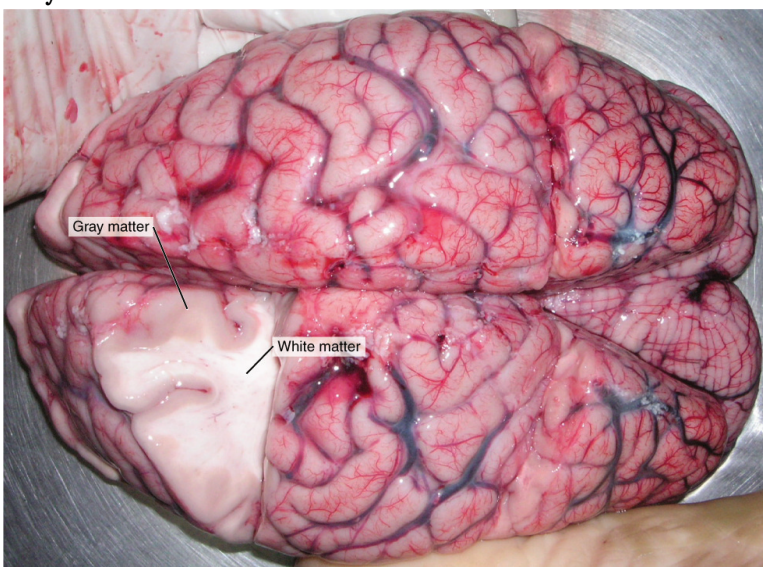


Figure 2. *A brain removed during an autopsy, with a partial section removed, shows white matter surrounded by gray matter. Gray matter makes up the outer cortex of the brain. (credit: modification of work by "Suseno"/Wikimedia Commons)*

Regardless of the appearance of stained or unstained tissue, the cell bodies of neurons or axons can be located in discrete anatomical structures that need to be named. Those names are specific to whether the structure is central or peripheral. A localized collection of neuron cell bodies in the CNS is referred to as a **nucleus**. In the PNS, a cluster of neuron cell bodies is referred to as a **ganglion**. Figure 3. (What Is a Nucleus?) indicates how the term nucleus has a few different meanings within anatomy and physiology. It is the center of an atom, where protons and neutrons are found; it is the center of a cell, where the DNA is found; and it is a center of some function in the CNS. There is also a potentially confusing use of the word ganglion (plural = ganglia) that has a historical explanation. In the central nervous system, there is a group of nuclei that are connected together and were once called the basal ganglia before "ganglion" became accepted as a description for a peripheral structure. Some sources refer to this group of nuclei as the "basal nuclei" to avoid confusion.

What Is a Nucleus?

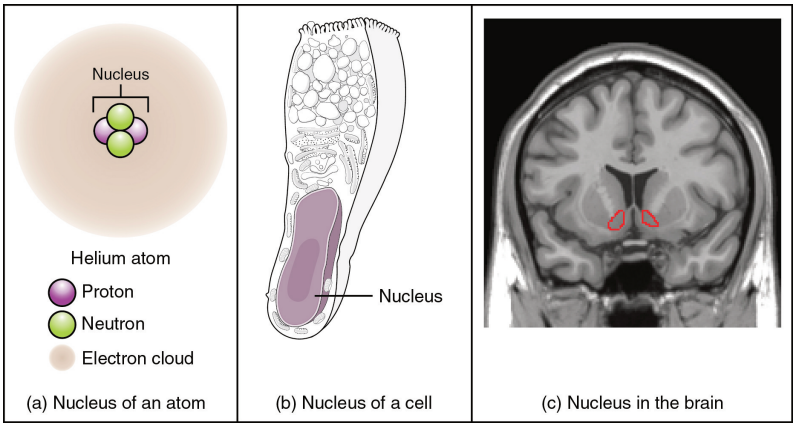


Figure 3. *(a) The nucleus of an atom contains its protons and neutrons. (b) The nucleus of a cell is the organelle that contains DNA. (c) A nucleus in the CNS is a localized center of function with the cell bodies of several neurons, shown here circled in red. (credit c: "Was a bee"/Wikimedia Commons)*

Terminology applied to bundles of axons also differs depending on location. A bundle of axons, or fibers, found in the CNS is called a **tract** whereas the same thing in the PNS would be called a **nerve**. There is an important point to make about these terms, which is that they can both be used to refer to the same bundle of axons. When those axons are in the PNS, the term is nerve, but if they are CNS, the term is tract. The most obvious example of this is the axons that project from the retina into the brain. Those axons are called the optic nerve as they leave the eye, but when they are inside the cranium, they are referred to as the optic tract. There is a specific place where the name changes, which is the optic chiasm, but they are still the same axons (Figure 4. Optic Nerve Versus Optic Tract). A similar situation outside of science can be described for some roads. Imagine a road called "Broad Street" in a town called "Anyville." The road leaves Anyville and goes to the next town over, called "Hometown." When the road crosses the line between the two towns and is in Hometown, its name changes to "Main Street." That is the idea behind the naming of the retinal axons. In the PNS, they are called the optic nerve, and in the CNS, they are the optic tract. Table (Structures of the CNS and PNS) helps to clarify which of these terms apply to the central or peripheral nervous systems.

Optic Nerve Versus Optic Tract

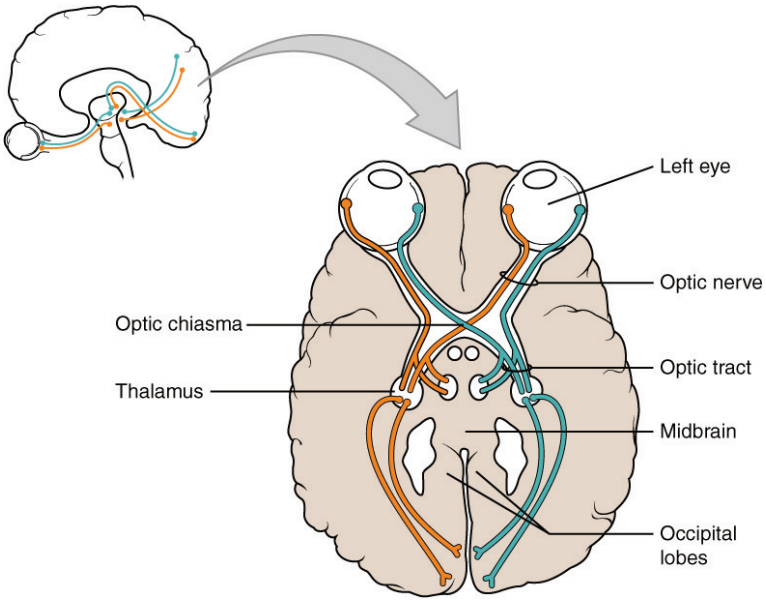


Figure 4. *This drawing of the connections of the eye to the brain shows the optic nerve extending from the eye to the chiasm, where the structure continues as the optic tract. The same axons extend from the eye to the brain through these two bundles of fibers, but the chiasm represents the border between peripheral and central.*

In 2003, the Nobel Prize in Physiology or Medicine was awarded to Paul C. Lauterbur and Sir Peter Mansfield for discoveries related to magnetic resonance imaging (MRI). This is a tool to see the structures of the body (not just the nervous system) that depends on magnetic fields associated with certain atomic nuclei. The utility of this technique in the nervous system is that fat tissue and water appear as different shades between black and white. Because white matter is fatty (from myelin) and gray matter is not, they can be easily distinguished in MRI images. Visit the Nobel Prize web site to play an interactive game that demonstrates the use of this technology and compares it with other types of imaging technologies. Also, the results from an MRI session are compared with images obtained from X-ray or computed tomography. How do the imaging techniques shown in this game indicate the separation of white and gray matter compared with the freshly dissected tissue shown earlier?

Structures of the CNS and PNS

	CNS	**PNS**
Group of Neuron Cell Bodies (i.e., gray matter)	Nucleus	Ganglion
Bundle of Axons (i.e., white matter)	Tract	Nerve

Functional Divisions of the Nervous System

The nervous system can also be divided on the basis of its functions, but anatomical divisions and functional divisions are different. The CNS and the PNS both contribute to the same functions, but those functions can be attributed to different regions of the brain (such as the cerebral cortex or the hypothalamus) or to different ganglia in the periphery. The problem with trying to fit functional differences into anatomical divisions is that sometimes the same structure can be part of several functions. For example, the optic nerve carries signals from the retina that are either used for the conscious perception of visual stimuli, which takes place in the cerebral cortex, or for the reflexive responses of smooth muscle tissue that are processed through the hypothalamus.

There are two ways to consider how the nervous system is divided functionally. First, the basic functions of the nervous system are sensation, integration, and response. Secondly, control of the body can be somatic or autonomic—divisions that are largely defined by the structures that are involved in the response. There is also a region of the peripheral nervous system that is called the enteric nervous system that is responsible for a specific set of the functions within the realm of autonomic control related to gastrointestinal functions.

Basic Functions

The nervous system is involved in receiving information about the environment around us (sensation) and generating responses to that information (motor responses). The nervous system can be divided into regions that are responsible for **sensation** (sensory functions) and for the **response** (motor functions). But there is a third function that needs to be included. Sensory input needs to be integrated with other sensations, as well as with memories, emotional state, or learning (cognition). Some regions of the nervous system are termed **integration** or association areas. The process of integration combines sensory perceptions and higher cognitive functions such as memories, learning, and emotion to produce a response.

Sensation. The first major function of the nervous system is sensation—receiving information about the environment to gain input about what is happening outside the body (or, sometimes, within the body). The sensory functions of the nervous system register the presence of a change from homeostasis or a particular event in the environment, known as a **stimulus**. The senses we think of most are the "big five": taste, smell, touch, sight, and hearing. The stimuli for taste and smell are both chemical substances (molecules, compounds, ions, etc.), touch is physical or mechanical stimuli that interact with the skin, sight is light stimuli, and hearing is the perception of sound, which is a physical stimulus similar to some aspects of touch. There are actually more senses than just those, but that list represents the major senses. Those five are all senses that receive stimuli from the outside world, and of which there is conscious perception. Additional sensory stimuli might be from the internal environment (inside the body), such as the stretch of an organ wall or the concentration of certain ions in the blood.

Response. The nervous system produces a response on the basis of the stimuli perceived by sensory structures. An obvious response would be the movement of muscles, such as withdrawing a hand from a hot stove, but there are broader uses of the term. The nervous system can cause the contraction of all three types of muscle tissue. For example, skeletal muscle contracts to move the skeleton, cardiac muscle is influenced as heart rate increases during exercise, and smooth muscle contracts as the digestive system moves food along the digestive tract. Responses also include the neural control of glands in the body as well, such as the production and secretion of sweat by the eccrine and merocrine sweat glands found in the skin to lower body temperature.

Responses can be divided into those that are voluntary or conscious (contraction of skeletal muscle) and those that are involuntary (contraction of smooth muscles, regulation of cardiac muscle, activation of glands). Voluntary responses are governed by the somatic nervous system and involuntary responses are governed by the autonomic nervous system, which are discussed in the next section.

Integration. Stimuli that are received by sensory structures are communicated to the nervous system where that information is processed. This is called integration. Stimuli are compared with, or integrated with, other stimuli, memories of previous stimuli, or the state of a person at a particular time. This leads to the specific response that will be generated. Seeing a baseball pitched to a batter will not automatically cause the batter to swing. The trajectory of the ball and its speed will need to be considered. Maybe the count is three balls and one strike, and the batter wants to let this pitch go by in the hope of getting a walk to first base. Or maybe the batter's team is so far ahead, it would be fun to just swing away.

Controlling the Body

The nervous system can be divided into two parts mostly on the basis of a functional difference in responses. The **somatic nervous system (SNS)** is responsible for conscious perception and voluntary motor responses.

Voluntary motor response means the contraction of skeletal muscle, but those contractions are not always voluntary in the sense that you have to want to perform them. Some somatic motor responses are reflexes, and often happen without a conscious decision to perform them. If your friend jumps out from behind a corner and yells "Boo!" you will be startled and you might scream or leap back. You didn't decide to do that, and you may not have wanted to give your friend a reason to laugh at your expense, but it is a reflex involving skeletal muscle contractions. Other motor responses become automatic (in other words, unconscious) as a person learns motor skills (referred to as "habit learning" or "procedural memory").

The **autonomic nervous system (ANS)** is responsible for involuntary control of the body, usually for the sake of homeostasis (regulation of the internal environment). Sensory input for autonomic functions can be from sensory structures tuned to external or internal environmental stimuli. The motor output extends to smooth and cardiac muscle as well as glandular tissue. The role of the autonomic system is to regulate the organ systems of the body, which usually means to control homeostasis. Sweat glands, for example, are controlled by the autonomic system. When you are hot, sweating helps cool your body down. That is a homeostatic mechanism. But when you are nervous, you might start sweating also. That is not homeostatic, it is the physiological response to an emotional state.

There is another division of the nervous system that describes functional responses. The **enteric nervous system (ENS)** is responsible for controlling the smooth muscle and glandular tissue in your digestive system. It is a large part of the PNS, and is not dependent on the CNS. It is sometimes valid, however, to consider the enteric system to be a part of the autonomic system because the neural structures that make up the enteric system are a component of the autonomic output that regulates digestion. There are some differences between the two, but for our purposes here there will be a good bit of overlap. See Figure 5. (Somatic, Autonomic, and Enteric Structures of the Nervous System) for examples of where these divisions of the nervous system can be found.

Somatic, Autonomic, and Enteric Structures of the Nervous System

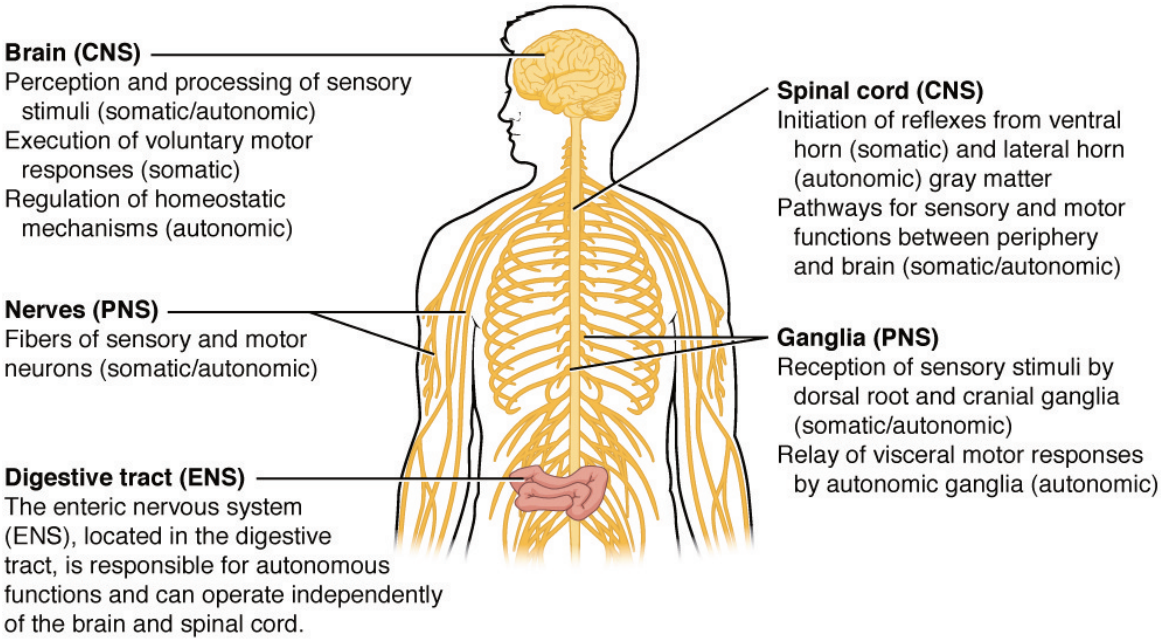


Figure 5. *Somatic structures include the spinal nerves, both motor and sensory fibers, as well as the sensory ganglia (posterior root ganglia and cranial nerve ganglia). Autonomic structures are found in the nerves also, but include the sympathetic and parasympathetic ganglia. The enteric nervous system includes the nervous tissue within the organs of the digestive tract.*

Visit this site to read about a woman that notices that her daughter is having trouble walking up the stairs. This leads to the discovery of a hereditary condition that affects the brain and spinal cord. The electromyography and MRI tests indicated deficiencies in the spinal cord and cerebellum, both of which are responsible for controlling coordinated movements. To what functional division of the nervous system would these structures belong?

EVERYDAY CONNECTION

How Much of Your Brain Do You Use?Have you ever heard the claim that humans only use 10 percent of their brains? Maybe you have seen an advertisement on a website saying that there is a secret to unlocking the full potential of your mind—as if there were 90 percent of your brain sitting idle, just waiting for you to use it. If you see an ad like that, don't click. It isn't true.

An easy way to see how much of the brain a person uses is to take measurements of brain activity while performing a task. An example of this kind of measurement is functional magnetic resonance imaging (fMRI), which generates a map of the most active areas and can be generated and presented in three dimensions (Figure 6. fMRI). This procedure is different from the standard MRI technique because it is measuring changes in the tissue in time with an experimental condition or event.

fMRI

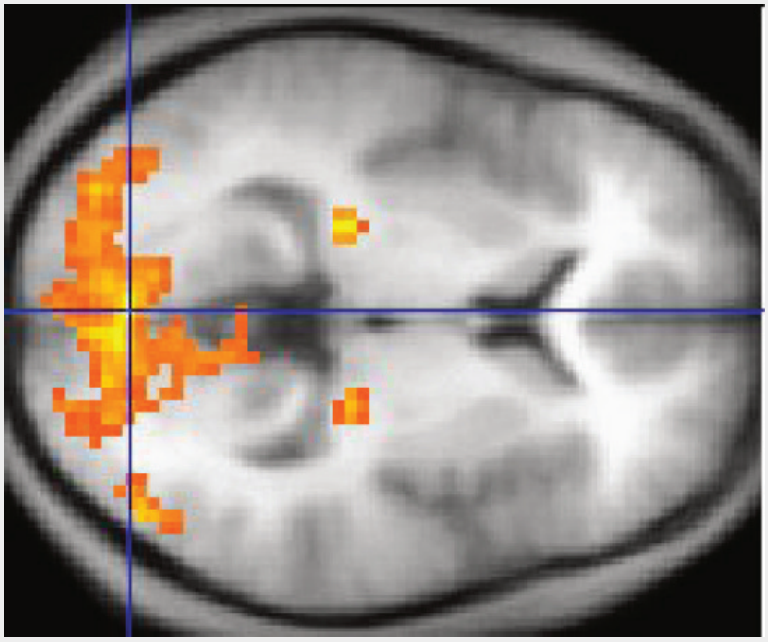


Figure 6. *This fMRI shows activation of the visual cortex in response to visual stimuli. (credit: "Superborsuk"/Wikimedia Commons)*

The underlying assumption is that active nervous tissue will have greater blood flow. By having the subject perform a visual task, activity all over the brain can be measured. Consider this possible experiment: the subject is told to look at a screen with a black dot in the middle (a fixation point).

A photograph of a face is projected on the screen away from the center. The subject has to look at the photograph and decipher what it is. The subject has been instructed to push a button if the photograph is of someone they recognize. The photograph might be of a celebrity, so the subject would press the button, or it might be of a random person unknown to the subject, so the subject would not press the button.

In this task, visual sensory areas would be active, integrating areas would be active, motor areas responsible for moving the eyes would be active, and motor areas for pressing the button with a finger would be active. Those areas are distributed all around the brain and the fMRI images would show activity in more than just 10 percent of the brain (some evidence suggests that about 80 percent of the brain is using energy—based on blood flow to the tissue—during well-defined tasks similar to the one suggested above). This task does not even include all of the functions the brain performs. There is no language response, the body is mostly lying still in the MRI machine, and it does not consider the autonomic functions that would be ongoing in the background.

Chapter Review

The nervous system can be separated into divisions on the basis of anatomy and physiology. The anatomical divisions are the central and peripheral nervous systems. The CNS is the brain and spinal cord. The PNS is everything else. Functionally, the nervous system can be divided into those regions that are responsible for sensation, those that are responsible for integration, and those that are responsible for generating responses. All of these functional areas are found in both the central and peripheral anatomy.

Considering the anatomical regions of the nervous system, there are specific names for the structures within each division. A localized collection of neuron cell bodies is referred to as a nucleus in the CNS and as a ganglion in the PNS. A bundle of axons is referred to as a tract in the CNS and as a nerve in the PNS. Whereas nuclei and ganglia are specifically in the central or peripheral divisions, axons can cross the boundary between the two. A single axon can be part of a nerve and a tract. The name for that specific structure depends on its location.

Nervous tissue can also be described as gray matter and white matter on the basis of its appearance in unstained tissue. These descriptions are more often used in the CNS. Gray matter is where nuclei are found and white matter is where tracts are found. In the PNS, ganglia are basically gray matter and nerves are white matter.

The nervous system can also be divided on the basis of how it controls the body. The somatic nervous system (SNS) is responsible for functions that result in moving skeletal muscles. Any sensory or integrative functions that result in the movement of skeletal muscle would be considered somatic. The autonomic nervous system (ANS) is responsible for functions that affect cardiac or smooth muscle tissue, or that cause glands to produce their secretions. Autonomic functions are distributed between central and peripheral regions of the nervous system. The sensations that lead to autonomic functions can be the same sensations that are part of initiating somatic responses. Somatic and autonomic integrative functions may overlap as well.

A special division of the nervous system is the enteric nervous system, which is responsible for controlling the digestive organs. Parts of the autonomic nervous system overlap with the enteric nervous system. The enteric nervous system is exclusively found in the periphery because it is the nervous tissue in the organs of the digestive system.

Nervous Tissue

By the end of this section, you will be able to:

- Describe the basic structure of a neuron
- Identify the different types of neurons on the basis of polarity
- List the glial cells of the CNS and describe their function
- List the glial cells of the PNS and describe their function

Nervous tissue is composed of two types of cells, neurons and glial cells. Neurons are the primary type of cell that most anyone associates with the nervous system. They are responsible for the computation and communication that the nervous system provides. They are electrically active and release chemical signals to target cells. Glial cells, or glia, are known to play a supporting role for nervous tissue. Ongoing research pursues an expanded role that glial cells might play in signaling, but neurons are still considered the basis of this function. Neurons are important, but without glial support they would not be able to perform their function.

Neurons

Neurons are the cells considered to be the basis of nervous tissue. They are responsible for the electrical signals that communicate information about sensations, and that produce movements in response to those stimuli, along with inducing thought processes within the brain. An important part of the function of neurons is in their structure, or shape. The three-dimensional shape of these cells makes the immense numbers of connections within the nervous system possible.

Parts of a Neuron

As you learned in the first section, the main part of a neuron is the cell body, which is also known as the soma (soma = "body"). The cell body contains the nucleus and most of the major organelles. But what makes neurons special is that they have many extensions of their cell membranes, which are generally referred to as processes. Neurons are usually described as having one, and only one, axon—a fiber that emerges from the cell body and projects to target cells. That single axon can branch repeatedly to communicate with many target cells. It is the axon that propagates the nerve impulse, which is communicated to one or more cells. The other processes of the neuron are dendrites, which receive information from other neurons at specialized areas of contact called **synapses**. The dendrites are usually highly branched processes, providing locations for other neurons to communicate with the cell body. Information flows through a neuron from the dendrites, across the cell body, and down the axon. This gives the neuron a polarity—meaning that information flows in this one direction. Figure 1. (Parts of a Neuron) shows the relationship of these parts to one another.

Parts of a Neuron

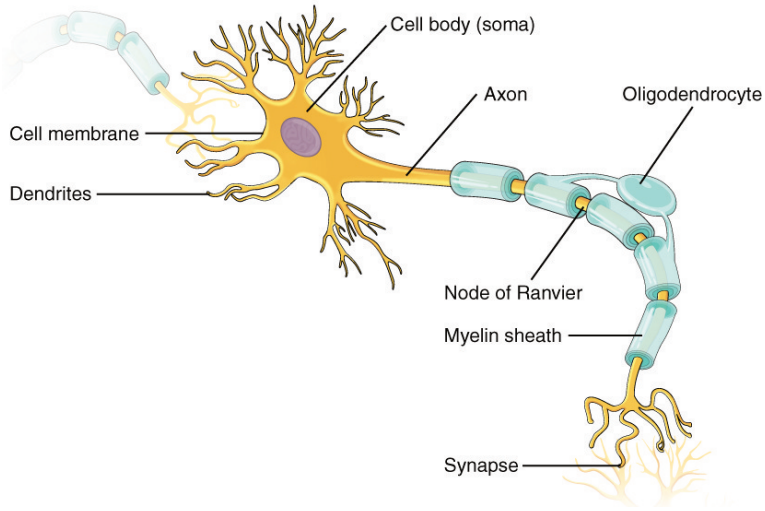


Figure 1. *The major parts of the neuron are labeled on a multipolar neuron from the CNS.*

Where the axon emerges from the cell body, there is a special region referred to as the **axon hillock**. This is a tapering of the cell body toward the axon fiber. Within the axon hillock, the cytoplasm changes to a solution of limited components called **axoplasm**. Because the axon hillock represents the beginning of the axon, it is also referred to as the **initial segment**.

Many axons are wrapped by an insulating substance called myelin, which is actually made from glial cells. Myelin acts as insulation much like the plastic or rubber that is used to insulate electrical wires. A key difference between myelin and the insulation on a wire is that there are gaps in the myelin covering of an axon. Each gap is called a **node of Ranvier** and is important to the way that electrical signals travel down the axon. The length of the axon between each gap, which is wrapped in myelin, is referred to as an **axon segment**. At the end of the axon is the **axon terminal**, where there are usually several branches extending toward the target cell, each of which ends in an enlargement called a **synaptic end bulb**. These bulbs are what make the connection with the target cell at the synapse.

> Visit this site to learn about how nervous tissue is composed of neurons and glial cells. Neurons are dynamic cells with the ability to make a vast number of connections, to respond incredibly quickly to stimuli, and to initiate movements on the basis of those stimuli. They are the focus of intense research because failures in physiology can lead to devastating illnesses. Why are neurons only found in animals? Based on what this article says about neuron function, why wouldn't they be helpful for plants or microorganisms?

Types of Neurons

There are many neurons in the nervous system—a number in the trillions. And there are many different types of neurons. They can be classified by many different criteria. The first way to classify them is by the number of

processes attached to the cell body. Using the standard model of neurons, one of these processes is the axon, and the rest are dendrites. Because information flows through the neuron from dendrites or cell bodies toward the axon, these names are based on the neuron's polarity (Figure 2. Neuron Classification by Shape).

Neuron Classification by Shape

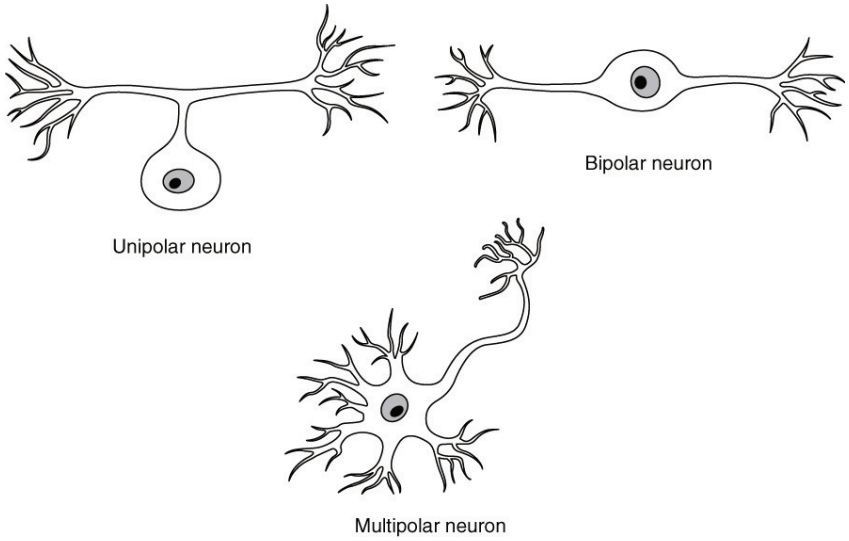


Figure 2. *Unipolar cells have one process that includes both the axon and dendrite. Bipolar cells have two processes, the axon and a dendrite. Multipolar cells have more than two processes, the axon and two or more dendrites.*

Unipolar cells have only one process emerging from the cell. True unipolar cells are only found in invertebrate animals, so the unipolar cells in humans are more appropriately called "pseudo-unipolar" cells. Invertebrate unipolar cells do not have dendrites. Human unipolar cells have an axon that emerges from the cell body, but it splits so that the axon can extend along a very long distance. At one end of the axon are dendrites, and at the other end, the axon forms synaptic connections with a target. Unipolar cells are exclusively sensory neurons and have two unique characteristics. First, their dendrites are receiving sensory information, sometimes directly from the stimulus itself. Secondly, the cell bodies of unipolar neurons are always found in ganglia. Sensory reception is a peripheral function (those dendrites are in the periphery, perhaps in the skin) so the cell body is in the periphery, though closer to the CNS in a ganglion. The axon projects from the dendrite endings, past the cell body in a ganglion, and into the central nervous system.

Bipolar cells have two processes, which extend from each end of the cell body, opposite to each other. One is the axon and one the dendrite. Bipolar cells are not very common. They are found mainly in the olfactory epithelium (where smell stimuli are sensed), and as part of the retina.

Multipolar neurons are all of the neurons that are not unipolar or bipolar. They have one axon and two or more dendrites (usually many more). With the exception of the unipolar sensory ganglion cells, and the two specific bipolar cells mentioned above, all other neurons are multipolar. Some cutting edge research suggests that certain neurons in the CNS do not conform to the standard model of "one, and only one" axon. Some sources describe a fourth type of neuron, called an anaxonic neuron. The name suggests that it has no axon (an- = "without"), but this is not accurate. Anaxonic neurons are very small, and if you look through a microscope at the standard resolution used in histology (approximately 400X to 1000X total magnification), you will not be able to distinguish any process specifically as an axon or a dendrite. Any of those processes can function as an axon depending on the conditions at any given time. Nevertheless, even if they cannot be easily seen, and one specific process is definitively the axon, these neurons have multiple processes and are therefore multipolar.

Neurons can also be classified on the basis of where they are found, who found them, what they do, or even what chemicals they use to communicate with each other. Some neurons referred to in this section on the nervous system are named on the basis of those sorts of classifications (Figure 3. Other Neurons Classification). For example, a multipolar neuron that has a very important role to play in a part of the brain called the cerebellum is known as a Purkinje (commonly pronounced per-KIN-gee) cell. It is named after the anatomist who discovered it (Jan Evangilista Purkinje, 1787–1869).

Other Neuron Classifications

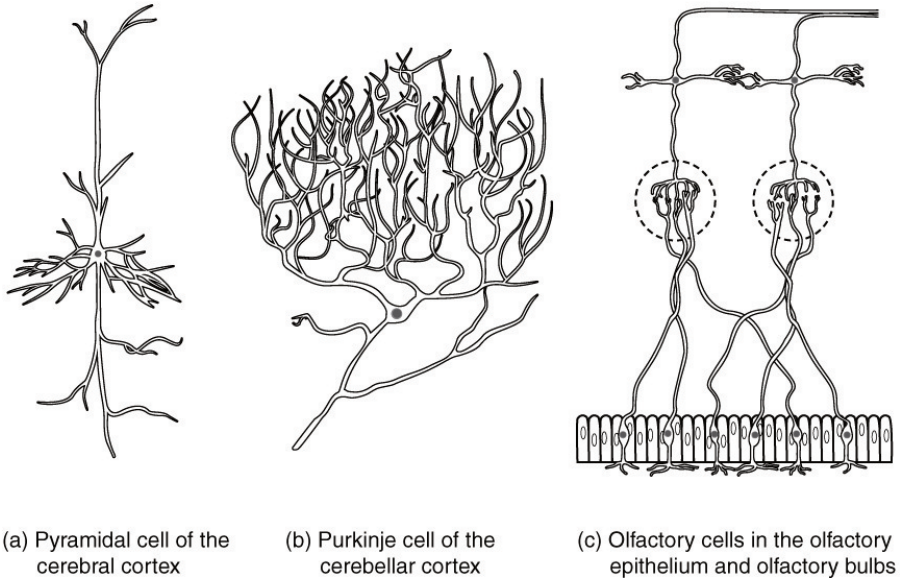


Figure 3. *Three examples of neurons that are classified on the basis of other criteria. (a) The pyramidal cell is a multipolar cell with a cell body that is shaped something like a pyramid. (b) The Purkinje cell in the cerebellum was named after the scientist who originally described it. (c) Olfactory neurons are named for the functional group with which they belong.*

Glial Cells

Glial cells, or neuroglia or simply glia, are the other type of cell found in nervous tissue. They are considered to be supporting cells, and many functions are directed at helping neurons complete their function for communication. The name glia comes from the Greek word that means "glue," and was coined by the German pathologist Rudolph Virchow, who wrote in 1856: "This connective substance, which is in the brain, the spinal cord, and the special sense nerves, is a kind of glue (neuroglia) in which the nervous elements are planted." Today, research into nervous tissue has shown that there are many deeper roles that these cells play. And research may find much more about them in the future.

There are six types of glial cells. Four of them are found in the CNS and two are found in the PNS. Table (Glial Cell Types by Location and Basic Function) outlines some common characteristics and functions.

Glial Cell Types by Location and Basic Function		
CNS glia	**PNS glia**	**Basic function**
Astrocyte	Satellite cell	Support
Oligodendrocyte	Schwann cell	Insulation, myelination
Microglia	–	Immune surveillance and phagocytosis
Ependymal cell	–	Creating CSF

Glial Cells of the CNS

One cell providing support to neurons of the CNS is the **astrocyte**, so named because it appears to be star-shaped under the microscope (astro- = "star"). Astrocytes have many processes extending from their main cell body (not axons or dendrites like neurons, just cell extensions). Those processes extend to interact with neurons, blood vessels, or the connective tissue covering the CNS that is called the pia mater (Figure 4. Glial Cells of the CNS). Generally, they are supporting cells for the neurons in the central nervous system. Some ways in which they support neurons in the central nervous system are by maintaining the concentration of chemicals in the extracellular space, removing excess signaling molecules, reacting to tissue damage, and contributing to the **blood-brain barrier (BBB)**. The blood-brain barrier is a physiological barrier that keeps many substances that circulate in the rest of the body from getting into the central nervous system, restricting what can cross from circulating blood into the CNS. Nutrient molecules, such as glucose or amino acids, can pass through the BBB, but other molecules cannot. This actually causes problems with drug delivery to the CNS. Pharmaceutical companies are challenged to design drugs that can cross the BBB as well as have an effect on the nervous system.

Glial Cells of the CNS

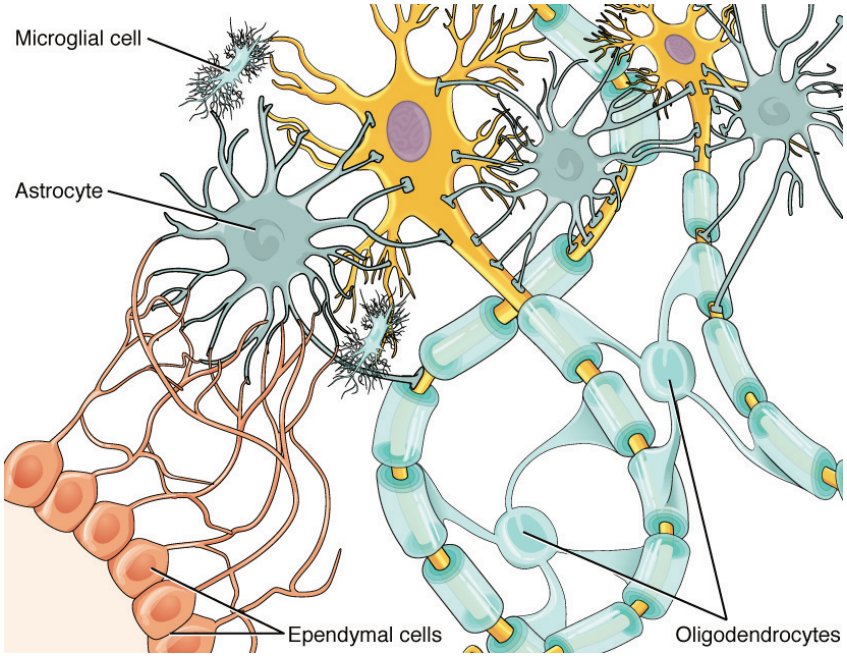


Figure 4. *The CNS has astrocytes, oligodendrocytes, microglia, and ependymal cells that support the neurons of the CNS in several ways.*

Like a few other parts of the body, the brain has a privileged blood supply. Very little can pass through by diffusion. Most substances that cross the wall of a blood vessel into the CNS must do so through an active transport process. Because of this, only specific types of molecules can enter the CNS. Glucose—the primary energy source—is allowed, as are amino acids. Water and some other small particles, like gases and ions, can enter. But most everything else cannot, including white blood cells, which are one of the body's main lines of defense. While this barrier protects the CNS from exposure to toxic or pathogenic substances, it also keeps out the cells that could protect the brain and spinal cord from disease and damage. The BBB also makes it harder for pharmaceuticals to be developed that can affect the nervous system. Aside from finding efficacious substances, the means of delivery is also crucial.

Also found in CNS tissue is the **oligodendrocyte**, sometimes called just "oligo," which is the glial cell type that insulates axons in the CNS. The name means "cell of a few branches" (oligo- = "few"; dendro- = "branches"; -cyte = "cell"). There are a few processes that extend from the cell body. Each one reaches out and surrounds an axon to insulate it in myelin. One oligodendrocyte will provide the myelin for multiple axon segments, either for the same axon or for separate axons. The function of myelin will be discussed below.

Microglia are, as the name implies, smaller than most of the other glial cells. Ongoing research into these cells, although not entirely conclusive, suggests that they may originate as white blood cells, called macrophages, that become part of the CNS during early development. While their origin is not conclusively determined, their function is related to what macrophages do in the rest of the body. When macrophages encounter diseased or damaged cells in the rest of the body, they ingest and digest those cells or the pathogens that cause disease. Microglia are the cells in the CNS that can do this in normal, healthy tissue, and they are therefore also referred to as CNS-resident macrophages.

The **ependymal cell** is a glial cell that filters blood to make **cerebrospinal fluid (CSF)**, the fluid that circulates through the CNS. Because of the privileged blood supply inherent in the BBB, the extracellular space in nervous tissue does not easily exchange components with the blood. Ependymal cells line each **ventricle**, one of four central cavities that are remnants of the hollow center of the neural tube formed during the embryonic development of the brain. The **choroid plexus** is a specialized structure in the ventricles where ependymal cells come in contact with blood vessels and filter and absorb components of the blood to produce cerebrospinal fluid. Because of this, ependymal cells can be considered a component of the BBB, or a place where the BBB breaks down. These glial cells appear similar to epithelial cells, making a single layer of cells with little intracellular space and tight connections between adjacent cells. They also have cilia on their apical surface to help move the CSF through the ventricular space. The relationship of these glial cells to the structure of the CNS is seen in Figure 4. (Glial Cells of the CNS).

Glial Cells of the PNS

One of the two types of glial cells found in the PNS is the **satellite cell**. Satellite cells are found in sensory and autonomic ganglia, where they surround the cell bodies of neurons. This accounts for the name, based on their appearance under the microscope. They provide support, performing similar functions in the periphery as astrocytes do in the CNS—except, of course, for establishing the BBB.

The second type of glial cell is the **Schwann cell**, which insulate axons with myelin in the periphery. Schwann cells are different than oligodendrocytes, in that a Schwann cell wraps around a portion of only one axon segment and no others. Oligodendrocytes have processes that reach out to multiple axon segments, whereas the entire Schwann cell surrounds just one axon segment. The nucleus and cytoplasm of the Schwann cell are on the

edge of the myelin sheath. The relationship of these two types of glial cells to ganglia and nerves in the PNS is seen in Figure 5. (Glial Cells of the PNS).

Glial Cells of the PNS

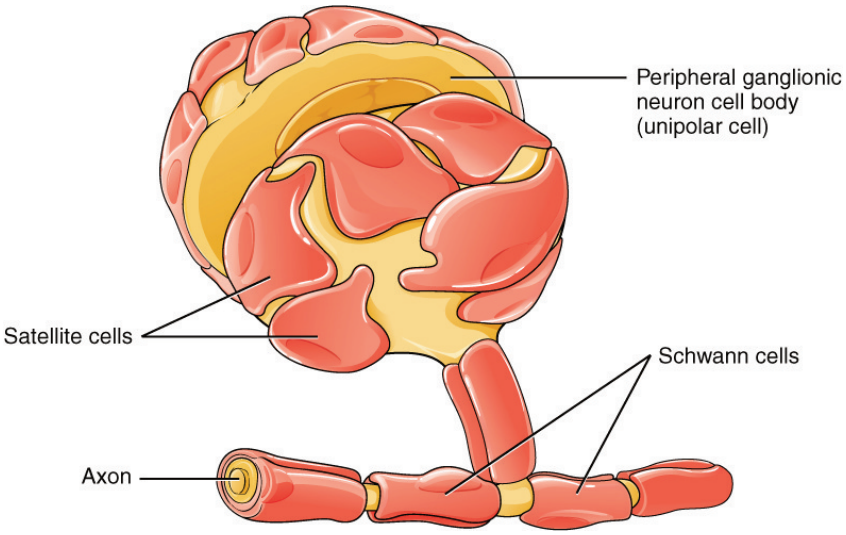


Figure 5. *The PNS has satellite cells and Schwann cells.*

Myelin

The insulation for axons in the nervous system is provided by glial cells, oligodendrocytes in the CNS, and Schwann cells in the PNS. Whereas the manner in which either cell is associated with the axon segment, or segments, that it insulates is different, the means of myelinating an axon segment is mostly the same in the two situations. Myelin is a lipid-rich sheath that surrounds the axon and by doing so creates a **myelin sheath** that facilitates the transmission of electrical signals along the axon. The lipids are essentially the phospholipids of the glial cell membrane. Myelin, however, is more than just the membrane of the glial cell. It also includes important proteins that are integral to that membrane. Some of the proteins help to hold the layers of the glial cell membrane closely together.

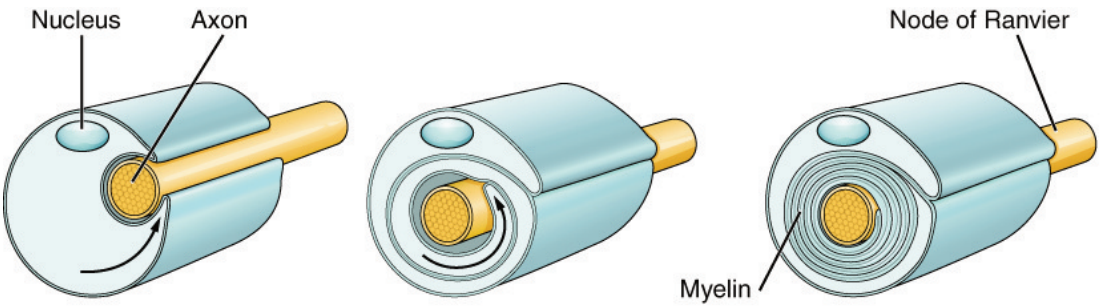
The appearance of the myelin sheath can be thought of as similar to the pastry wrapped around a hot dog for “pigs in a blanket” or a similar food. The glial cell is wrapped around the axon several times with little to no cytoplasm between the glial cell layers. For oligodendrocytes, the rest of the cell is separate from the myelin sheath as a cell process extends back toward the cell body. A few other processes provide the same insulation for other axon segments in the area. For Schwann cells, the outermost layer of the cell membrane contains cytoplasm and the nucleus of the cell as a bulge on one side of the myelin sheath. During development, the glial cell is loosely or incompletely wrapped around the axon (Figure 6 a. the Process of Myelination). The edges of this loose enclosure extend toward each other, and one end tucks under the other. The inner edge wraps around the axon, creating several layers, and the other edge closes around the outside so that the axon is completely enclosed.

View the University of Michigan WebScope to see an electron micrograph of a cross-section of a

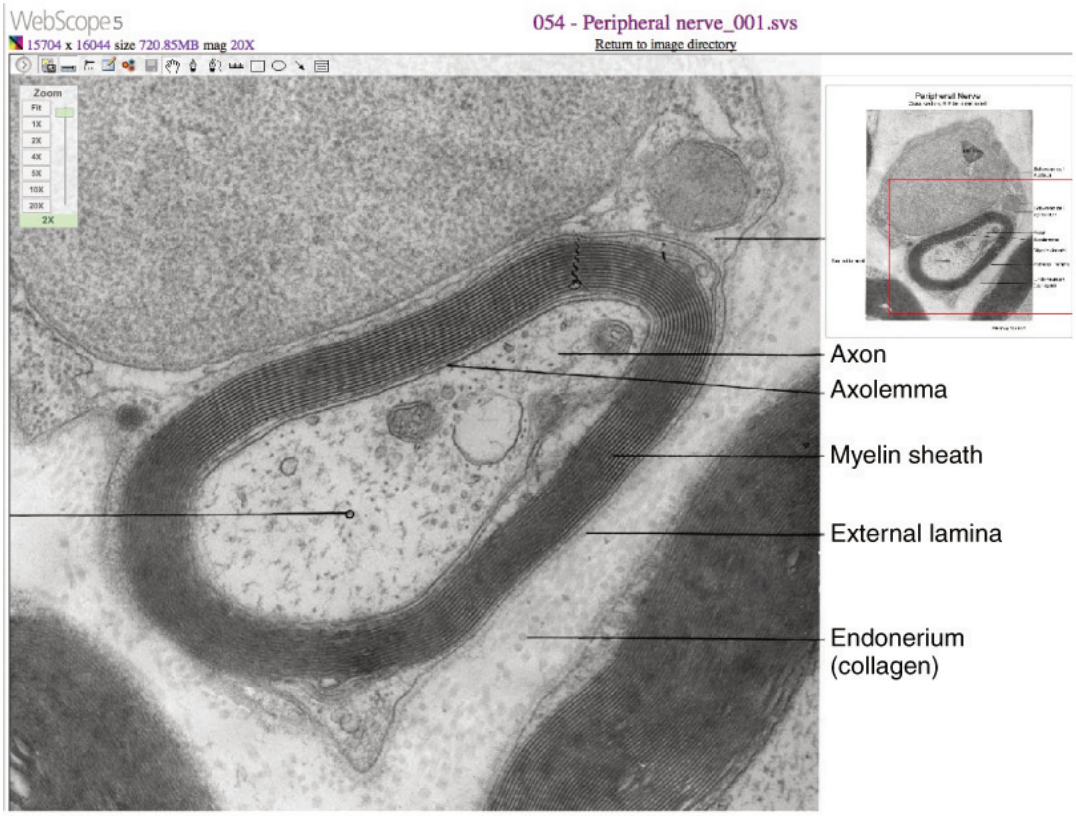
myelinated nerve fiber. The axon contains microtubules and neurofilaments that are bounded by a plasma membrane known as the axolemma. Outside the plasma membrane of the axon is the myelin sheath, which is composed of the tightly wrapped plasma membrane of a Schwann cell. What aspects of the cells in this image react with the stain to make them a deep, dark, black color, such as the multiple layers that are the myelin sheath?

Myelin sheaths can extend for one or two millimeters, depending on the diameter of the axon. Axon diameters can be as small as 1 to 20 micrometers. Because a micrometer is 1/1000 of a millimeter, this means that the length of a myelin sheath can be 100–1000 times the diameter of the axon. Figure 1. (Parts of a Neuron), Figure 4. (Glial Cells of the CNS), and Figure 5. (Glial Cells of the PNS) show the myelin sheath surrounding an axon segment, but are not to scale. If the myelin sheath were drawn to scale, the neuron would have to be immense—possibly covering an entire wall of the room in which you are sitting.

The Process of Myelination



(a)



(b)

Figure 6. *Myelinating glia wrap several layers of cell membrane around the cell membrane of an axon segment. A single Schwann cell insulates a segment of a peripheral nerve, whereas in the CNS, an oligodendrocyte may provide insulation for a few separate axon segments. EM × 1,460,000. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

DISORDERS OF THE...

Nervous Tissue Several diseases can result from the demyelination of axons. The causes of these diseases are not the same; some have genetic causes, some are caused by pathogens, and others are the result of autoimmune disorders. Though the causes are varied, the results are largely similar. The

myelin insulation of axons is compromised, making electrical signaling slower.

Multiple sclerosis (MS) is one such disease. It is an example of an autoimmune disease. The antibodies produced by lymphocytes (a type of white blood cell) mark myelin as something that should not be in the body. This causes inflammation and the destruction of the myelin in the central nervous system. As the insulation around the axons is destroyed by the disease, scarring becomes obvious. This is where the name of the disease comes from; sclerosis means hardening of tissue, which is what a scar is. Multiple scars are found in the white matter of the brain and spinal cord. The symptoms of MS include both somatic and autonomic deficits. Control of the musculature is compromised, as is control of organs such as the bladder.

Guillain-Barré (pronounced gee-YAN bah-RAY) syndrome is an example of a demyelinating disease of the peripheral nervous system. It is also the result of an autoimmune reaction, but the inflammation is in peripheral nerves. Sensory symptoms or motor deficits are common, and autonomic failures can lead to changes in the heart rhythm or a drop in blood pressure, especially when standing, which causes dizziness.

Chapter Review

Nervous tissue contains two major cell types, neurons and glial cells. Neurons are the cells responsible for communication through electrical signals. Glial cells are supporting cells, maintaining the environment around the neurons.

Neurons are polarized cells, based on the flow of electrical signals along their membrane. Signals are received at the dendrites, are passed along the cell body, and propagate along the axon towards the target, which may be another neuron, muscle tissue, or a gland. Many axons are insulated by a lipid-rich substance called myelin. Specific types of glial cells provide this insulation.

Several types of glial cells are found in the nervous system, and they can be categorized by the anatomical division in which they are found. In the CNS, astrocytes, oligodendrocytes, microglia, and ependymal cells are found. Astrocytes are important for maintaining the chemical environment around the neuron and are crucial for regulating the blood-brain barrier. Oligodendrocytes are the myelinating glia in the CNS. Microglia act as phagocytes and play a role in immune surveillance. Ependymal cells are responsible for filtering the blood to produce cerebrospinal fluid, which is a circulatory fluid that performs some of the functions of blood in the brain and spinal cord because of the BBB. In the PNS, satellite cells are supporting cells for the neurons, and Schwann cells insulate peripheral axons.

The Function of Nervous Tissue

By the end of this section, you will be able to:

- Distinguish the major functions of the nervous system: sensation, integration, and response
- List the sequence of events in a simple sensory receptor–motor response pathway

Having looked at the components of nervous tissue, and the basic anatomy of the nervous system, next comes an understanding of how nervous tissue is capable of communicating within the nervous system. Before getting to the nuts and bolts of how this works, an illustration of how the components come together will be helpful. An example is summarized in Figure 1. (Testing the Water).

Testing the Water

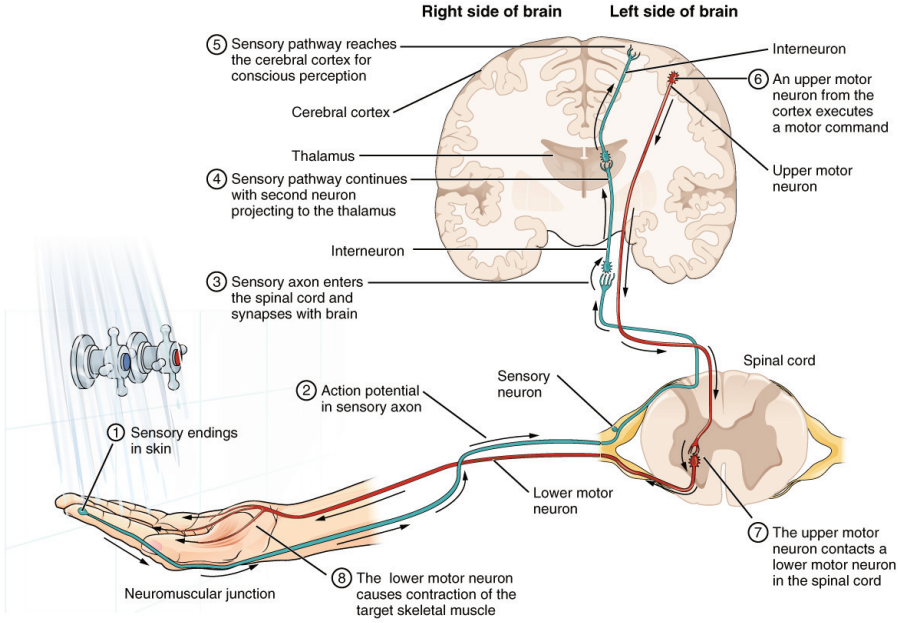


Figure 1. *(1) The sensory neuron has endings in the skin that sense a stimulus such as water temperature. The strength of the signal that starts here is dependent on the strength of the stimulus. (2) The graded potential from the sensory endings, if strong enough, will initiate an action potential at the initial segment of the axon (which is immediately adjacent to the sensory endings in the skin). (3) The axon of the peripheral sensory neuron enters the spinal cord and contacts another neuron in the gray matter. The contact is a synapse where another graded potential is caused by the release of a chemical signal from the axon terminals. (4) An action potential is initiated at the initial segment of this neuron and travels up the sensory pathway to a region of the brain called the thalamus. Another synapse passes the information along to the next neuron. (5) The sensory pathway ends when the signal reaches the cerebral cortex. (6) After integration with neurons in other parts of the cerebral cortex, a motor command is sent from the precentral gyrus of the frontal cortex. (7) The upper motor neuron sends an action potential down to the spinal cord. The target of the upper motor neuron is the dendrites of the lower motor neuron*

in the gray matter of the spinal cord. (8) The axon of the lower motor neuron emerges from the spinal cord in a nerve and connects to a muscle through a neuromuscular junction to cause contraction of the target muscle.

Imagine you are about to take a shower in the morning before going to school. You have turned on the faucet to start the water as you prepare to get in the shower. After a few minutes, you expect the water to be a temperature that will be comfortable to enter. So you put your hand out into the spray of water. What happens next depends on how your nervous system interacts with the stimulus of the water temperature and what you do in response to that stimulus.

Found in the skin of your fingers or toes is a type of sensory receptor that is sensitive to temperature, called a **thermoreceptor**. When you place your hand under the shower (Figure 2. The Sensory Input), the cell membrane of the thermoreceptors changes its electrical state (voltage). The amount of change is dependent on the strength of the stimulus (how hot the water is). This is called a **graded potential**. If the stimulus is strong, the voltage of the cell membrane will change enough to generate an electrical signal that will travel down the axon. You have learned about this type of signaling before, with respect to the interaction of nerves and muscles at the neuromuscular junction. The voltage at which such a signal is generated is called the threshold, and the resulting electrical signal is called an **action potential**. In this example, the action potential travels—a process known as **propagation**—along the axon from the axon hillock to the axon terminals and into the synaptic end bulbs. When this signal reaches the end bulbs, it causes the release of a signaling molecule called a **neurotransmitter**.

The Sensory Input

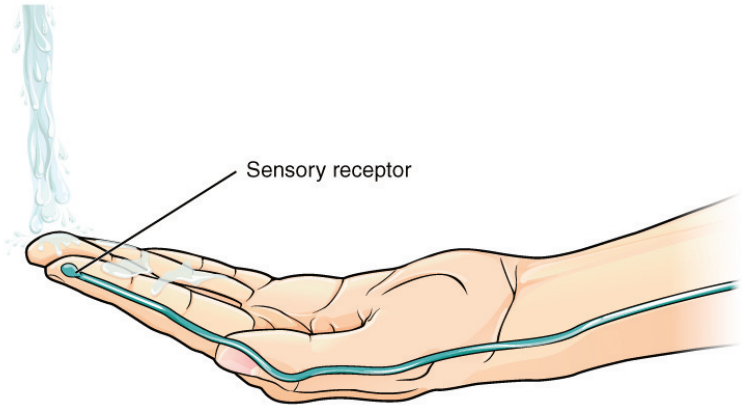


Figure 2. *Receptors in the skin sense the temperature of the water.*

The neurotransmitter diffuses across the short distance of the synapse and binds to a receptor protein of the target neuron. When the molecular signal binds to the receptor, the cell membrane of the target neuron changes its electrical state and a new graded potential begins. If that graded potential is strong enough to reach threshold, the second neuron generates an action potential at its axon hillock. The target of this neuron is another neuron in the **thalamus** of the brain, the part of the CNS that acts as a relay for sensory information. At another synapse, neurotransmitter is released and binds to its receptor. The thalamus then sends the sensory information to the **cerebral cortex**, the outermost layer of gray matter in the brain, where conscious perception of that water temperature begins.

Within the cerebral cortex, information is processed among many neurons, integrating the stimulus of the water temperature with other sensory stimuli, with your emotional state (you just aren't ready to wake up; the bed is calling to you), memories (perhaps of the lab notes you have to study before a quiz). Finally, a plan is developed about what to do, whether that is to turn the temperature up, turn the whole shower off and go back to bed, or step into the shower. To do any of these things, the cerebral cortex has to send a command out to your body to move muscles (Figure 3. The Motor Response).

The Motor Response

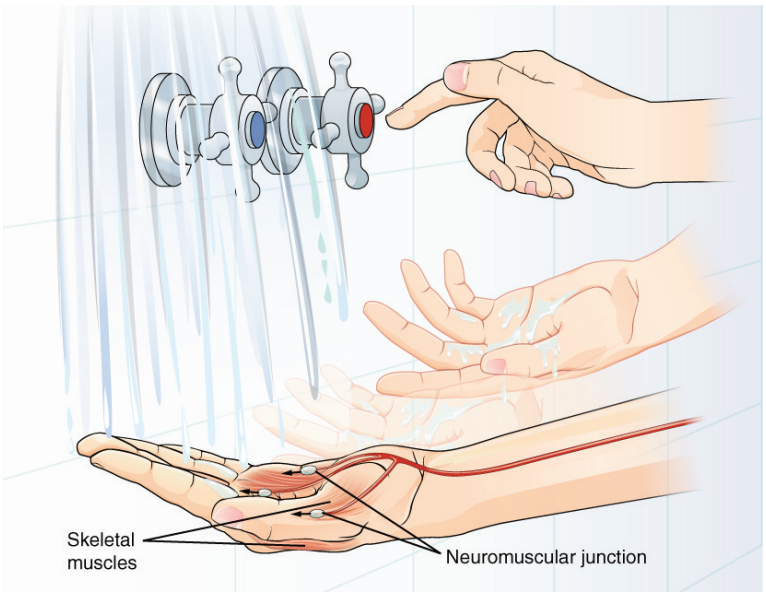


Figure 3. *On the basis of the sensory input and the integration in the CNS, a motor response is formulated and executed.*

A region of the cortex is specialized for sending signals down to the spinal cord for movement. The **upper motor neuron** is in this region, called the **precentral gyrus of the frontal cortex**, which has an axon that extends all the way down the spinal cord. At the level of the spinal cord at which this axon makes a synapse, a graded potential occurs in the cell membrane of a **lower motor neuron**. This second motor neuron is responsible for causing muscle fibers to contract. In the manner described in the chapter on muscle tissue, an action potential travels along the motor neuron axon into the periphery. The axon terminates on muscle fibers at the neuromuscular junction. Acetylcholine is released at this specialized synapse, which causes the muscle action potential to begin, following a large potential known as an end plate potential. When the lower motor neuron excites the muscle fiber, it contracts. All of this occurs in a fraction of a second, but this story is the basis of how the nervous system functions.

CAREER CONNECTIONS

NeurophysiologistUnderstanding how the nervous system works could be a driving force in your career. Studying neurophysiology is a very rewarding path to follow. It means that there is a lot of work to do, but the rewards are worth the effort.

The career path of a research scientist can be straightforward: college, graduate school, postdoctoral research, academic research position at a university. A Bachelor's degree in science will get you started, and for neurophysiology that might be in biology, psychology, computer science, engineering, or neuroscience. But the real specialization comes in graduate school. There are many different programs out there to study the nervous system, not just neuroscience itself. Most graduate programs are doctoral, meaning that a Master's degree is not part of the work. These are usually considered five-year programs, with the first two years dedicated to course work and finding a research mentor, and the last three years dedicated to finding a research topic and pursuing that with

a near single-mindedness. The research will usually result in a few publications in scientific journals, which will make up the bulk of a doctoral dissertation. After graduating with a Ph.D., researchers will go on to find specialized work called a postdoctoral fellowship within established labs. In this position, a researcher starts to establish their own research career with the hopes of finding an academic position at a research university.

Other options are available if you are interested in how the nervous system works. Especially for neurophysiology, a medical degree might be more suitable so you can learn about the clinical applications of neurophysiology and possibly work with human subjects. An academic career is not a necessity. Biotechnology firms are eager to find motivated scientists ready to tackle the tough questions about how the nervous system works so that therapeutic chemicals can be tested on some of the most challenging disorders such as Alzheimer's disease or Parkinson's disease, or spinal cord injury.

Others with a medical degree and a specialization in neuroscience go on to work directly with patients, diagnosing and treating mental disorders. You can do this as a psychiatrist, a neuropsychologist, a neuroscience nurse, or a neurodiagnostic technician, among other possible career paths.

Chapter Review

Sensation starts with the activation of a sensory ending, such as the thermoreceptor in the skin sensing the temperature of the water. The sensory endings in the skin initiate an electrical signal that travels along the sensory axon within a nerve into the spinal cord, where it synapses with a neuron in the gray matter of the spinal cord. The temperature information represented in that electrical signal is passed to the next neuron by a chemical signal that diffuses across the small gap of the synapse and initiates a new electrical signal in the target cell. That signal travels through the sensory pathway to the brain, passing through the thalamus, where conscious perception of the water temperature is made possible by the cerebral cortex. Following integration of that information with other cognitive processes and sensory information, the brain sends a command back down to the spinal cord to initiate a motor response by controlling a skeletal muscle. The motor pathway is composed of two cells, the upper motor neuron and the lower motor neuron. The upper motor neuron has its cell body in the cerebral cortex and synapses on a cell in the gray matter of the spinal cord. The lower motor neuron is that cell in the gray matter of the spinal cord and its axon extends into the periphery where it synapses with a skeletal muscle in a neuromuscular junction.

The Action Potential

By the end of this section, you will be able to:

- Describe the components of the membrane that establish the resting membrane potential
- Describe the changes that occur to the membrane that result in the action potential

The functions of the nervous system—sensation, integration, and response—depend on the functions of the neurons underlying these pathways. To understand how neurons are able to communicate, it is necessary to describe the role of an **excitable membrane** in generating these signals. The basis of this communication is the action potential, which demonstrates how changes in the membrane can constitute a signal. Looking at the way these signals work in more variable circumstances involves a look at graded potentials, which will be covered in the next section.

Electrically Active Cell Membranes

Most cells in the body make use of charged particles, ions, to build up a charge across the cell membrane. Previously, this was shown to be a part of how muscle cells work. For skeletal muscles to contract, based on excitation–contraction coupling, requires input from a neuron. Both of the cells make use of the cell membrane to regulate ion movement between the extracellular fluid and cytosol.

As you learned in the chapter on cells, the cell membrane is primarily responsible for regulating what can cross the membrane and what stays on only one side. The cell membrane is a phospholipid bilayer, so only substances that can pass directly through the hydrophobic core can diffuse through unaided. Charged particles, which are hydrophilic by definition, cannot pass through the cell membrane without assistance (Figure 1. Cell Membrane and Transmembrane Proteins). Transmembrane proteins, specifically channel proteins, make this possible. Several passive transport channels, as well as active transport pumps, are necessary to generate a transmembrane potential and an action potential. Of special interest is the carrier protein referred to as the sodium/potassium pump that moves sodium ions (Na^+) out of a cell and potassium ions (K^+) into a cell, thus regulating ion concentration on both sides of the cell membrane.

Cell Membrane and Transmembrane Proteins

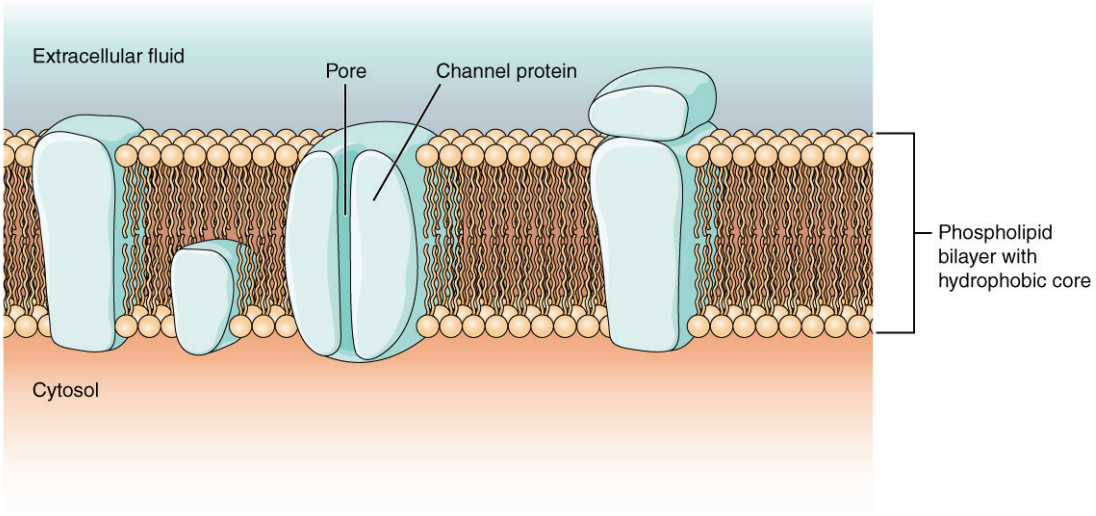


Figure 1. *The cell membrane is composed of a phospholipid bilayer and has many transmembrane proteins, including different types of channel proteins that serve as ion channels.*

The sodium/potassium pump requires energy in the form of adenosine triphosphate (ATP), so it is also referred to as an ATPase. As was explained in the cell chapter, the concentration of Na^+ is higher outside the cell than inside, and the concentration of K^+ is higher inside the cell than outside. That means that this pump is moving the ions against the concentration gradients for sodium and potassium, which is why it requires energy. In fact, the pump basically maintains those concentration gradients.

Ion channels are pores that allow specific charged particles to cross the membrane in response to an existing concentration gradient. Proteins are capable of spanning the cell membrane, including its hydrophobic core, and can interact with the charge of ions because of the varied properties of amino acids found within specific domains or regions of the protein channel. Hydrophobic amino acids are found in the domains that are apposed to the hydrocarbon tails of the phospholipids. Hydrophilic amino acids are exposed to the fluid environments of the extracellular fluid and cytosol. Additionally, the ions will interact with the hydrophilic amino acids, which will be selective for the charge of the ion. Channels for cations (positive ions) will have negatively charged side chains in the pore. Channels for anions (negative ions) will have positively charged side chains in the pore. This is called **electrochemical exclusion**, meaning that the channel pore is charge-specific.

Ion channels can also be specified by the diameter of the pore. The distance between the amino acids will be specific for the diameter of the ion when it dissociates from the water molecules surrounding it. Because of the surrounding water molecules, larger pores are not ideal for smaller ions because the water molecules will interact, by hydrogen bonds, more readily than the amino acid side chains. This is called **size exclusion**. Some ion channels are selective for charge but not necessarily for size, and thus are called a **nonspecific channel**. These nonspecific channels allow cations—particularly Na^+, K^+, and Ca^{2+}—to cross the membrane, but exclude anions.

Ion channels do not always freely allow ions to diffuse across the membrane. Some are opened by certain events, meaning the channels are **gated**. So another way that channels can be categorized is on the basis of how they are gated. Although these classes of ion channels are found primarily in the cells of nervous or muscular tissue, they also can be found in the cells of epithelial and connective tissues.

A **ligand-gated channel** opens because a signaling molecule, a ligand, binds to the extracellular region of the channel. This type of channel is also known as an **ionotropic receptor** because when the ligand, known as a neurotransmitter in the nervous system, binds to the protein, ions cross the membrane changing its charge (Figure 2. Ligand-Gated Channels).

Ligand-Gated Channels

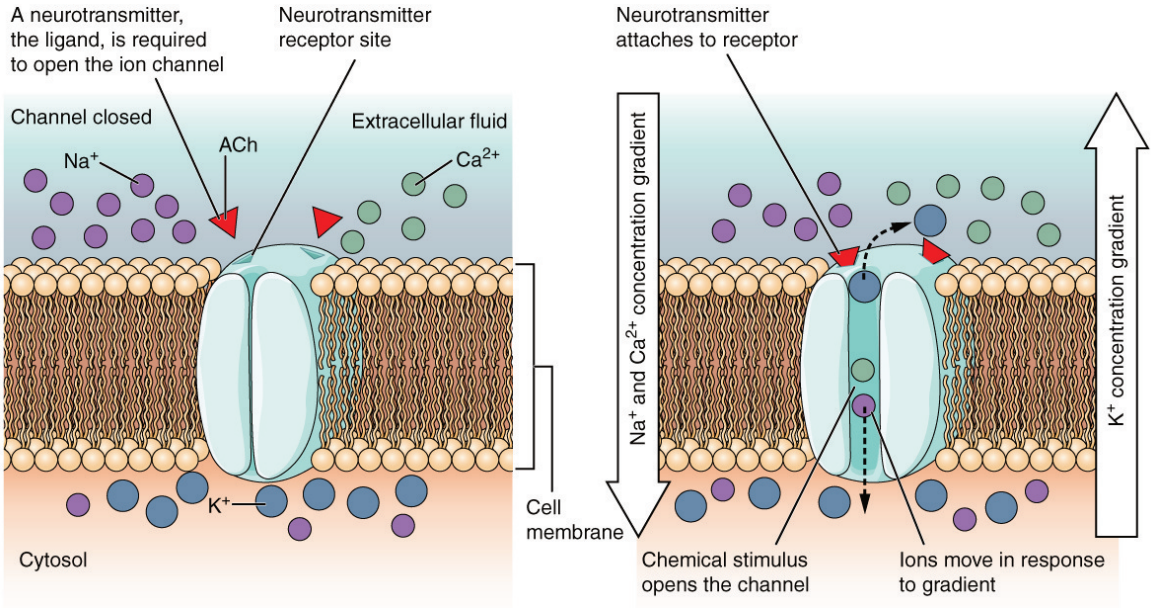


Figure 2. *When the ligand, in this case the neurotransmitter acetylcholine, binds to a specific location on the extracellular surface of the channel protein, the pore opens to allow select ions through. The ions, in this case, are cations of sodium, calcium, and potassium.*

A **mechanically gated channel** opens because of a physical distortion of the cell membrane. Many channels associated with the sense of touch (somatosensation) are mechanically gated. For example, as pressure is applied to the skin, these channels open and allow ions to enter the cell. Similar to this type of channel would be the channel that opens on the basis of temperature changes, as in testing the water in the shower (Figure 3. Mechanically Gated Channels).

Mechanically Gated Channels

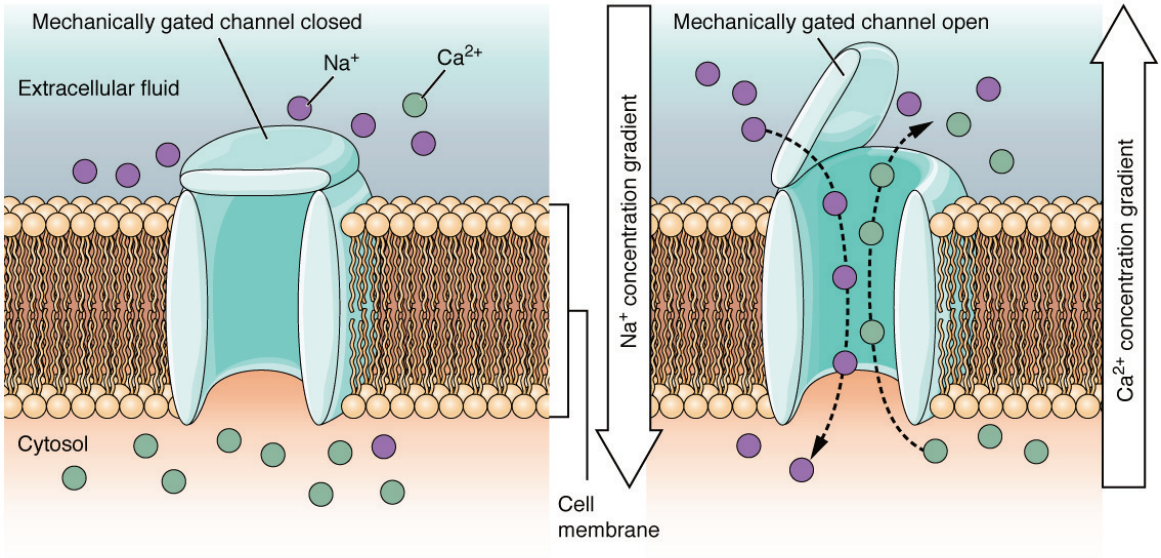


Figure 3. *When a mechanical change occurs in the surrounding tissue, such as pressure or touch, the channel is physically opened. Thermoreceptors work on a similar principle. When the local tissue temperature changes, the protein reacts by physically opening the channel.*

A **voltage-gated channel** is a channel that responds to changes in the electrical properties of the membrane in which it is embedded. Normally, the inner portion of the membrane is at a negative voltage. When that voltage becomes less negative, the channel begins to allow ions to cross the membrane (Figure 4. Voltage-Gated Channels).

Voltage-Gated Channels

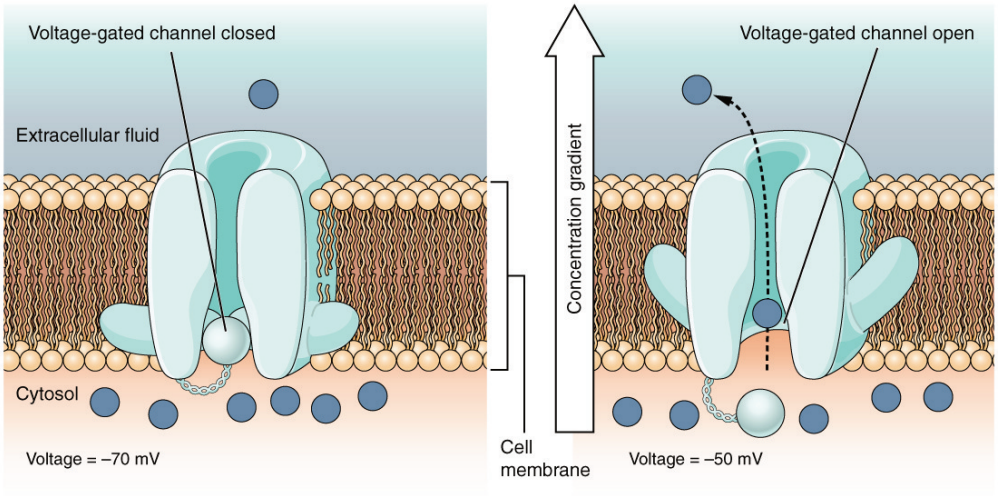


Figure 4. *Voltage-gated channels open when the transmembrane voltage changes around them. Amino acids in the structure of the protein are sensitive to charge and cause the pore to open to the selected ion.*

A **leakage channel** is randomly gated, meaning that it opens and closes at random, hence the reference to leaking. There is no actual event that opens the channel; instead, it has an intrinsic rate of switching between the open and closed states. Leakage channels contribute to the resting transmembrane voltage of the excitable membrane (Figure 5. Leakage Channels).

Leakage Channels

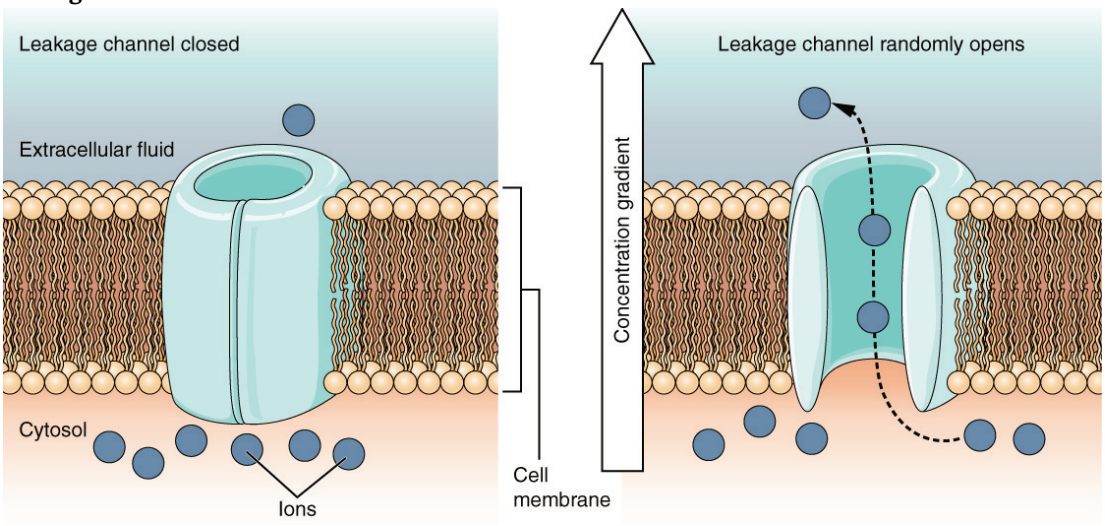


Figure 5. *In certain situations, ions need to move across the membrane randomly. The particular electrical properties of certain cells are modified by the presence of this type of channel.*

The Membrane Potential

The electrical state of the cell membrane can have several variations. These are all variations in the **membrane potential**. A potential is a distribution of charge across the cell membrane, measured in millivolts (mV). The standard is to compare the inside of the cell relative to the outside, so the membrane potential is a value representing the charge on the intracellular side of the membrane based on the outside being zero, relatively speaking (Figure 6. Measuring Charge across a Membrane with a Voltmeter).

Measuring Charge across a Membrane with a Voltmeter

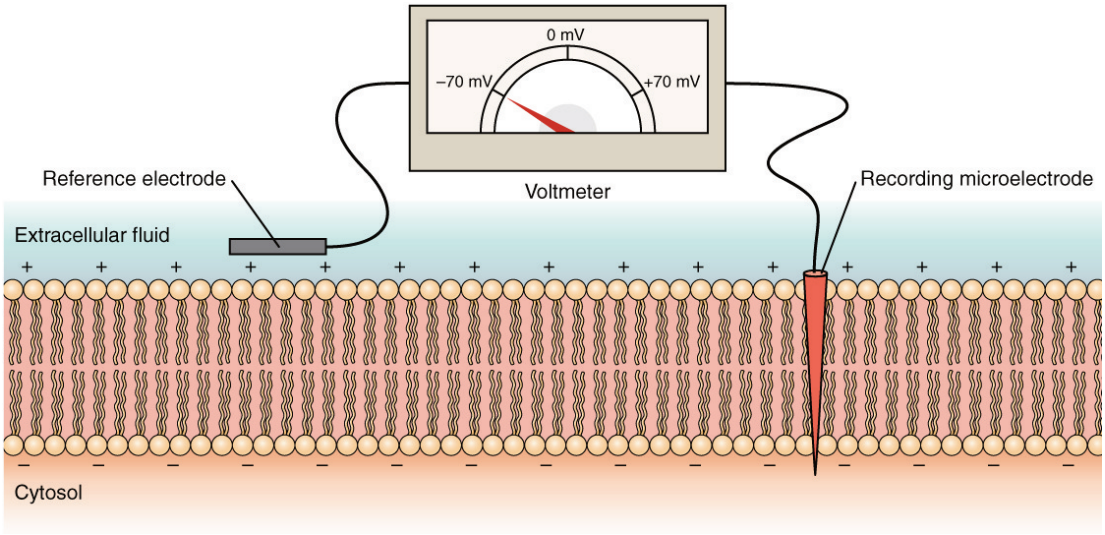


Figure 6. *A recording electrode is inserted into the cell and a reference electrode is outside the cell. By comparing the charge measured by these two electrodes, the transmembrane voltage is determined. It is conventional to express that value for the cytosol relative to the outside.*

The concentration of ions in extracellular and intracellular fluids is largely balanced, with a net neutral charge. However, a slight difference in charge occurs right at the membrane surface, both internally and externally. It is the difference in this very limited region that has all the power in neurons (and muscle cells) to generate electrical signals, including action potentials.

Before these electrical signals can be described, the resting state of the membrane must be explained. When the cell is at rest, and the ion channels are closed (except for leakage channels which randomly open), ions are distributed across the membrane in a very predictable way. The concentration of Na^+ outside the cell is 10 times greater than the concentration inside. Also, the concentration of K^+ inside the cell is greater than outside. The cytosol contains a high concentration of anions, in the form of phosphate ions and negatively charged proteins. Large anions are a component of the inner cell membrane, including specialized phospholipids and proteins associated with the inner leaflet of the membrane (leaflet is a term used for one side of the lipid bilayer membrane). The negative charge is localized in the large anions.

With the ions distributed across the membrane at these concentrations, the difference in charge is measured at -70 mV, the value described as the **resting membrane potential**. The exact value measured for the resting membrane potential varies between cells, but -70 mV is most commonly used as this value. This voltage would actually be much lower except for the contributions of some important proteins in the membrane. Leakage channels allow Na^+ to slowly move into the cell or K^+ to slowly move out, and the Na^+/K^+ pump restores them. This may appear to be a waste of energy, but each has a role in maintaining the membrane potential.

The Action Potential

Resting membrane potential describes the steady state of the cell, which is a dynamic process that is balanced by ion leakage and ion pumping. Without any outside influence, it will not change. To get an electrical signal started, the membrane potential has to change.

This starts with a channel opening for Na^+ in the membrane. Because the concentration of $Na^+$is higher outside the cell than inside the cell by a factor of 10, ions will rush into the cell that are driven largely by the concentration gradient. Because sodium is a positively charged ion, it will change the relative voltage immediately inside the cell relative to immediately outside. The resting potential is the state of the membrane at a voltage of -70 mV, so the sodium cation entering the cell will cause it to become less negative. This is known as **depolarization**, meaning the membrane potential moves toward zero.

The concentration gradient for Na^+ is so strong that it will continue to enter the cell even after the membrane potential has become zero, so that the voltage immediately around the pore begins to become positive. The electrical gradient also plays a role, as negative proteins below the membrane attract the sodium ion. The membrane potential will reach +30 mV by the time sodium has entered the cell.

As the membrane potential reaches +30 mV, other voltage-gated channels are opening in the membrane. These channels are specific for the potassium ion. A concentration gradient acts on K^+, as well. As K^+ starts to leave the cell, taking a positive charge with it, the membrane potential begins to move back toward its resting voltage. This is called **repolarization**, meaning that the membrane voltage moves back toward the -70 mV value of the resting membrane potential.

Repolarization returns the membrane potential to the -70 mV value that indicates the resting potential, but it actually overshoots that value. Potassium ions reach equilibrium when the membrane voltage is below -70 mV, so a period of hyperpolarization occurs while the K^+channels are open. Those K^+ channels are slightly delayed in closing, accounting for this short overshoot.

What has been described here is the action potential, which is presented as a graph of voltage over time in Figure 7. (Graph of Action Potential). It is the electrical signal that nervous tissue generates for communication. The change in the membrane voltage from -70 mV at rest to +30 mV at the end of depolarization is a 100-mV change. That can also be written as a 0.1-V change. To put that value in perspective, think about a battery. An AA battery that you might find in a television remote has a voltage of 1.5 V, or a 9-V battery (the rectangular battery with two posts on one end) is, obviously, 9 V. The change seen in the action potential is one or two orders of magnitude less than the charge in these batteries. In fact, the membrane potential can be described as a battery. A charge is stored across the membrane that can be released under the correct conditions. A battery in your remote has stored a charge that is "released" when you push a button.

Graph of Action Potential

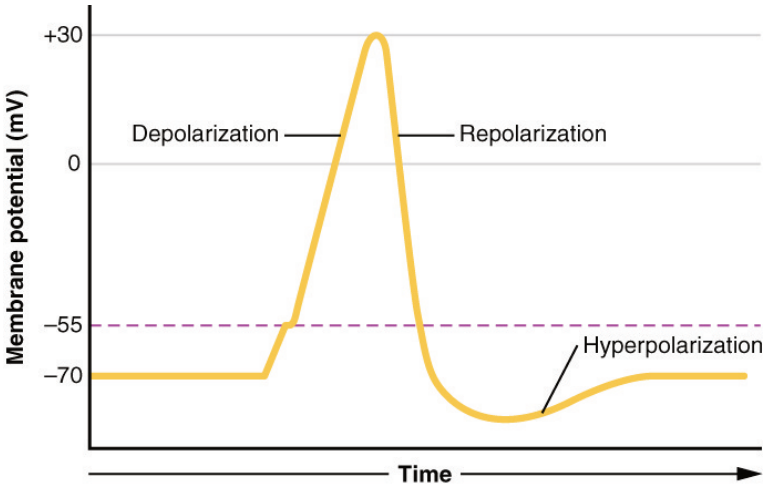


Figure 7. *Plotting voltage measured across the cell membrane against time, the action potential begins with depolarization, followed by repolarization, which goes past the resting potential into hyperpolarization, and finally the membrane returns to rest.*

What happens across the membrane of an electrically active cell is a dynamic process that is hard to visualize with static images or through text descriptions. View this animation to learn more about this process. What is the difference between the driving force for Na^+ and K^+? And what is similar about the movement of these two ions?

The question is, now, what initiates the action potential? The description above conveniently glosses over that point. But it is vital to understanding what is happening. The membrane potential will stay at the resting voltage until something changes. The description above just says that a Na^+ channel opens. Now, to say "a channel opens" does not mean that one individual transmembrane protein changes. Instead, it means that one kind of channel opens. There are a few different types of channels that allow Na^+ to cross the membrane. A ligand-gated Na^+ channel will open when a neurotransmitter binds to it and a mechanically gated Na^+channel will open when a physical stimulus affects a sensory receptor (like pressure applied to the skin compresses a touch receptor). Whether it is a neurotransmitter binding to its receptor protein or a sensory stimulus activating a sensory receptor cell, some stimulus gets the process started. Sodium starts to enter the cell and the membrane becomes less negative.

A third type of channel that is an important part of depolarization in the action potential is the voltage-gated Na^+ channel. The channels that start depolarizing the membrane because of a stimulus help the cell to depolarize from -70 mV to -55 mV. Once the membrane reaches that voltage, the voltage-gated Na^+ channels open. This is what is known as the threshold. Any depolarization that does not change the membrane potential to -55 mV or higher will not reach threshold and thus will not result in an action potential. Also, any stimulus that depolarizes the membrane to -55 mV or beyond will cause a large number of channels to open and an action potential will be initiated.

Because of the threshold, the action potential can be likened to a digital event—it either happens or it does not. If the threshold is not reached, then no action potential occurs. If depolarization reaches -55 mV, then the action potential continues and runs all the way to +30 mV, at which K^+ causes repolarization, including the hyperpolarizing overshoot. Also, those changes are the same for every action potential, which means that

once the threshold is reached, the exact same thing happens. A stronger stimulus, which might depolarize the membrane well past threshold, will not make a "bigger" action potential. Action potentials are "all or none." Either the membrane reaches the threshold and everything occurs as described above, or the membrane does not reach the threshold and nothing else happens. All action potentials peak at the same voltage (+30 mV), so one action potential is not bigger than another. Stronger stimuli will initiate multiple action potentials more quickly, but the individual signals are not bigger. Thus, for example, you will not feel a greater sensation of pain, or have a stronger muscle contraction, because of the size of the action potential because they are not different sizes.

As we have seen, the depolarization and repolarization of an action potential are dependent on two types of channels (the voltage-gated Na^+ channel and the voltage-gated K^+ channel). The voltage-gated Na^+ channel actually has two gates. One is the **activation gate**, which opens when the membrane potential crosses -55 mV. The other gate is the **inactivation gate**, which closes after a specific period of time—on the order of a fraction of a millisecond. When a cell is at rest, the activation gate is closed and the inactivation gate is open. However, when the threshold is reached, the activation gate opens, allowing Na^+ to rush into the cell. Timed with the peak of depolarization, the inactivation gate closes. During repolarization, no more sodium can enter the cell. When the membrane potential passes -55 mV again, the activation gate closes. After that, the inactivation gate re-opens, making the channel ready to start the whole process over again.

The voltage-gated K^+ channel has only one gate, which is sensitive to a membrane voltage of -50 mV. However, it does not open as quickly as the voltage-gated Na^+ channel does. It might take a fraction of a millisecond for the channel to open once that voltage has been reached. The timing of this coincides exactly with when the Na^+ flow peaks, so voltage-gated K^+ channels open just as the voltage-gated Na^+ channels are being inactivated. As the membrane potential repolarizes and the voltage passes -50 mV again, the channel closes—again, with a little delay. Potassium continues to leave the cell for a short while and the membrane potential becomes more negative, resulting in the hyperpolarizing overshoot. Then the channel closes again and the membrane can return to the resting potential because of the ongoing activity of the non-gated channels and the Na^+/K^+ pump.

All of this takes place within approximately 2 milliseconds (Figure 8. Stages of an Action Potential). While an action potential is in progress, another one cannot be initiated. That effect is referred to as the **refractory period**. There are two phases of the refractory period: the **absolute refractory period** and the **relative refractory period**. During the absolute phase, another action potential will not start. This is because of the inactivation gate of the voltage-gated Na^+ channel. Once that channel is back to its resting conformation (less than -55 mV), a new action potential could be started, but only by a stronger stimulus than the one that initiated the current action potential. This is because of the flow of K^+ out of the cell. Because that ion is rushing out, any Na^+ that tries to enter will not depolarize the cell, but will only keep the cell from hyperpolarizing.

Stages of an Action Potential

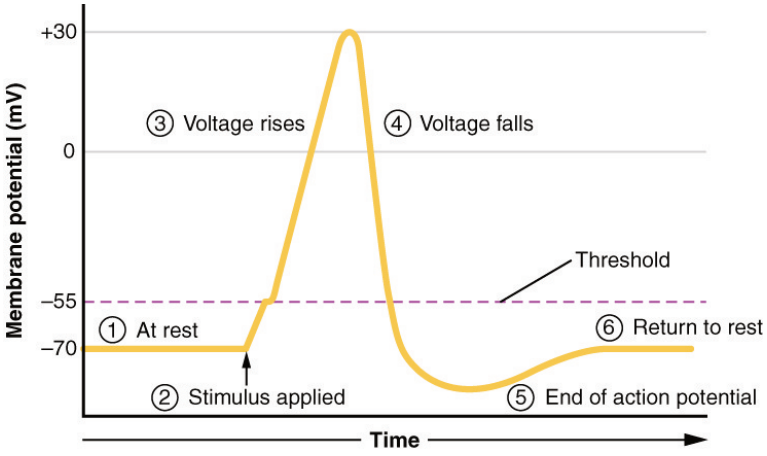


Figure 8. *Plotting voltage measured across the cell membrane against time, the events of the action potential can be related to specific changes in the membrane voltage. (1) At rest, the membrane voltage is -70 mV. (2) The membrane begins to depolarize when an external stimulus is applied. (3) The membrane voltage begins a rapid rise toward +30 mV. (4) The membrane voltage starts to return to a negative value. (5) Repolarization continues past the resting membrane voltage, resulting in hyperpolarization. (6) The membrane voltage returns to the resting value shortly after hyperpolarization.*

Propagation of the Action Potential

The action potential is initiated at the beginning of the axon, at what is called the initial segment. There is a high density of voltage-gated Na^+ channels so that rapid depolarization can take place here. Going down the length of the axon, the action potential is propagated because more voltage-gated Na^+ channels are opened as the depolarization spreads. This spreading occurs because Na^+ enters through the channel and moves along the inside of the cell membrane. As the Na^+ moves, or flows, a short distance along the cell membrane, its positive charge depolarizes a little more of the cell membrane. As that depolarization spreads, new voltage-gated Na^+ channels open and more ions rush into the cell, spreading the depolarization a little farther.

Because voltage-gated Na^+ channels are inactivated at the peak of the depolarization, they cannot be opened again for a brief time—the absolute refractory period. Because of this, depolarization spreading back toward previously opened channels has no effect. The action potential must propagate toward the axon terminals; as a result, the polarity of the neuron is maintained, as mentioned above.

Propagation, as described above, applies to unmyelinated axons. When myelination is present, the action potential propagates differently. Sodium ions that enter the cell at the initial segment start to spread along the length of the axon segment, but there are no voltage-gated Na^+channels until the first node of Ranvier. Because there is not constant opening of these channels along the axon segment, the depolarization spreads at an optimal speed. The distance between nodes is the optimal distance to keep the membrane still depolarized above threshold at the next node. As Na^+ spreads along the inside of the membrane of the axon segment, the charge starts to dissipate. If the node were any farther down the axon, that depolarization would have fallen off too much for voltage-gated Na^+ channels to be activated at the next node of Ranvier. If the nodes were any closer together, the speed of propagation would be slower.

Propagation along an unmyelinated axon is referred to as **continuous conduction**; along the length of a myelinated axon, it is **saltatory conduction**. Continuous conduction is slow because there are always voltage-gated Na^+ channels opening, and more and more Na^+ is rushing into the cell. Saltatory conduction is faster because the action potential basically jumps from one node to the next (saltare = "to leap"), and the new influx of Na^+ renews the depolarized membrane. Along with the myelination of the axon, the diameter of the axon can influence the speed of conduction. Much as water runs faster in a wide river than in a narrow creek, Na^+-based depolarization spreads faster down a wide axon than down a narrow one. This concept is known as **resistance** and is generally true for electrical wires or plumbing, just as it is true for axons, although the specific conditions are different at the scales of electrons or ions versus water in a river.

HOMEOSTATIC IMBALANCES

Potassium Concentration Glial cells, especially astrocytes, are responsible for maintaining the

chemical environment of the CNS tissue. The concentrations of ions in the extracellular fluid are the basis for how the membrane potential is established and changes in electrochemical signaling. If the balance of ions is upset, drastic outcomes are possible.

Normally the concentration of K^+ is higher inside the neuron than outside. After the repolarizing phase of the action potential, K^+ leakage channels and the Na^+/K^+ pump ensure that the ions return to their original locations. Following a stroke or other ischemic event, extracellular K^+ levels are elevated. The astrocytes in the area are equipped to clear excess K^+ to aid the pump. But when the level is far out of balance, the effects can be irreversible.

Astrocytes can become reactive in cases such as these, which impairs their ability to maintain the local chemical environment. The glial cells enlarge and their processes swell. They lose their K^+ buffering ability and the function of the pump is affected, or even reversed. One of the early signs of cell disease is this "leaking" of sodium ions into the body cells. This sodium/potassium imbalance negatively affects the internal chemistry of cells, preventing them from functioning normally.

Visit this site to see a virtual neurophysiology lab, and to observe electrophysiological processes in the nervous system, where scientists directly measure the electrical signals produced by neurons. Often, the action potentials occur so rapidly that watching a screen to see them occur is not helpful. A speaker is powered by the signals recorded from a neuron and it "pops" each time the neuron fires an action potential. These action potentials are firing so fast that it sounds like static on the radio. Electrophysiologists can recognize the patterns within that static to understand what is happening. Why is the leech model used for measuring the electrical activity of neurons instead of using humans?

Chapter Review

The nervous system is characterized by electrical signals that are sent from one area to another. Whether those areas are close or very far apart, the signal must travel along an axon. The basis of the electrical signal is the controlled distribution of ions across the membrane. Transmembrane ion channels regulate when ions can move in or out of the cell, so that a precise signal is generated. This signal is the action potential which has a very characteristic shape based on voltage changes across the membrane in a given time period.

The membrane is normally at rest with established Na^+ and K^+ concentrations on either side. A stimulus will start the depolarization of the membrane, and voltage-gated channels will result in further depolarization followed by repolarization of the membrane. A slight overshoot of hyperpolarization marks the end of the action potential. While an action potential is in progress, another cannot be generated under the same conditions. While the voltage-gated Na^+ channel is inactivated, absolutely no action potentials can be generated. Once that channel has returned to its resting state, a new action potential is possible, but it must be started by a relatively stronger stimulus to overcome the K^+ leaving the cell.

The action potential travels down the axon as voltage-gated ion channels are opened by the spreading depolarization. In unmyelinated axons, this happens in a continuous fashion because there are voltage-gated channels throughout the membrane. In myelinated axons, propagation is described as saltatory because voltage-gated channels are only found at the nodes of Ranvier and the electrical events seem to "jump" from one node to the next. Saltatory conduction is faster than continuous conduction, meaning that myelinated axons propagate their signals faster. The diameter of the axon also makes a difference as ions diffusing within the cell have less resistance in a wider space.

Communication Between Neurons

By the end of this section, you will be able to:

- Explain the differences between the types of graded potentials
- Categorize the major neurotransmitters by chemical type and effect

The electrical changes taking place within a neuron, as described in the previous section, are similar to a light switch being turned on. A stimulus starts the depolarization, but the action potential runs on its own once a threshold has been reached. The question is now, "What flips the light switch on?" Temporary changes to the cell membrane voltage can result from neurons receiving information from the environment, or from the action of one neuron on another. These special types of potentials influence a neuron and determine whether an action potential will occur or not. Many of these transient signals originate at the synapse.

Graded Potentials

Local changes in the membrane potential are called graded potentials and are usually associated with the dendrites of a neuron. The amount of change in the membrane potential is determined by the size of the stimulus that causes it. In the example of testing the temperature of the shower, slightly warm water would only initiate a small change in a thermoreceptor, whereas hot water would cause a large amount of change in the membrane potential.

Graded potentials can be of two sorts, either they are depolarizing or hyperpolarizing (Figure 1. Graded Potentials). For a membrane at the resting potential, a graded potential represents a change in that voltage either above -70 mV or below -70 mV. Depolarizing graded potentials are often the result of Na^+or Ca^{2+} entering the cell. Both of these ions have higher concentrations outside the cell than inside; because they have a positive charge, they will move into the cell causing it to become less negative relative to the outside. Hyperpolarizing graded potentials can be caused by K^+leaving the cell or Cl^- entering the cell. If a positive charge moves out of a cell, the cell becomes more negative; if a negative charge enters the cell, the same thing happens.

Graded Potentials

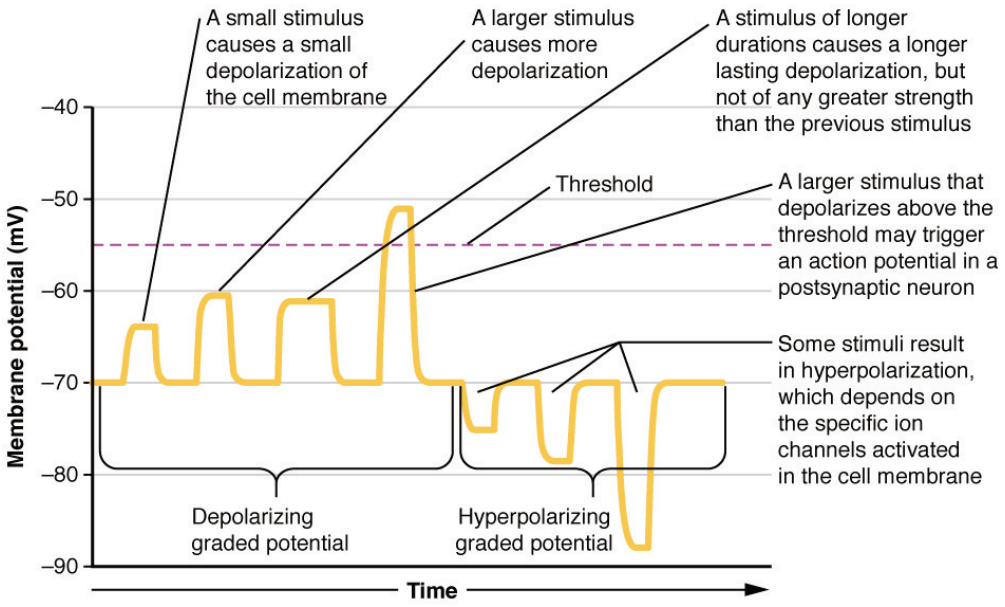


Figure 1. *Graded potentials are temporary changes in the membrane voltage, the characteristics of which depend on the size of the stimulus. Some types of stimuli cause depolarization of the membrane, whereas others cause hyperpolarization. It depends on the specific ion channels that are activated in the cell membrane.*

Types of Graded Potentials

For the unipolar cells of sensory neurons—both those with free nerve endings and those within encapsulations—graded potentials develop in the dendrites that influence the generation of an action potential in the axon of the same cell. This is called a **generator potential**. For other sensory receptor cells, such as taste cells or photoreceptors of the retina, graded potentials in their membranes result in the release of neurotransmitters at synapses with sensory neurons. This is called a **receptor potential**.

A **postsynaptic potential (PSP)** is the graded potential in the dendrites of a neuron that is receiving synapses from other cells. Postsynaptic potentials can be depolarizing or hyperpolarizing. Depolarization in a postsynaptic potential is called an **excitatory postsynaptic potential (EPSP)** because it causes the membrane potential to move toward threshold. Hyperpolarization in a postsynaptic potential is an **inhibitory postsynaptic potential (IPSP)** because it causes the membrane potential to move away from threshold.

Summation

All types of graded potentials will result in small changes of either depolarization or hyperpolarization in the voltage of a membrane. These changes can lead to the neuron reaching threshold if the changes add together, or **summate**. The combined effects of different types of graded potentials are illustrated in Figure 2. (Postsynaptic Potential Summation). If the total change in voltage in the membrane is a positive 15 mV, meaning that the membrane depolarizes from -70 mV to -55 mV, then the graded potentials will result in the membrane reaching threshold.

For receptor potentials, threshold is not a factor because the change in membrane potential for receptor cells directly causes neurotransmitter release. However, generator potentials can initiate action potentials in the sensory neuron axon, and postsynaptic potentials can initiate an action potential in the axon of other neurons. Graded potentials summate at a specific location at the beginning of the axon to initiate the action potential, namely the initial segment. For sensory neurons, which do not have a cell body between the dendrites and the axon, the initial segment is directly adjacent to the dendritic endings. For all other neurons, the axon hillock is essentially the initial segment of the axon, and it is where summation takes place. These locations have a high density of voltage-gated Na^+ channels that initiate the depolarizing phase of the action potential.

Summation can be spatial or temporal, meaning it can be the result of multiple graded potentials at different locations on the neuron, or all at the same place but separated in time. **Spatial summation** is related to associating the activity of multiple inputs to a neuron with each other. **Temporal summation** is the relationship of multiple action potentials from a single cell resulting in a significant change in the membrane potential. Spatial and temporal summation can act together, as well.

Postsynaptic Potential Summation

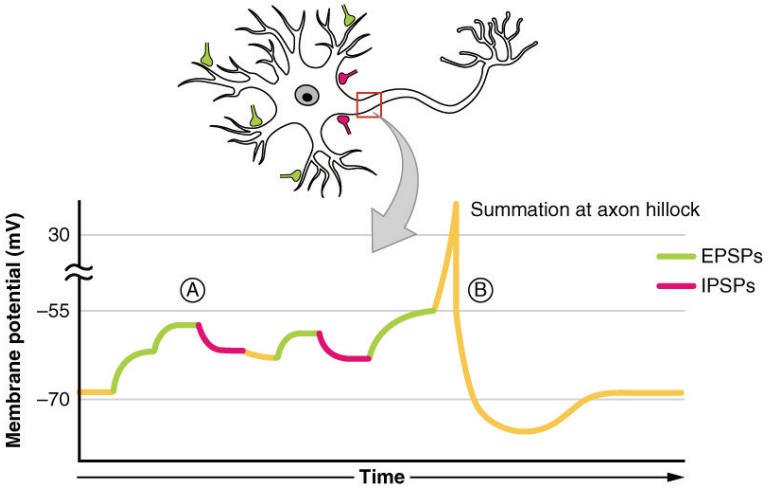


Figure 2. *The result of summation of postsynaptic potentials is the overall change in the membrane potential. At point* A*, several different excitatory postsynaptic potentials add up to a large depolarization. At point* B*, a mix of excitatory and inhibitory postsynaptic potentials result in a different end result for the membrane potential.*

Watch this video to learn about summation. The process of converting electrical signals to chemical signals and back requires subtle changes that can result in transient increases or decreases in membrane voltage. To cause a lasting change in the target cell, multiple signals are usually added together, or summated. Does spatial summation have to happen all at once, or can the separate signals arrive on the postsynaptic neuron at slightly different times? Explain your answer.

Synapses

There are two types of connections between electrically active cells, chemical synapses and electrical synapses. In a **chemical synapse**, a chemical signal—namely, a neurotransmitter—is released from one cell and it affects

the other cell. In an **electrical synapse**, there is a direct connection between the two cells so that ions can pass directly from one cell to the next. If one cell is depolarized in an electrical synapse, the joined cell also depolarizes because the ions pass between the cells. Chemical synapses involve the transmission of chemical information from one cell to the next. This section will concentrate on the chemical type of synapse.

An example of a chemical synapse is the neuromuscular junction (NMJ) described in the chapter on muscle tissue. In the nervous system, there are many more synapses that are essentially the same as the NMJ. All synapses have common characteristics, which can be summarized in this list:

- presynaptic element
- neurotransmitter (packaged in vesicles)
- synaptic cleft
- receptor proteins
- postsynaptic element
- neurotransmitter elimination or re-uptake

For the NMJ, these characteristics are as follows: the presynaptic element is the motor neuron's axon terminals, the neurotransmitter is acetylcholine, the synaptic cleft is the space between the cells where the neurotransmitter diffuses, the receptor protein is the nicotinic acetylcholine receptor, the postsynaptic element is the sarcolemma of the muscle cell, and the neurotransmitter is eliminated by acetylcholinesterase. Other synapses are similar to this, and the specifics are different, but they all contain the same characteristics.

Neurotransmitter Release

When an action potential reaches the axon terminals, voltage-gated Ca^{2+} channels in the membrane of the synaptic end bulb open. The concentration of Ca^{2+} increases inside the end bulb, and the Ca^{2+} ion associates with proteins in the outer surface of neurotransmitter vesicles. The Ca^{2+} facilitates the merging of the vesicle with the presynaptic membrane so that the neurotransmitter is released through exocytosis into the small gap between the cells, known as the **synaptic cleft**.

Once in the synaptic cleft, the neurotransmitter diffuses the short distance to the postsynaptic membrane and can interact with neurotransmitter receptors. Receptors are specific for the neurotransmitter, and the two fit together like a key and lock. One neurotransmitter binds to its receptor and will not bind to receptors for other neurotransmitters, making the binding a specific chemical event (Figure 3. The Synapse).

The Synapse

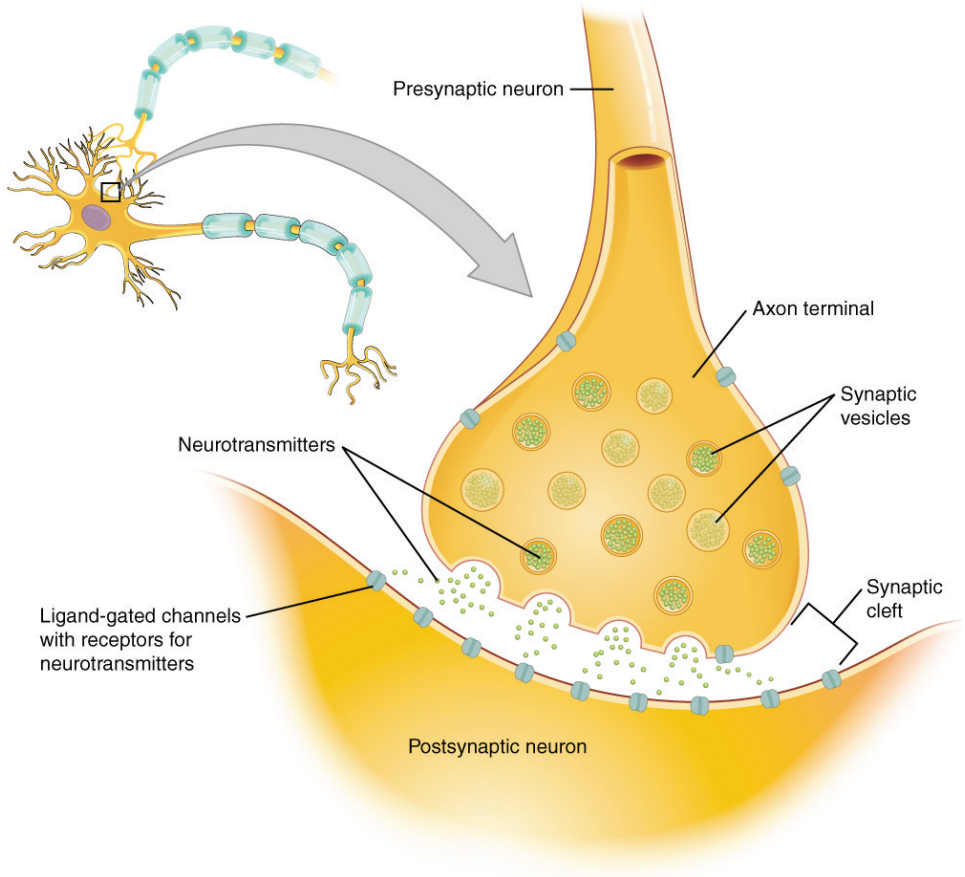


Figure 3. *The synapse is a connection between a neuron and its target cell (which is not necessarily a neuron). The presynaptic element is the synaptic end bulb of the axon where Ca^{2+} enters the bulb to cause vesicle fusion and neurotransmitter release. The neurotransmitter diffuses across the synaptic cleft to bind to its receptor. The neurotransmitter is cleared from the synapse either by enzymatic degradation, neuronal reuptake, or glial reuptake.*

Neurotransmitter Systems

There are several systems of neurotransmitters that are found at various synapses in the nervous system. These groups refer to the chemicals that are the neurotransmitters, and within the groups are specific systems.

The first group, which is a neurotransmitter system of its own, is the **cholinergic system**. It is the system based on acetylcholine. This includes the NMJ as an example of a cholinergic synapse, but cholinergic synapses are found in other parts of the nervous system. They are in the autonomic nervous system, as well as distributed throughout the brain.

The cholinergic system has two types of receptors, the **nicotinic receptor** is found in the NMJ as well as other synapses. There is also an acetylcholine receptor known as the **muscarinic receptor**. Both of these receptors are named for drugs that interact with the receptor in addition to acetylcholine. Nicotine will bind to the nicotinic receptor and activate it similar to acetylcholine. Muscarine, a product of certain mushrooms, will bind to the muscarinic receptor. However, nicotine will not bind to the muscarinic receptor and muscarine will not bind to the nicotinic receptor.

Another group of neurotransmitters are amino acids. This includes glutamate (Glu), GABA (gamma-aminobutyric acid, a derivative of glutamate), and glycine (Gly). These amino acids have an amino group and a carboxyl group in their chemical structures. Glutamate is one of the 20 amino acids that are used to make proteins. Each amino acid neurotransmitter would be part of its own system, namely the glutamatergic, GABAergic, and glycinergic systems. They each have their own receptors and do not interact with each other. Amino acid neurotransmitters are eliminated from the synapse by reuptake. A pump in the cell membrane of the presynaptic element, or sometimes a neighboring glial cell, will clear the amino acid from the synaptic cleft so that it can be recycled, repackaged in vesicles, and released again.

Another class of neurotransmitter is the **biogenic amine**, a group of neurotransmitters that are enzymatically made from amino acids. They have amino groups in them, but no longer have carboxyl groups and are therefore no longer classified as amino acids. Serotonin is made from tryptophan. It is the basis of the serotonergic system, which has its own specific receptors. Serotonin is transported back into the presynaptic cell for repackaging.

Other biogenic amines are made from tyrosine, and include dopamine, norepinephrine, and epinephrine. Dopamine is part of its own system, the dopaminergic system, which has dopamine receptors. Dopamine is removed from the synapse by transport proteins in the presynaptic cell membrane. Norepinephrine and epinephrine belong to the adrenergic neurotransmitter system. The two molecules are very similar and bind to the same receptors, which are referred to as alpha and beta receptors. Norepinephrine and epinephrine are also transported back into the presynaptic cell. The chemical epinephrine (epi- = "on"; "-nephrine" = kidney) is also known as adrenaline (renal = "kidney"), and norepinephrine is sometimes referred to as noradrenaline. The adrenal gland produces epinephrine and norepinephrine to be released into the blood stream as hormones.

A **neuropeptide** is a neurotransmitter molecule made up of chains of amino acids connected by peptide bonds. This is what a protein is, but the term protein implies a certain length to the molecule. Some neuropeptides are quite short, such as met-enkephalin, which is five amino acids long. Others are long, such as beta-endorphin, which is 31 amino acids long. Neuropeptides are often released at synapses in combination with another neurotransmitter, and they often act as hormones in other systems of the body, such as vasoactive intestinal peptide (VIP) or substance P.

The effect of a neurotransmitter on the postsynaptic element is entirely dependent on the receptor protein. First, if there is no receptor protein in the membrane of the postsynaptic element, then the neurotransmitter has no effect. The depolarizing or hyperpolarizing effect is also dependent on the receptor. When acetylcholine binds to the nicotinic receptor, the postsynaptic cell is depolarized. This is because the receptor is a cation channel and positively charged Na^+ will rush into the cell. However, when acetylcholine binds to the muscarinic receptor, of which there are several variants, it might cause depolarization or hyperpolarization of the target cell.

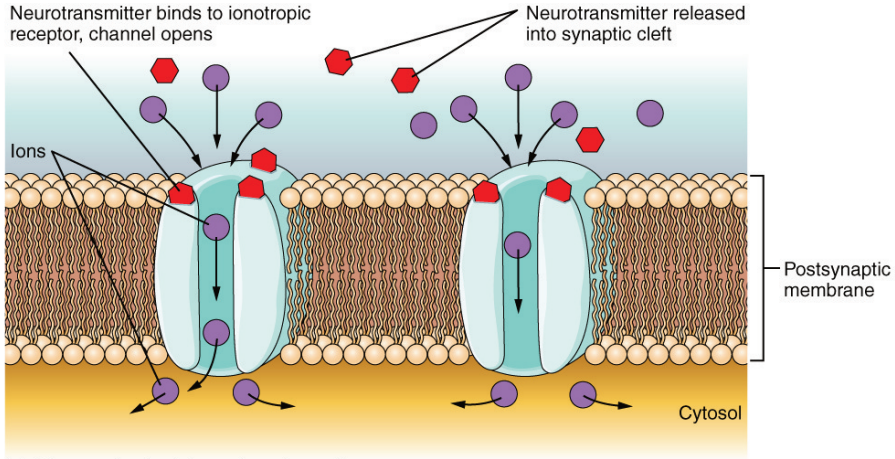
The amino acid neurotransmitters, glutamate, glycine, and GABA, are almost exclusively associated with just one effect. Glutamate is considered an excitatory amino acid, but only because Glu receptors in the adult cause depolarization of the postsynaptic cell. Glycine and GABA are considered inhibitory amino acids, again because their receptors cause hyperpolarization.

The biogenic amines have mixed effects. For example, the dopamine receptors that are classified as D1 receptors are excitatory whereas D2-type receptors are inhibitory. Biogenic amine receptors and neuropeptide receptors can have even more complex effects because some may not directly affect the membrane potential, but rather have an effect on gene transcription or other metabolic processes in the neuron. The characteristics of the various neurotransmitter systems presented in this section are organized in Table (Characteristics of Neurotransmitter Systems).

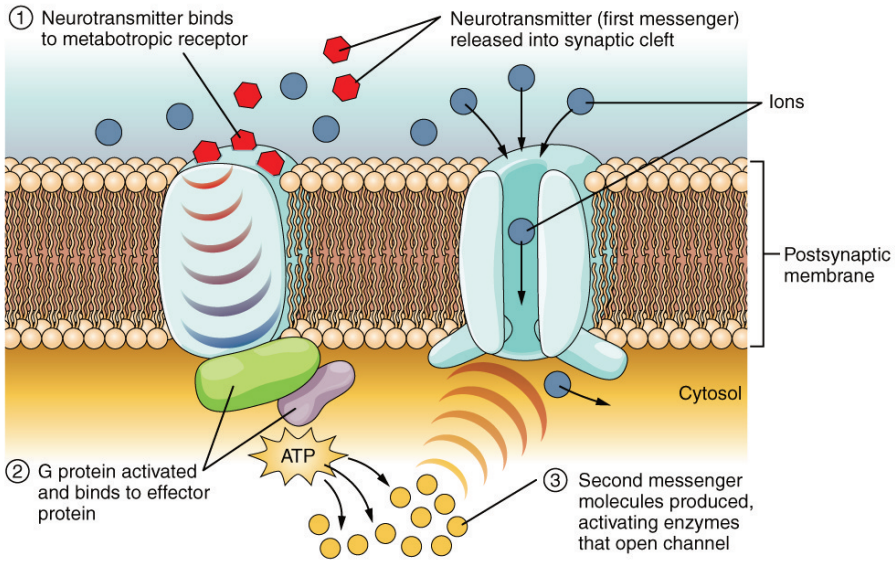
The important thing to remember about neurotransmitters, and signaling chemicals in general, is that the effect is entirely dependent on the receptor. Neurotransmitters bind to one of two classes of receptors at the cell surface, ionotropic or metabotropic (Figure 4. Receptor Types). Ionotropic receptors are ligand-gated ion channels, such as the nicotinic receptor for acetylcholine or the glycine receptor. A **metabotropic**

receptor involves a complex of proteins that result in metabolic changes within the cell. The receptor complex includes the transmembrane receptor protein, a G protein, and an effector protein. The neurotransmitter, referred to as the first messenger, binds to the receptor protein on the extracellular surface of the cell, and the intracellular side of the protein initiates activity of the G protein. The **G protein** is a guanosine triphosphate (GTP) hydrolase that physically moves from the receptor protein to the effector protein to activate the latter. An **effector protein** is an enzyme that catalyzes the generation of a new molecule, which acts as the intracellular mediator of the signal that binds to the receptor. This intracellular mediator is called the second messenger.

Different receptors use different second messengers. Two common examples of second messengers are cyclic adenosine monophosphate (cAMP) and inositol triphosphate (IP_3). The enzyme adenylate cyclase (an example of an effector protein) makes cAMP, and phospholipase C is the enzyme that makes IP_3. Second messengers, after they are produced by the effector protein, cause metabolic changes within the cell. These changes are most likely the activation of other enzymes in the cell. In neurons, they often modify ion channels, either opening or closing them. These enzymes can also cause changes in the cell, such as the activation of genes in the nucleus, and therefore the increased synthesis of proteins. In neurons, these kinds of changes are often the basis of stronger connections between cells at the synapse and may be the basis of learning and memory.



(a) Direct activation brings about immediate response



(b) Indirect activation involves a prolonged response, amplified over time

Figure 4. *(a) An ionotropic receptor is a channel that opens when the neurotransmitter binds to it. (b)* A

metabotropic receptor is a complex that causes metabolic changes in the cell when the neurotransmitter binds to it (1). After binding, the G protein hydrolyzes GTP and moves to the effector protein (2). When the G protein contacts the effector protein, a second messenger is generated, such as cAMP (3). The second messenger can then go on to cause changes in the neuron, such as opening or closing ion channels, metabolic changes, and changes in gene transcription.

Watch this video to learn about the release of a neurotransmitter. The action potential reaches the end of the axon, called the axon terminal, and a chemical signal is released to tell the target cell to do something—either to initiate a new action potential, or to suppress that activity. In a very short space, the electrical signal of the action potential is changed into the chemical signal of a neurotransmitter and then back to electrical changes in the target cell membrane. What is the importance of voltage-gated calcium channels in the release of neurotransmitters?

Characteristics of Neurotransmitter Systems

System	Cholinergic	Amino acids	Biogenic amines	Neuropeptides
Neurotransmitters	Acetylcholine	Glutamate, glycine, GABA	Serotonin (5-HT), dopamine, norepinephrine, (epinephrine)	Met-enkephalin, beta-endorphin, VIP, Substance P, etc.
Receptors	Nicotinic and muscarinic receptors	Glu receptors, gly receptors, GABA receptors	5-HT receptors, D1 and D2 receptors, α-adrenergic and β-adrenergic receptors	Receptors are too numerous to list, but are specific to the peptides.
Elimination	Degradation by acetylcholinesterase	Reuptake by neurons or glia	Reuptake by neurons	Degradation by enzymes called peptidases
Postsynaptic effect	Nicotinic receptor causes depolarization. Muscarinic receptors can cause both depolarization or hyperpolarization depending on the subtype.	Glu receptors cause depolarization. Gly and GABA receptors cause hyperpolarization.	Depolarization or hyperpolarization depends on the specific receptor. For example, D1 receptors cause depolarization and D2 receptors cause hyperpolarization.	Depolarization or hyperpolarization depends on the specific receptor.

DISORDERS OF THE…

Nervous System The underlying cause of some neurodegenerative diseases, such as Alzheimer's and Parkinson's, appears to be related to proteins—specifically, to proteins behaving badly. One of the strongest theories of what causes Alzheimer's disease is based on the accumulation of beta-amyloid plaques, dense conglomerations of a protein that is not functioning correctly. Parkinson's disease is linked to an increase in a protein known as alpha-synuclein that is toxic to the cells of the substantia nigra nucleus in the midbrain.

For proteins to function correctly, they are dependent on their three-dimensional shape. The linear sequence of amino acids folds into a three-dimensional shape that is based on the interactions

between and among those amino acids. When the folding is disturbed, and proteins take on a different shape, they stop functioning correctly. But the disease is not necessarily the result of functional loss of these proteins; rather, these altered proteins start to accumulate and may become toxic. For example, in Alzheimer's, the hallmark of the disease is the accumulation of these amyloid plaques in the cerebral cortex. The term coined to describe this sort of disease is "proteopathy" and it includes other diseases. Creutzfeld-Jacob disease, the human variant of the prion disease known as mad cow disease in the bovine, also involves the accumulation of amyloid plaques, similar to Alzheimer's. Diseases of other organ systems can fall into this group as well, such as cystic fibrosis or type 2 diabetes. Recognizing the relationship between these diseases has suggested new therapeutic possibilities. Interfering with the accumulation of the proteins, and possibly as early as their original production within the cell, may unlock new ways to alleviate these devastating diseases.

Chapter Review

The basis of the electrical signal within a neuron is the action potential that propagates down the axon. For a neuron to generate an action potential, it needs to receive input from another source, either another neuron or a sensory stimulus. That input will result in opening ion channels in the neuron, resulting in a graded potential based on the strength of the stimulus. Graded potentials can be depolarizing or hyperpolarizing and can summate to affect the probability of the neuron reaching threshold.

Graded potentials can be the result of sensory stimuli. If the sensory stimulus is received by the dendrites of a unipolar sensory neuron, such as the sensory neuron ending in the skin, the graded potential is called a generator potential because it can directly generate the action potential in the initial segment of the axon. If the sensory stimulus is received by a specialized sensory receptor cell, the graded potential is called a receptor potential. Graded potentials produced by interactions between neurons at synapses are called postsynaptic potentials (PSPs). A depolarizing graded potential at a synapse is called an excitatory PSP, and a hyperpolarizing graded potential at a synapse is called an inhibitory PSP.

Synapses are the contacts between neurons, which can either be chemical or electrical in nature. Chemical synapses are far more common. At a chemical synapse, neurotransmitter is released from the presynaptic element and diffuses across the synaptic cleft. The neurotransmitter binds to a receptor protein and causes a change in the postsynaptic membrane (the PSP). The neurotransmitter must be inactivated or removed from the synaptic cleft so that the stimulus is limited in time.

The particular characteristics of a synapse vary based on the neurotransmitter system produced by that neuron. The cholinergic system is found at the neuromuscular junction and in certain places within the nervous system. Amino acids, such as glutamate, glycine, and gamma-aminobutyric acid (GABA) are used as neurotransmitters. Other neurotransmitters are the result of amino acids being enzymatically changed, as in the biogenic amines, or being covalently bonded together, as in the neuropeptides.

License

1.3 Anatomy of the Nervous System

Introduction

Human Nervous System

Figure 1. *The ability to balance like an acrobat combines functions throughout the nervous system. The central and peripheral divisions coordinate control of the body using the senses of balance, body position, and touch on the soles of the feet. (credit: Rhett Sutphin)*

After studying this chapter, you will be able to:

- Relate the developmental processes of the embryonic nervous system to the adult structures
- Name the major regions of the adult nervous system
- Locate regions of the cerebral cortex on the basis of anatomical landmarks common to all human brains
- Describe the regions of the spinal cord in cross-section
- List the cranial nerves in order of anatomical location and provide the central and peripheral connections

- List the spinal nerves by vertebral region and by which nerve plexus each supplies

The nervous system is responsible for controlling much of the body, both through somatic (voluntary) and autonomic (involuntary) functions. The structures of the nervous system must be described in detail to understand how many of these functions are possible. There is a physiological concept known as localization of function that states that certain structures are specifically responsible for prescribed functions. It is an underlying concept in all of anatomy and physiology, but the nervous system illustrates the concept very well.

Fresh, unstained nervous tissue can be described as gray or white matter, and within those two types of tissue it can be very hard to see any detail. However, as specific regions and structures have been described, they were related to specific functions. Understanding these structures and the functions they perform requires a detailed description of the anatomy of the nervous system, delving deep into what the central and peripheral structures are.

The place to start this study of the nervous system is the beginning of the individual human life, within the womb. The embryonic development of the nervous system allows for a simple framework on which progressively more complicated structures can be built. With this framework in place, a thorough investigation of the nervous system is possible.

The Embryologic Perspective

By the end of this section, you will be able to:

- Describe the growth and differentiation of the neural tube
- Relate the dierent stages of development to the adult structures of the central nervous system
- Explain the expansion of the ventricular system of the adult brain from the central canal of the neural tube
- Describe the connections of the diencephalon and cerebellum on the basis of patterns of embryonic development

Starting from an embryologic perspective allows you to understand more easily how the parts relate to each other. The embryonic nervous system begins as a very simple structure essentially just a straight line, which then gets increasingly complex. Looking at the development of the nervous system with a couple of early snapshots makes it easier to understand the whole complex system.The brain is a complex organ composed of gray parts and white matter, which can be hard to distinguish.

Many structures that appear to be adjacent in the adult brain are not connected, and the connections that exist may seem arbitrary. But there is an underlying order to the system that comes from how different parts

develop. By following the developmental pattern, it is possible to learn what the major regions of the nervous system are.

The Neural Tube

To begin, a sperm cell and an egg cell fuse to become a fertilized egg. The fertilized egg cell, or zygote, starts dividing to generate the cells that make up an entire organism. Sixteen days after fertilization, the developing embryo's cells belong to one of three germ layers that give rise to the different tissues in the body. The endoderm, or inner tissue, is responsible for generating the lining tissues of various spaces within the body, such as the mucosae of the digestive and respiratory systems. The mesoderm, or middle tissue, gives rise to most of the muscle and connective tissues. Finally the ectoderm, or outer tissue, develops into the integumentary system (the skin) and the nervous system. It is probably not dicult to see that the outer tissue of the embryo becomes the outer covering of the body. But how is it responsible for the nervous system?

As the embryo develops, a portion of the ectoderm differentiates into a specialized region of neuroectoderm, which is the precursor for the tissue of the nervous system. Molecular signals induce cells in this region to differentiate into the neuroepithelium, forming a **neural plate**. The cells then begin to change shape, causing the tissue to buckle and fold inward (Figure 1. Early Embryonic Development of Nervous System). A **neural groove** forms, visible as a line along the dorsal surface of the embryo. The ridge-like edge on either side of the neural groove is referred as the **neural fold**. As the neural folds come together and converge, the underlying structure forms into a tube just beneath the ectoderm called the **neural tube**. Cells from the neural folds then separate from the ectoderm to form a cluster of cells referred to as the **neural crest**, which runs lateral to the neural tube. The neural crest migrates away from the nascent, or embryonic, central nervous system (CNS) that will form along the neural groove and develops into several parts of the peripheral nervous system (PNS), including the enteric nervous tissue. Many tissues that are not part of the nervous system also arise from the neural crest, such as craniofacial cartilage and bone, and melanocytes.

Early Embryonic Development of Nervous System

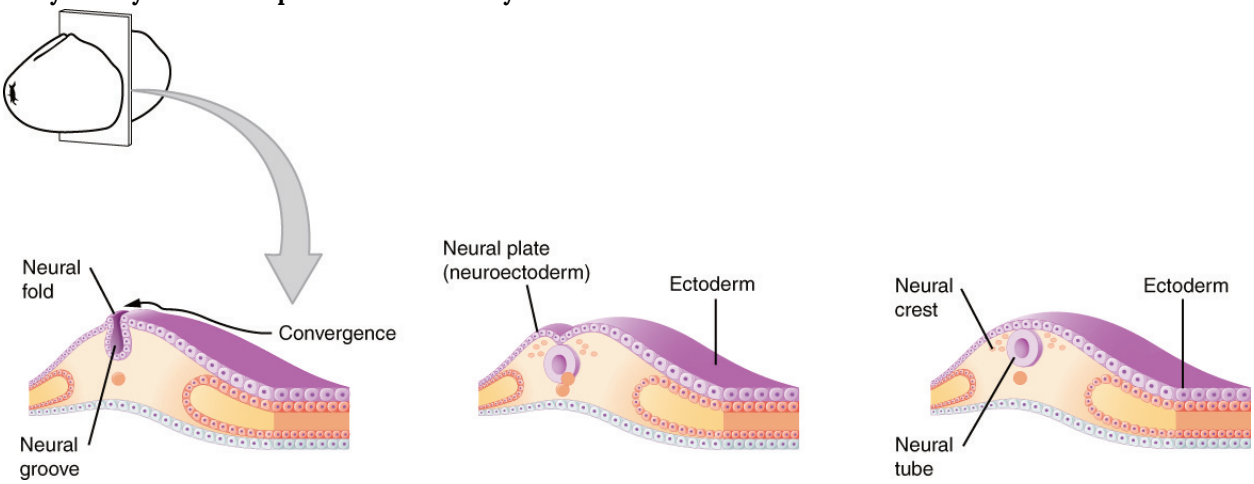


Figure 1. *The neuroectoderm begins to fold inward to form the neural groove. As the two sides of the neural groove converge, they form the neural tube, which lies beneath the ectoderm. The anterior end of the neural tube will develop into the brain, and the posterior portion will become the spinal cord. The neural crest develops into peripheral structures.*

At this point, the early nervous system is a simple, hollow tube. It runs from the anterior end of the embryo to the posterior end. Beginning at 25 days, the anterior end develops into the brain, and the posterior portion becomes the spinal cord. This is the most basic arrangement of tissue in the nervous system, and it gives rise to the more complex structures by the fourth week of development.

Primary Vesicles

As the anterior end of the neural tube starts to develop into the brain, it undergoes a couple of enlargements; the result is the production of sac-like vesicles. Similar to a child's balloon animal, the long, straight neural tube begins to take on a new shape. Three vesicles form at the first stage, which are called **primary vesicles**. These vesicles are given names that are based on Greek words, the main root word being *enkephalon*, which means brain (en- = inside; kephalon = head). The prefix to each generally corresponds to its position along the length of the developing nervous system.

The **prosencephalon** (pros- = in front) is the forward-most vesicle, and the term can be loosely translated to mean **forebrain**. The **mesencephalon** (mes- = middle) is the next vesicle, which can be called the **midbrain**. The third vesicle at this stage is the **rhombencephalon**. The first part of this word is also the root of the word rhombus, which is a geometrical figure with four sides of equal length (a square is a rhombus with 90 ◦ angles). Whereas prosencephalon and mesencephalon translate into the English words forebrain and midbrain, there is not a word for four-sided-figure-brain. However, the third vesicle can be called the **hindbrain**. One way of thinking about how the brain is arranged is to use these three regions – forebrain, midbrain, and hindbrain – which are based on the primary vesicle stage of development (Figure 2 a. Primary and Secondary Vesicle Stages of Development).

Secondary Vesicles

The brain continues to develop, and the vesicles differentiate further (see Figure 2 b. Primary and Secondary Vesicle Stages of Development). The three primary vesicles become five **secondary vesicles**. The prosencephalon enlarges into two new vesicles called the **telencephalon** and the **diencephalon**. The telencephalon will become the cerebrum. The diencephalon gives rise to several adult structures; two that will be important are the thalamus and the hypothalamus. In the embryonic diencephalon, a structure known as the eye cup develops, which will eventually become the retina, the nervous tissue of the eye called the retina. This is a rare example of nervous tissue developing as part of the CNS structures in the embryo, but becoming a peripheral structure in the fully formed nervous system.

The mesencephalon does not differentiate into any finer divisions. The midbrain is an established region of the brain at the primary vesicle stage of development and remains that way. The rest of the brain develops around it and constitutes a large percentage of the mass of the brain. Dividing the brain into forebrain, midbrain, and hindbrain is useful in considering its developmental pattern, but the midbrain is a small proportion of the entire brain, relatively speaking.

The rhombencephalon develops into the **metencephalon** and **myelencephalon**. The metencephalon corresponds to the adult structure known as the pons and also gives rise to the cerebellum. The cerebellum (from the Latin meaning little brain) accounts for about 10 percent of the mass of the brain and is an important structure in itself. The most significant connection between the cerebellum and the rest of the brain is at the

pons, because the pons and cerebellum develop out of the same vesicle. The myelencephalon corresponds to the adult structure known as the medulla oblongata. The structures that come from the mesencephalon and rhombencephalon, except for the cerebellum, are collectively considered the **brain stem**, which specifically includes the midbrain, pons, and medulla.

Primary and Secondary Vesicle Stages of Development

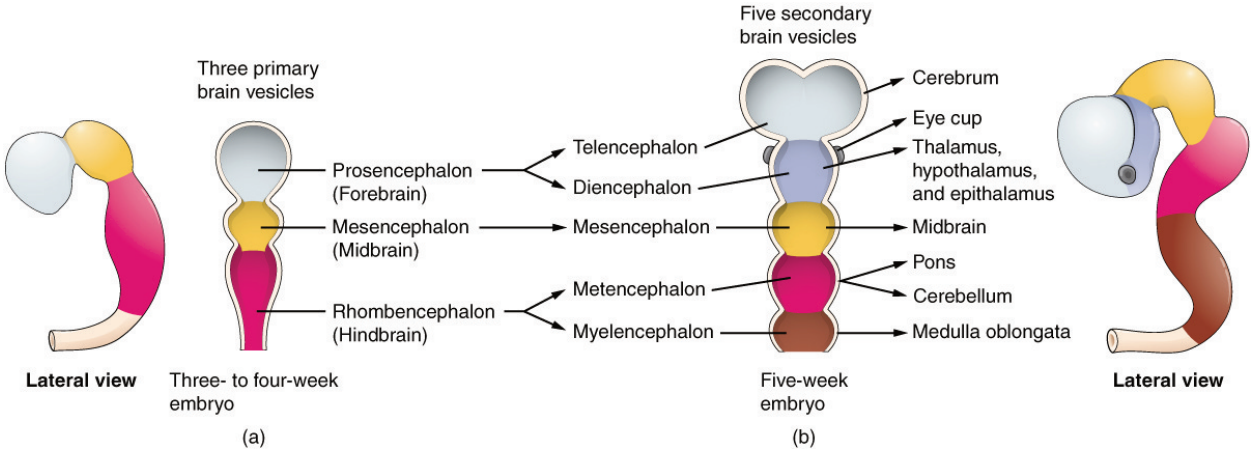


Figure 2. *The embryonic brain develops complexity through enlargements of the neural tube called vesicles; (a) The primary vesicle stage has three regions, and (b) the secondary vesicle stage has five regions.*

Watch this animation to examine the development of the brain, starting with the neural tube. As the anterior end of the neural tube develops, it enlarges into the primary vesicles that establish the forebrain, midbrain, and hindbrain. Those structures continue to develop throughout the rest of embryonic development and into adolescence. They are the basis of the structure of the fully developed adult brain. How would you describe the difference in the relative sizes of the three regions of the brain when comparing the early (25th embryonic day) brain and the adult brain?

Spinal Cord Development

While the brain is developing from the anterior neural tube, the spinal cord is developing from the posterior neural tube. However, its structure does not differ from the basic layout of the neural tube. It is a long, straight cord with a small, hollow space down the center. The neural tube is defined in terms of its anterior versus posterior portions, but it also has a dorsal-ventral dimension. As the neural tube separates from the rest of the ectoderm, the side closest to the surface is dorsal, and the deeper side is ventral.

As the spinal cord develops, the cells making up the wall of the neural tube proliferate and differentiate into the neurons and glia of the spinal cord. The dorsal tissues will be associated with sensory functions, and the ventral tissues will be associated with motor functions.

Relating Embryonic Development to the Adult Brain

Embryonic development can help in understanding the structure of the adult brain because it establishes a framework on which more complex structures can be built. First, the neural tube establishes the anterior-posterior dimension of the nervous system, which is called the **neuraxis**. The embryonic nervous system in mammals can be said to have a standard arrangement. Humans (and other primates, to some degree) make this complicated by standing up and walking on two legs. The anterior-posterior dimension of the neuraxis overlays the superior-inferior dimension of the body. However, there is a major curve between the brain stem and forebrain, which is called the **cephalic flexure**. Because of this, the neuraxis starts in an inferior position – the end of the spinal cord – and ends in an anterior position, the front of the cerebrum. If this is confusing, just imagine a four-legged animal standing up on two legs. Without the exure in the brain stem, and at the top of the neck, that animal would be looking straight up instead of straight in front (Figure 3. Human Neuraxis).

Human Neuraxis

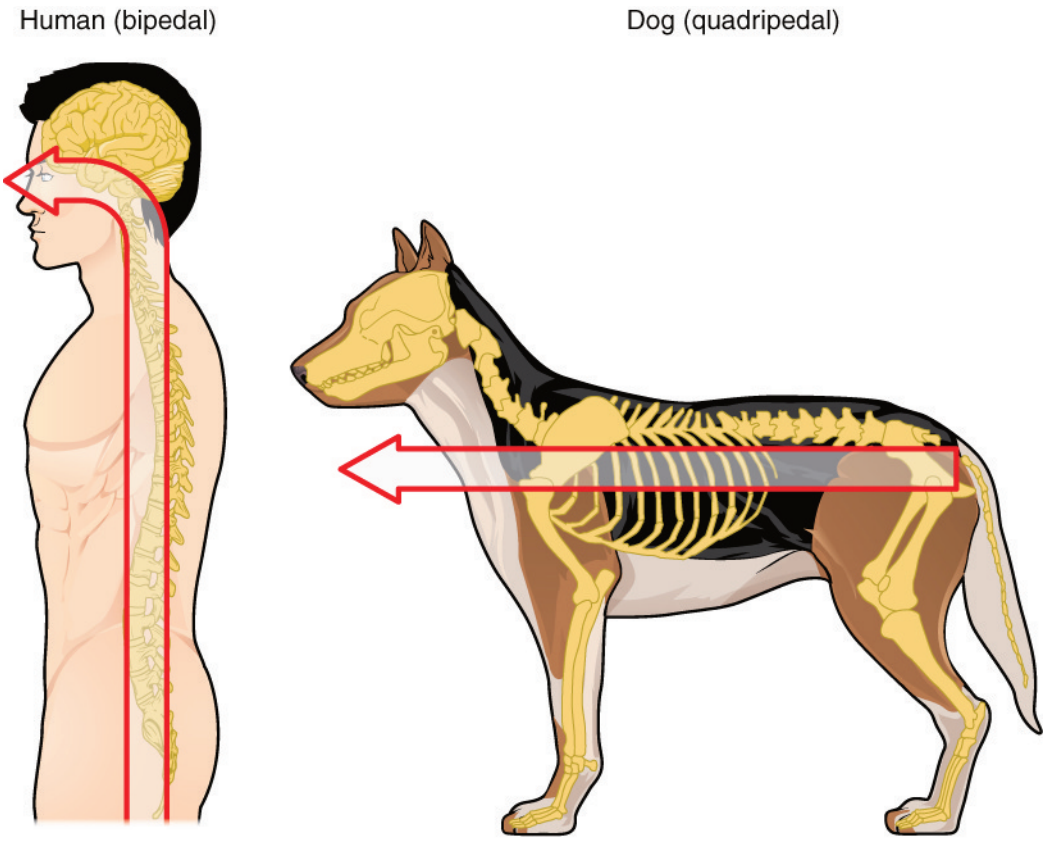


Figure 3. *The mammalian nervous system is arranged with the neural tube running along an anterior to posterior axis, from nose to tail for a four-legged animal like a dog. Humans, as two-legged animals, have a bend in the neuraxis between the brain stem and the diencephalon, along with a bend in the neck, so that the eyes and the face are oriented forward.*

In summary, the primary vesicles help to establish the basic regions of the nervous system: forebrain, midbrain, and hindbrain. These divisions are useful in certain situations, but they are not equivalent regions. The midbrain is small compared with the hindbrain and particularly the forebrain. The secondary vesicles go on to establish the major regions of the adult nervous system that will be followed in this text. The telencephalon is the cerebrum, which is the major portion of the human brain. The diencephalon continues to be referred to by this Greek

name, because there is no better term for it (dia- = through). The diencephalon is between the cerebrum and the rest of the nervous system and can be described as the region through which all projections have to pass between the cerebrum and everything else. The brain stem includes the midbrain, pons, and medulla, which correspond to the mesencephalon, metencephalon, and myelencephalon. The cerebellum, being a large portion of the brain, is considered a separate region. Table (Stages of Embryonic Development) connects the different stages of development to the adult structures of the CNS.

One other benefit of considering embryonic development is that certain connections are more obvious because of how these adult structures are related. The retina, which began as part of the diencephalon, is primarily connected to the diencephalon. The eyes are just inferior to the anterior-most part of the cerebrum, but the optic nerve extends back to the thalamus as the optic tract, with branches into a region of the hypothalamus. There is also a connection of the optic tract to the midbrain, but the mesencephalon is adjacent to the diencephalon, so that is not difficult to imagine. The cerebellum originates out of the metencephalon, and its largest white matter connection is to the pons, also from the metencephalon. There are connections between the cerebellum and both the medulla and midbrain, which are adjacent structures in the secondary vesicle stage of development. In the adult brain, the cerebellum seems close to the cerebrum, but there is no direct connection between them.

Another aspect of the adult CNS structures that relates to embryonic development is the ventricles – open spaces within the CNS where cerebrospinal uid circulates. They are the remnant of the hollow center of the neural tube. The four ventricles and the tubular spaces associated with them can be linked back to the hollow center of the embryonic brain (see Table (Stages of Embryonic Development)).

Stages of Embryonic Development

Neural Tube	Primary vesicle stage	Secondary vesicle stage	Adult structures	Ventricles
Anterior neural tube	Prosencephalon	Telencephalon	Cerebrum	Lateral ventricles
Anterior neural tube	Prosencephalon	Diencephalon	Diencephalon	Third ventricle
Anterior neural tube	Mesencephalon	Mesencephalon	Midbrain	Cerebral aqueduct
Anterior neural tube	Rhombencephalon	Metencephalon	Pons cerebellum	Fourth ventricle
Anterior neural tube	Rhombencephalon	Myelencephalon	Medulla	Fourth ventricle
Posterior neural tube			Spinal cord	Central canal

Disorders of the . . .

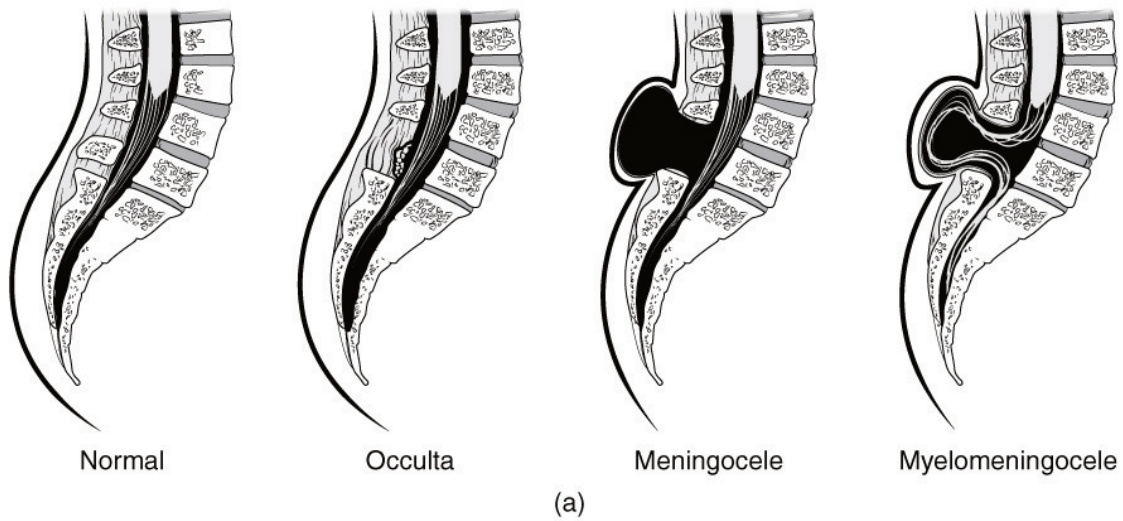
Nervous System

Early formation of the nervous system depends on the formation of the neural tube. A groove forms along the dorsal surface of the embryo, which becomes deeper until its edges meet and close o to form the tube. If this fails to happen, especially in the posterior region where the spinal cord forms, a developmental defect called spina bida occurs. The closing of the neural tube is important for more than just the proper formation of the nervous system. The surrounding tissues are dependent on the correct development of the tube. The connective tissues surrounding the CNS can be involved as well.

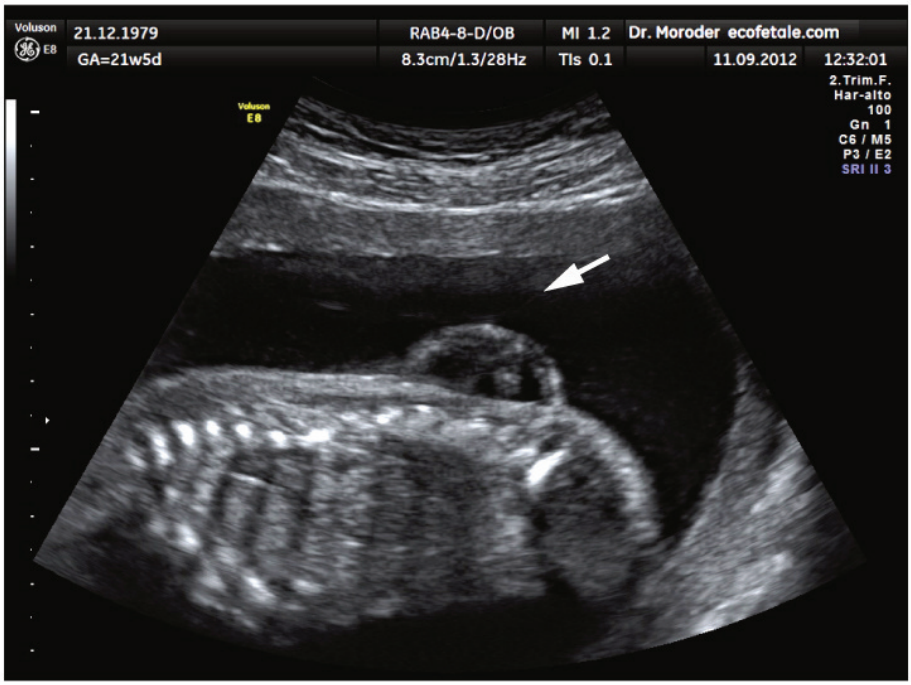
There are three classes of this disorder: occulta, meningocele, and myelomeningocele (Figure 4. Spinal Bifida). The first type, spina bifida occulta, is the mildest because the vertebral bones do not fully surround the spinal cord, but the spinal cord itself is not affected. No functional differences may be noticed, which is what the word occulta means; it is hidden spina bifida. The other two types both involve the formation of a cysta uid-lled sac of the connective tissues that cover the spinal cord called the meninges. Meningocele means that the meninges protrude through the spinal column but nerves may not be involved and few symptoms are present, though complications may arise later in life. Myelomeningocele means that the meninges protrude and spinal nerves are involved, and therefore severe neurological symptoms can be present.

Often surgery to close the opening or to remove the cyst is necessary. The earlier that surgery can be performed, the better the chances of controlling or limiting further damage or infection at the opening. For many children with meningocele, surgery will alleviate the pain, although they may experience some functional loss. Because the myelomeningocele form of spina bida involves more extensive damage to the nervous tissue, neurological damage may persist, but symptoms can often be handled. Complications of the spinal cord may present later in life, but overall life expectancy is not reduced.

Spinal Bifida



(a)



(b)

Figure 4. *(a) Spinal bifida is a birth defect of the spinal cord caused when the neural tube does not completely close, but the rest of development continues. The result is the emergence of meninges and neural tissue through the vertebral column. (b) Fetal myelomeningocele is evident in this ultrasound taken at 21 weeks.*

Watch this video to learn about the white matter in the cerebrum that develops during childhood and adolescence. This is a composite of MRI images taken of the brains of people from 5 years of age through 20 years of age, demonstrating how the cerebrum changes. As the color changes to blue, the ratio of gray matter to white matter changes. The caption for the video describes it as "less gray matter," which is another way of saying "more white matter." If the brain does not finish developing until approximately 20 years of age, can teenagers be held responsible for behaving badly?

Chapter Review

The development of the nervous system starts early in embryonic development. The outer layer of the embryo, the ectoderm, gives rise to the skin and the nervous system. A specialized region of this layer, the neuroectoderm, becomes a groove that folds in and becomes the neural tube beneath the dorsal surface of the embryo. The anterior end of the neural tube develops into the brain, and the posterior region becomes the spinal cord. Tissues at the edges of the neural groove, when it closes o, are called the neural crest and migrate through the embryo to give rise to PNS structures as well as some non-nervous tissues.

The brain develops from this early tube structure and gives rise to specific regions of the adult brain. As the neural tube grows and differentiates, it enlarges into three vesicles that correspond to the forebrain, midbrain, and hindbrain regions of the adult brain. Later in development, two of these three vesicles differentiate further, resulting in ve vesicles. Those ve vesicles can be aligned with the four major regions of the adult brain. The cerebrum is formed directly from the telencephalon. The diencephalon is the only region that keeps its embryonic name. The mesencephalon, metencephalon, and myelencephalon become the brain stem. The cerebellum also develops from the metencephalon and is a separate region of the adult brain.

The spinal cord develops out of the rest of the neural tube and retains the tube structure, with the nervous tissue thickening and the hollow center becoming a very small central canal through the cord. The rest of the hollow center of the neural tube corresponds to open spaces within the brain called the ventricles, where cerebrospinal fluid is found.

The Central Nervous System

By the end of this section, you will be able to:

- Name the major regions of the adult brain
- Describe the connections between the cerebrum and brain stem through the diencephalon, and from those regions into the spinal cord

- Recognize the complex connections within the subcortical structures of the basal nuclei
- Explain the arrangement of gray and white matter in the spinal cord

The brain and the spinal cord are the central nervous system, and they represent the main organs of the nervous system. The spinal cord is a single structure, whereas the adult brain is described in terms of four major regions: the cerebrum, the diencephalon, the brain stem, and the cerebellum. A person's conscious experiences are based on neural activity in the brain. The regulation of homeostasis is governed by a specialized region in the brain. The coordination of reflexes depends on the integration of sensory and motor pathways in the spinal cord.

The Cerebrum

The iconic gray mantle of the human brain, which appears to make up most of the mass of the brain, is the **cerebrum** (Figure 1. The Cerebrum). The wrinkled portion is the **cerebral cortex**, and the rest of the structure is beneath that outer covering. There is a large separation between the two sides of the cerebrum called the **longitudinal fissure**. It separates the cerebrum into two distinct halves, a right and left **cerebral hemisphere**. Deep within the cerebrum, the white matter of the **corpus callosum** provides the major pathway for communication between the two hemispheres of the cerebral cortex.

The Cerebrum

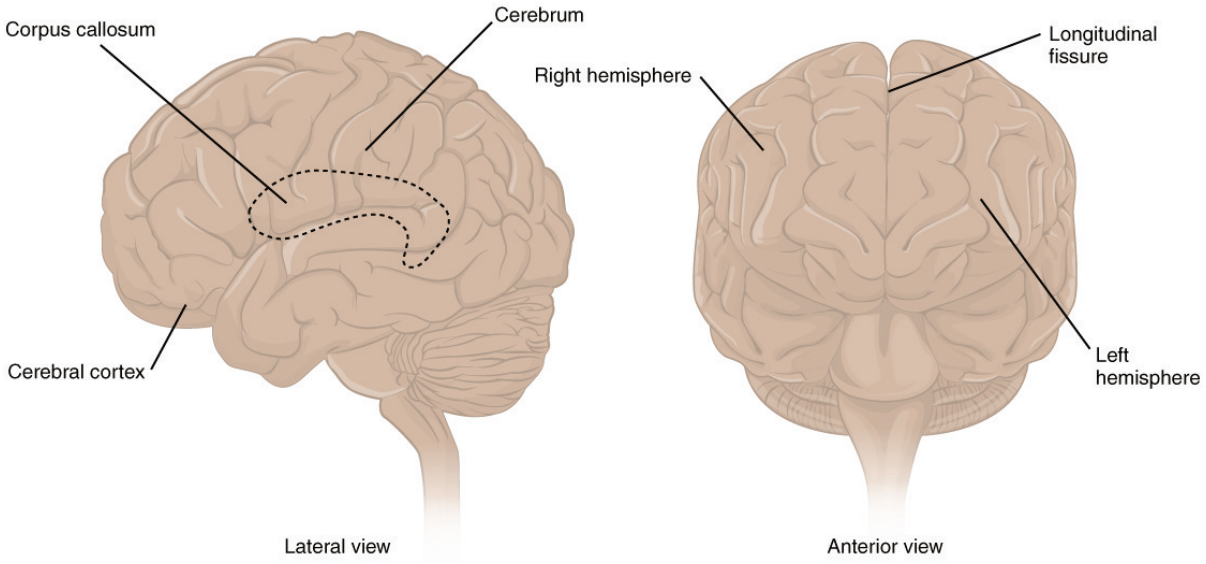


Figure 1. *The cerebrum is a large component of the CNS in humans, and the most obvious aspect of it is the folded surface called the cerebral cortex.*

Many of the higher neurological functions, such as memory, emotion, and consciousness, are the result of cerebral function. The complexity of the cerebrum is different across vertebrate species. The cerebrum of the most primitive vertebrates is not much more than the connection for the sense of smell. In mammals, the cerebrum comprises the outer gray matter that is the cortex (from the Latin word meaning "bark of a tree") and several deep nuclei that belong to three important functional groups. The **basal nuclei** are responsible for

cognitive processing, the most important function being that associated with planning movements. The **basal forebrain** contains nuclei that are important in learning and memory. The **limbic cortex** is the region of the cerebral cortex that is part of the **limbic system**, a collection of structures involved in emotion, memory, and behavior.

Cerebral Cortex

The cerebrum is covered by a continuous layer of gray matter that wraps around either side of the forebrain—the cerebral cortex. This thin, extensive region of wrinkled gray matter is responsible for the higher functions of the nervous system. A **gyrus** (plural = gyri) is the ridge of one of those wrinkles, and a **sulcus** (plural = sulci) is the groove between two gyri. The pattern of these folds of tissue indicates specific regions of the cerebral cortex.

The head is limited by the size of the birth canal, and the brain must fit inside the cranial cavity of the skull. Extensive folding in the cerebral cortex enables more gray matter to fit into this limited space. If the gray matter of the cortex were peeled off of the cerebrum and laid out flat, its surface area would be roughly equal to one square meter.

The folding of the cortex maximizes the amount of gray matter in the cranial cavity. During embryonic development, as the telencephalon expands within the skull, the brain goes through a regular course of growth that results in everyone's brain having a similar pattern of folds. The surface of the brain can be mapped on the basis of the locations of large gyri and sulci. Using these landmarks, the cortex can be separated into four major regions, or lobes (Figure 2. Lobes of the Cerebral Cortex). The **lateral sulcus** that separates the **temporal lobe** from the other regions is one such landmark. Superior to the lateral sulcus are the **parietal lobe** and **frontal lobe**, which are separated from each other by the **central sulcus**. The posterior region of the cortex is the **occipital lobe**, which has no obvious anatomical border between it and the parietal or temporal lobes on the lateral surface of the brain. From the medial surface, an obvious landmark separating the parietal and occipital lobes is called the **parieto-occipital sulcus**. The fact that there is no obvious anatomical border between these lobes is consistent with the functions of these regions being interrelated.

Lobes of the Cerebral Cortex

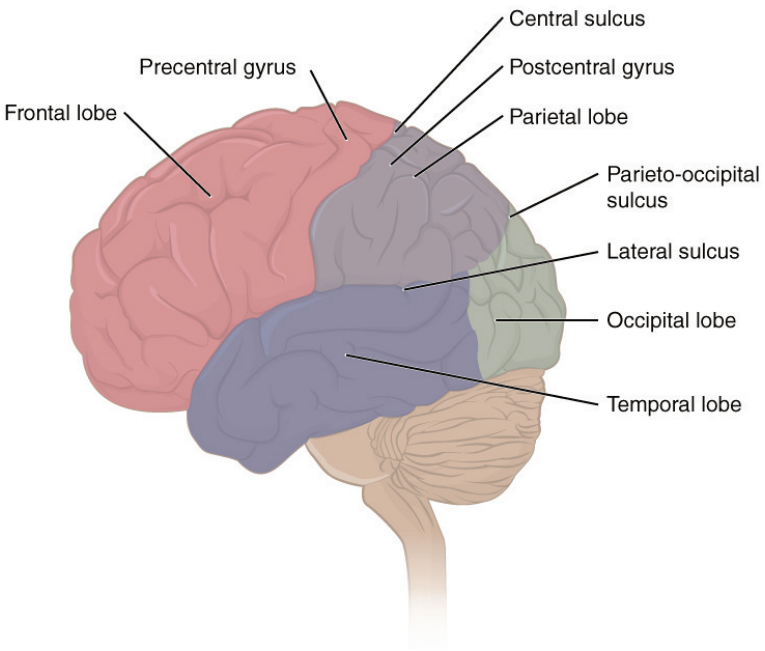


Figure 2. *The cerebral cortex is divided into four lobes. Extensive folding increases the surface area available for cerebral functions.*

Different regions of the cerebral cortex can be associated with particular functions, a concept known as localization of function. In the early 1900s, a German neuroscientist named Korbinian Brodmann performed an extensive study of the microscopic anatomy—the cytoarchitecture—of the cerebral cortex and divided the cortex into 52 separate regions on the basis of the histology of the cortex. His work resulted in a system of classification known as **Brodmann's areas**, which is still used today to describe the anatomical distinctions within the cortex (Figure 3. Brodmann's Areas of the Cerebral Cortex). The results from Brodmann's work on the anatomy align very well with the functional differences within the cortex. Areas 17 and 18 in the occipital lobe are responsible for primary visual perception. That visual information is complex, so it is processed in the temporal and parietal lobes as well.

The temporal lobe is associated with primary auditory sensation, known as Brodmann's areas 41 and 42 in the superior temporal lobe. Because regions of the temporal lobe are part of the limbic system, memory is an important function associated with that lobe. Memory is essentially a sensory function; memories are recalled sensations such as the smell of Mom's baking or the sound of a barking dog. Even memories of movement are really the memory of sensory feedback from those movements, such as stretching muscles or the movement of the skin around a joint. Structures in the temporal lobe are responsible for establishing long-term memory, but the ultimate location of those memories is usually in the region in which the sensory perception was processed.

The main sensation associated with the parietal lobe is **somatosensation**, meaning the general sensations associated with the body. Posterior to the central sulcus is the **postcentral gyrus**, the primary somatosensory cortex, which is identified as Brodmann's areas 1, 2, and 3. All of the tactile senses are processed in this area, including touch, pressure, tickle, pain, itch, and vibration, as well as more general senses of the body such as **proprioception** and **kinesthesia**, which are the senses of body position and movement, respectively.

Anterior to the central sulcus is the frontal lobe, which is primarily associated with motor functions. The **precentral gyrus** is the primary motor cortex. Cells from this region of the cerebral cortex are the upper motor neurons that instruct cells in the spinal cord to move skeletal muscles. Anterior to this region are a few areas that are associated with planned movements. The **premotor area** is responsible for thinking of a

movement to be made. The **frontal eye fields** are important in eliciting eye movements and in attending to visual stimuli. **Broca's area** is responsible for the production of language, or controlling movements responsible for speech; in the vast majority of people, it is located only on the left side. Anterior to these regions is the **prefrontal lobe**, which serves cognitive functions that can be the basis of personality, short-term memory, and consciousness. The prefrontal lobotomy is an outdated mode of treatment for personality disorders (psychiatric conditions) that profoundly affected the personality of the patient.

Brodmann's Areas of the Cerebral Cortex

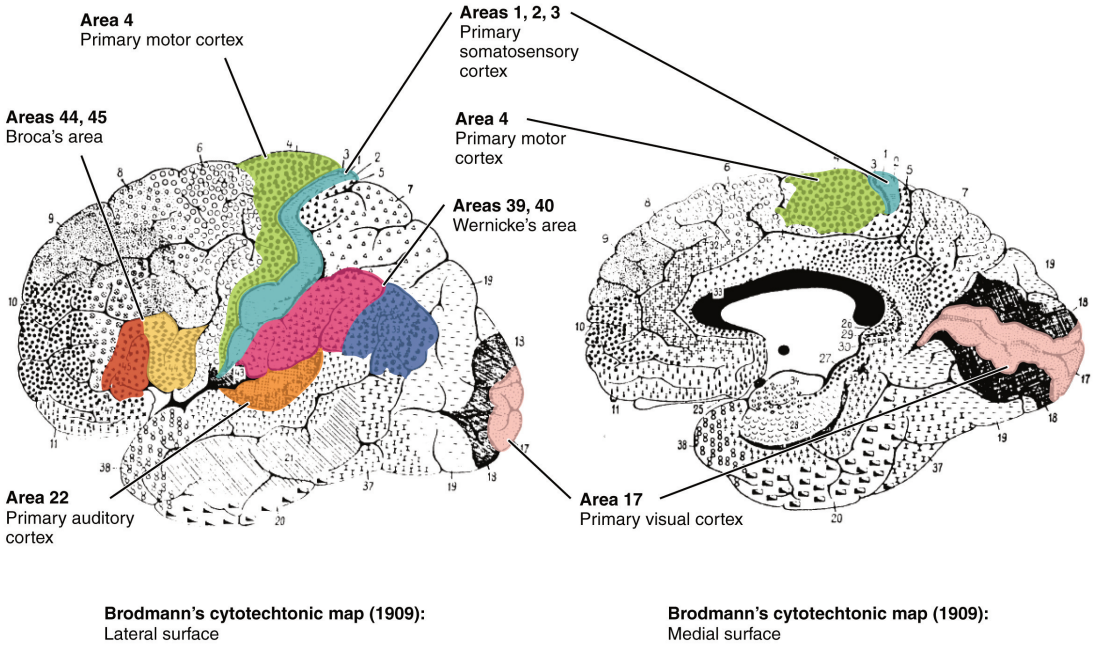


Figure 3. *Brodmann mapping of functionally distinct regions of the cortex was based on its cytoarchitecture at a microscopic level.*

Subcortical structures

Beneath the cerebral cortex are sets of nuclei known as **subcortical nuclei** that augment cortical processes. The nuclei of the basal forebrain serve as the primary location for acetylcholine production, which modulates the overall activity of the cortex, possibly leading to greater attention to sensory stimuli. Alzheimer's disease is associated with a loss of neurons in the basal forebrain. The **hippocampus** and **amygdala** are medial-lobe structures that, along with the adjacent cortex, are involved in long-term memory formation and emotional responses. The basal nuclei are a set of nuclei in the cerebrum responsible for comparing cortical processing with the general state of activity in the nervous system to influence the likelihood of movement taking place. For example, while a student is sitting in a classroom listening to a lecture, the basal nuclei will keep the urge to jump up and scream from actually happening. (The basal nuclei are also referred to as the basal ganglia, although that is potentially confusing because the term ganglia is typically used for peripheral structures.)

The major structures of the basal nuclei that control movement are the **caudate**, **putamen**, and **globus pallidus**, which are located deep in the cerebrum. The caudate is a long nucleus that follows the basic C-shape of the cerebrum from the frontal lobe, through the parietal and occipital lobes, into the temporal lobe. The putamen is mostly deep in the anterior regions of the frontal and parietal lobes. Together, the caudate and putamen are

called the **striatum**. The globus pallidus is a layered nucleus that lies just medial to the putamen; they are called the lenticular nuclei because they look like curved pieces fitting together like lenses. The globus pallidus has two subdivisions, the external and internal segments, which are lateral and medial, respectively. These nuclei are depicted in a frontal section of the brain in Figure 4. (Frontal Section of Cerebral Cortex and Basal Nuclei).

Frontal Section of Cerebral Cortex and Basal Nuclei

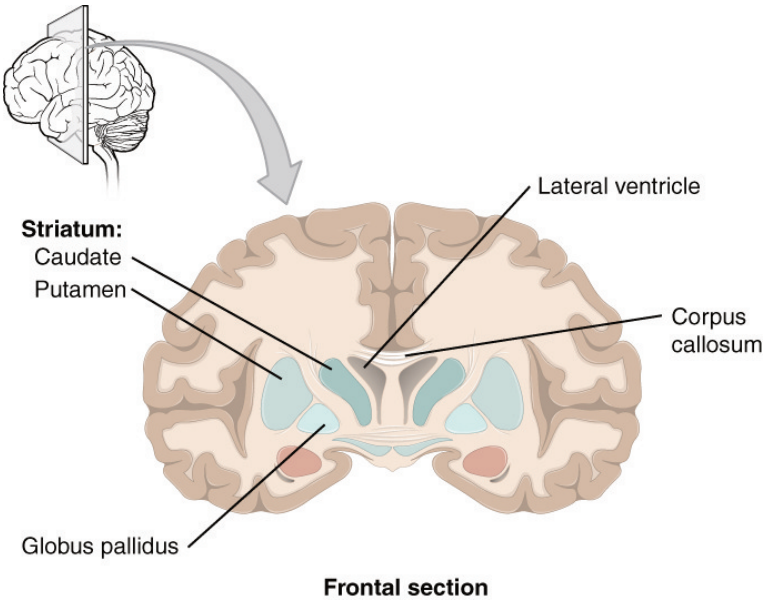


Figure 4. *The major components of the basal nuclei, shown in a frontal section of the brain, are the caudate (just lateral to the lateral ventricle), the putamen (inferior to the caudate and separated by the large white-matter structure called the internal capsule), and the globus pallidus (medial to the putamen).*

The basal nuclei in the cerebrum are connected with a few more nuclei in the brain stem that together act as a functional group that forms a motor pathway. Two streams of information processing take place in the basal nuclei. All input to the basal nuclei is from the cortex into the striatum (Figure 5. Connections of Basal Nuclei). The **direct pathway** is the projection of axons from the striatum to the globus pallidus internal segment (GPi) and the **substantia nigra pars reticulata** (SNr). The GPi/SNr then projects to the thalamus, which projects back to the cortex. The **indirect pathway** is the projection of axons from the striatum to the globus pallidus external segment (GPe), then to the subthalamic nucleus (STN), and finally to GPi/SNr. The two streams both target the GPi/SNr, but one has a direct projection and the other goes through a few intervening nuclei. The direct pathway causes the **disinhibition** of the thalamus (inhibition of one cell on a target cell that then inhibits the first cell), whereas the indirect pathway causes, or reinforces, the normal inhibition of the thalamus. The thalamus then can either excite the cortex (as a result of the direct pathway) or fail to excite the cortex (as a result of the indirect pathway).

Connections of Basal Nuclei

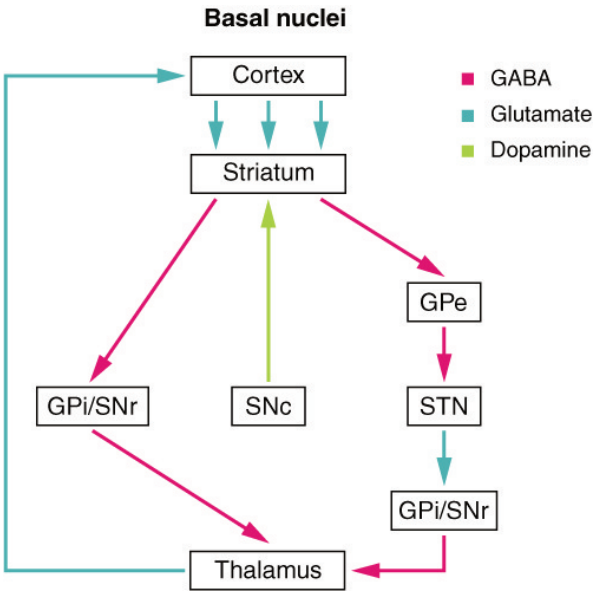


Figure 5. *Input to the basal nuclei is from the cerebral cortex, which is an excitatory connection releasing glutamate as a neurotransmitter. This input is to the striatum, or the caudate and putamen. In the direct pathway, the striatum projects to the internal segment of the globus pallidus and the substantia nigra pars reticulata (GPi/SNr). This is an inhibitory pathway, in which GABA is released at the synapse, and the target cells are hyperpolarized and less likely to fire. The output from the basal nuclei is to the thalamus, which is an inhibitory projection using GABA.*

The switch between the two pathways is the **substantia nigra pars compacta**, which projects to the striatum and releases the neurotransmitter dopamine. Dopamine receptors are either excitatory (D1-type receptors) or inhibitory (D2-type receptors). The direct pathway is activated by dopamine, and the indirect pathway is inhibited by dopamine. When the substantia nigra pars compacta is firing, it signals to the basal nuclei that the body is in an active state, and movement will be more likely. When the substantia nigra pars compacta is silent, the body is in a passive state, and movement is inhibited. To illustrate this situation, while a student is sitting listening to a lecture, the substantia nigra pars compacta would be silent and the student less likely to get up and walk around. Likewise, while the professor is lecturing, and walking around at the front of the classroom, the professor's substantia nigra pars compacta would be active, in keeping with his or her activity level.

Watch this video to learn about the basal nuclei (also known as the basal ganglia), which have two pathways that process information within the cerebrum. As shown in this video, the direct pathway is the shorter pathway through the system that results in increased activity in the cerebral cortex and increased motor activity. The direct pathway is described as resulting in "disinhibition" of the thalamus. What does disinhibition mean? What are the two neurons doing individually to cause this?

Watch this video to learn about the basal nuclei (also known as the basal ganglia), which have two

pathways that process information within the cerebrum. As shown in this video, the indirect pathway is the longer pathway through the system that results in decreased activity in the cerebral cortex, and therefore less motor activity. The indirect pathway has an extra couple of connections in it, including disinhibition of the subthalamic nucleus. What is the end result on the thalamus, and therefore on movement initiated by the cerebral cortex?

EVERYDAY CONNECTIONS

The Myth of Left Brain/Right Brain There is a persistent myth that people are "right-brained" or "left-brained," which is an oversimplification of an important concept about the cerebral hemispheres. There is some lateralization of function, in which the left side of the brain is devoted to language function and the right side is devoted to spatial and nonverbal reasoning. Whereas these functions are predominantly associated with those sides of the brain, there is no monopoly by either side on these functions. Many pervasive functions, such as language, are distributed globally around the cerebrum.

Some of the support for this misconception has come from studies of split brains. A drastic way to deal with a rare and devastating neurological condition (intractable epilepsy) is to separate the two hemispheres of the brain. After sectioning the corpus callosum, a split-brained patient will have trouble producing verbal responses on the basis of sensory information processed on the right side of the cerebrum, leading to the idea that the left side is responsible for language function.

However, there are well-documented cases of language functions lost from damage to the right side of the brain. The deficits seen in damage to the left side of the brain are classified as aphasia, a loss of speech function; damage on the right side can affect the use of language. Right-side damage can result in a loss of ability to understand figurative aspects of speech, such as jokes, irony, or metaphors. Nonverbal aspects of speech can be affected by damage to the right side, such as facial expression or body language, and right-side damage can lead to a "flat affect" in speech, or a loss of emotional expression in speech—sounding like a robot when talking.

The Diencephalon

The diencephalon is the one region of the adult brain that retains its name from embryologic development. The etymology of the word diencephalon translates to "through brain." It is the connection between the cerebrum and the rest of the nervous system, with one exception. The rest of the brain, the spinal cord, and the PNS all send information to the cerebrum through the diencephalon. Output from the cerebrum passes through the diencephalon. The single exception is the system associated with **olfaction**, or the sense of smell, which connects directly with the cerebrum. In the earliest vertebrate species, the cerebrum was not much more than olfactory bulbs that received peripheral information about the chemical environment (to call it smell in these organisms is imprecise because they lived in the ocean).

The diencephalon is deep beneath the cerebrum and constitutes the walls of the third ventricle. The diencephalon can be described as any region of the brain with "thalamus" in its name. The two major regions of the diencephalon are the thalamus itself and the hypothalamus (Figure 6. The Diencephalon). There are other structures, such as the **epithalamus**, which contains the pineal gland, or the **subthalamus**, which includes the subthalamic nucleus that is part of the basal nuclei.

Thalamus

The **thalamus** is a collection of nuclei that relay information between the cerebral cortex and the periphery, spinal cord, or brain stem. All sensory information, except for the sense of smell, passes through the thalamus before processing by the cortex. Axons from the peripheral sensory organs, or intermediate nuclei, synapse in the thalamus, and thalamic neurons project directly to the cerebrum. It is a requisite synapse in any sensory pathway, except for olfaction. The thalamus does not just pass the information on, it also processes that information. For example, the portion of the thalamus that receives visual information will influence what visual stimuli are important, or what receives attention.

The cerebrum also sends information down to the thalamus, which usually communicates motor commands. This involves interactions with the cerebellum and other nuclei in the brain stem. The cerebrum interacts with the basal nuclei, which involves connections with the thalamus. The primary output of the basal nuclei is to the thalamus, which relays that output to the cerebral cortex. The cortex also sends information to the thalamus that will then influence the effects of the basal nuclei.

Hypothalamus

Inferior and slightly anterior to the thalamus is the **hypothalamus**, the other major region of the diencephalon. The hypothalamus is a collection of nuclei that are largely involved in regulating homeostasis. The hypothalamus is the executive region in charge of the autonomic nervous system and the endocrine system through its regulation of the anterior pituitary gland. Other parts of the hypothalamus are involved in memory and emotion as part of the limbic system.

The Diencephalon

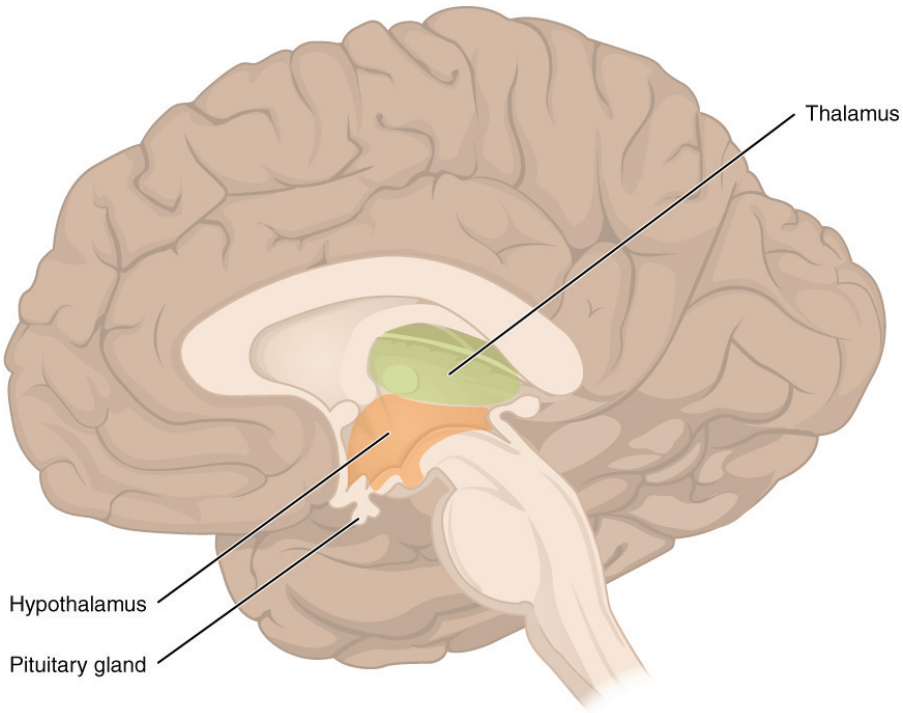


Figure 6. *The diencephalon is composed primarily of the thalamus and hypothalamus, which together define the walls of the third ventricle. The thalami are two elongated, ovoid structures on either side of the midline that make contact in the middle. The hypothalamus is inferior and anterior to the thalamus, culminating in a sharp angle to which the pituitary gland is attached.*

Brain Stem

The midbrain and hindbrain (composed of the pons and the medulla) are collectively referred to as the brain stem (Figure 7. The Brain Stem). The structure emerges from the ventral surface of the forebrain as a tapering cone that connects the brain to the spinal cord. Attached to the brain stem, but considered a separate region of the adult brain, is the cerebellum. The midbrain coordinates sensory representations of the visual, auditory, and somatosensory perceptual spaces. The pons is the main connection with the cerebellum. The pons and the medulla regulate several crucial functions, including the cardiovascular and respiratory systems and rates.

The cranial nerves connect through the brain stem and provide the brain with the sensory input and motor output associated with the head and neck, including most of the special senses. The major ascending and descending pathways between the spinal cord and brain, specifically the cerebrum, pass through the brain stem.
The Brain Stem

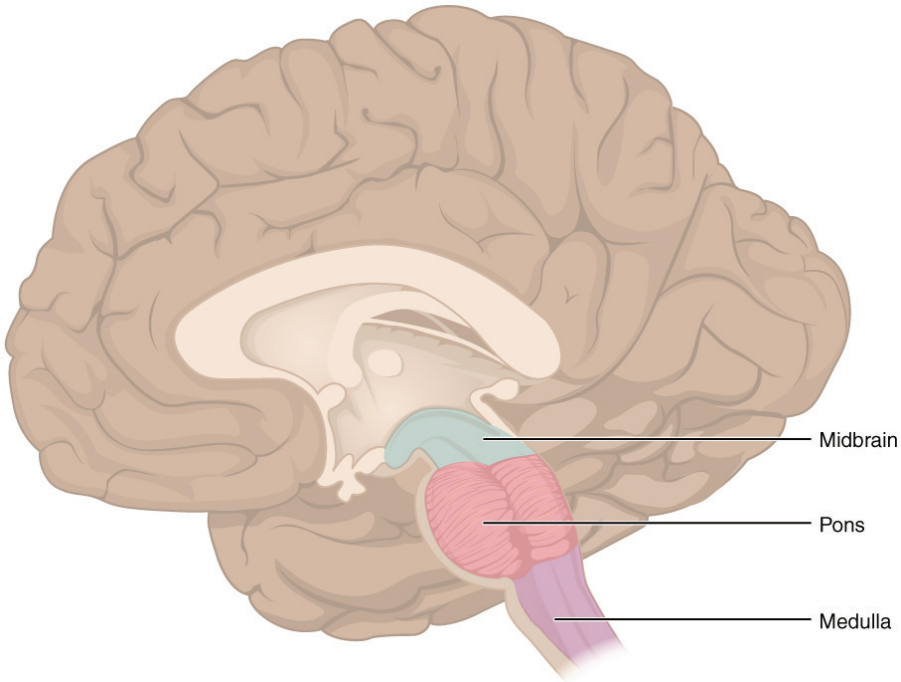


Figure 7. The brain stem comprises three regions: the midbrain, the pons, and the medulla.

Midbrain

One of the original regions of the embryonic brain, the midbrain is a small region between the thalamus and pons. It is separated into the **tectum** and **tegmentum**, from the Latin words for roof and floor, respectively. The cerebral aqueduct passes through the center of the midbrain, such that these regions are the roof and floor of that canal.

The tectum is composed of four bumps known as the colliculi (singular = colliculus), which means "little hill" in Latin. The **inferior colliculus** is the inferior pair of these enlargements and is part of the auditory brain stem pathway. Neurons of the inferior colliculus project to the thalamus, which then sends auditory information to the cerebrum for the conscious perception of sound. The **superior colliculus** is the superior pair and combines sensory information about visual space, auditory space, and somatosensory space. Activity in the superior colliculus is related to orienting the eyes to a sound or touch stimulus. If you are walking along the sidewalk on campus and you hear chirping, the superior colliculus coordinates that information with your awareness of the visual location of the tree right above you. That is the correlation of auditory and visual maps. If you suddenly feel something wet fall on your head, your superior colliculus integrates that with the auditory and visual maps and you know that the chirping bird just relieved itself on you. You want to look up to see the culprit, but do not.

The tegmentum is continuous with the gray matter of the rest of the brain stem. Throughout the midbrain, pons, and medulla, the tegmentum contains the nuclei that receive and send information through the cranial nerves, as well as regions that regulate important functions such as those of the cardiovascular and respiratory systems.

Pons

The word pons comes from the Latin word for bridge. It is visible on the anterior surface of the brain stem as the thick bundle of white matter attached to the cerebellum. The pons is the main connection between the cerebellum and the brain stem. The bridge-like white matter is only the anterior surface of the pons; the gray matter beneath that is a continuation of the tegmentum from the midbrain. Gray matter in the tegmentum region of the pons contains neurons receiving descending input from the forebrain that is sent to the cerebellum.

Medulla

The medulla is the region known as the myelencephalon in the embryonic brain. The initial portion of the name, "myel," refers to the significant white matter found in this region—especially on its exterior, which is continuous with the white matter of the spinal cord. The tegmentum of the midbrain and pons continues into the medulla because this gray matter is responsible for processing cranial nerve information. A diffuse region of gray matter throughout the brain stem, known as the **reticular formation**, is related to sleep and wakefulness, such as general brain activity and attention.

The Cerebellum

The **cerebellum**, as the name suggests, is the "little brain." It is covered in gyri and sulci like the cerebrum, and looks like a miniature version of that part of the brain (Figure 8. The Cerebellum). The cerebellum is largely responsible for comparing information from the cerebrum with sensory feedback from the periphery through the spinal cord. It accounts for approximately 10 percent of the mass of the brain.

The Cerebellum

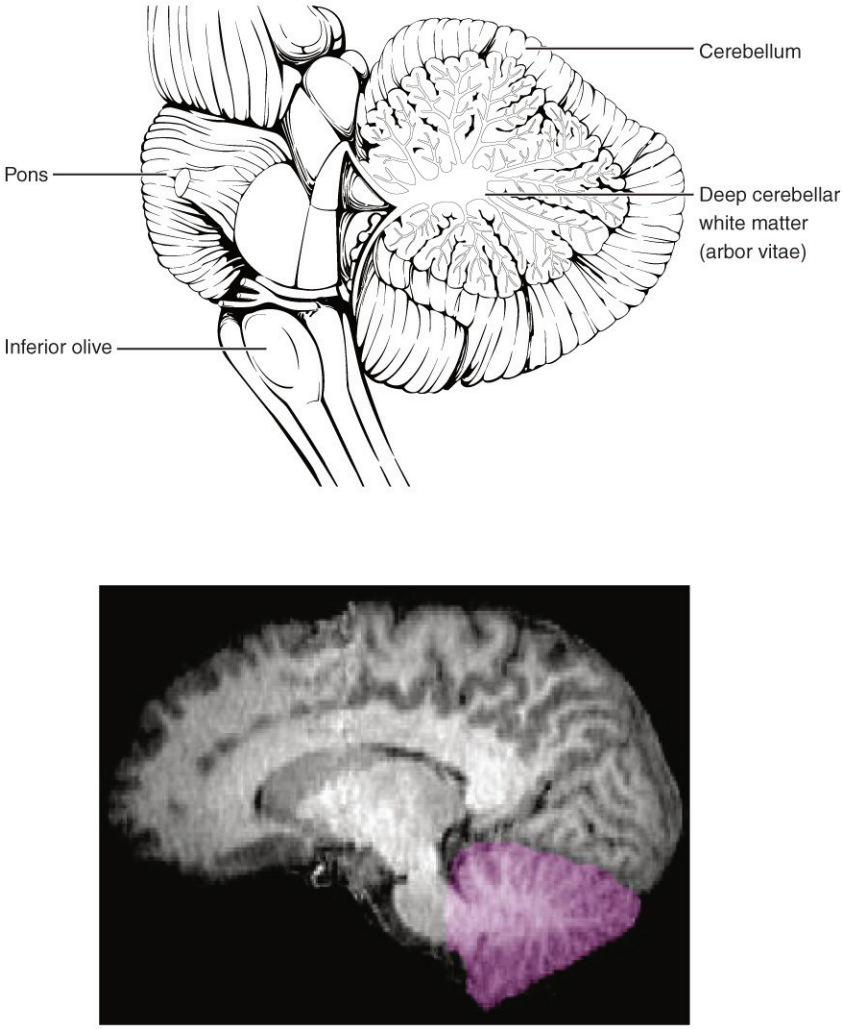


Figure 8. *The cerebellum is situated on the posterior surface of the brain stem. Descending input from the cerebellum enters through the large white matter structure of the pons. Ascending input from the periphery and spinal cord enters through the fibers of the inferior olive. Output goes to the midbrain, which sends a descending signal to the spinal cord.*

Descending fibers from the cerebrum have branches that connect to neurons in the pons. Those neurons project into the cerebellum, providing a copy of motor commands sent to the spinal cord. Sensory information from the periphery, which enters through spinal or cranial nerves, is copied to a nucleus in the medulla known as the **inferior olive**. Fibers from this nucleus enter the cerebellum and are compared with the descending commands from the cerebrum. If the primary motor cortex of the frontal lobe sends a command down to the spinal cord to initiate walking, a copy of that instruction is sent to the cerebellum. Sensory feedback from the muscles and joints, proprioceptive information about the movements of walking, and sensations of balance are sent to the cerebellum through the inferior olive and the cerebellum compares them. If walking is not coordinated, perhaps because the ground is uneven or a strong wind is blowing, then the cerebellum sends out a corrective command to compensate for the difference between the original cortical command and the sensory feedback. The output of the cerebellum is into the midbrain, which then sends a descending input to the spinal cord to correct the messages going to skeletal muscles.

The Spinal Cord

The description of the CNS is concentrated on the structures of the brain, but the spinal cord is another major organ of the system. Whereas the brain develops out of expansions of the neural tube into primary and then secondary vesicles, the spinal cord maintains the tube structure and is only specialized into certain regions. As the spinal cord continues to develop in the newborn, anatomical features mark its surface. The anterior midline is marked by the **anterior median fissure**, and the posterior midline is marked by the **posterior median sulcus**. Axons enter the posterior side through the **dorsal (posterior) nerve root**, which marks the **posterolateral sulcus** on either side. The axons emerging from the anterior side do so through the **ventral (anterior) nerve root**. Note that it is common to see the terms dorsal (dorsal = "back") and ventral (ventral = "belly") used interchangeably with posterior and anterior, particularly in reference to nerves and the structures of the spinal cord. You should learn to be comfortable with both.

On the whole, the posterior regions are responsible for sensory functions and the anterior regions are associated with motor functions. This comes from the initial development of the spinal cord, which is divided into the **basal plate** and the **alar plate**. The basal plate is closest to the ventral midline of the neural tube, which will become the anterior face of the spinal cord and gives rise to motor neurons. The alar plate is on the dorsal side of the neural tube and gives rise to neurons that will receive sensory input from the periphery.

The length of the spinal cord is divided into regions that correspond to the regions of the vertebral column. The name of a spinal cord region corresponds to the level at which spinal nerves pass through the intervertebral foramina. Immediately adjacent to the brain stem is the cervical region, followed by the thoracic, then the lumbar, and finally the sacral region. The spinal cord is not the full length of the vertebral column because the spinal cord does not grow significantly longer after the first or second year, but the skeleton continues to grow. The nerves that emerge from the spinal cord pass through the intervertebral formina at the respective levels. As the vertebral column grows, these nerves grow with it and result in a long bundle of nerves that resembles a horse's tail and is named the **cauda equina**. The sacral spinal cord is at the level of the upper lumbar vertebral bones. The spinal nerves extend from their various levels to the proper level of the vertebral column.

Gray Horns

In cross-section, the gray matter of the spinal cord has the appearance of an ink-blot test, with the spread of the gray matter on one side replicated on the other—a shape reminiscent of a bulbous capital "H." As shown in Figure 9. (Cross-section of Spinal Cord), the gray matter is subdivided into regions that are referred to as horns. The **posterior horn** is responsible for sensory processing. The **anterior horn** sends out motor signals to the skeletal muscles. The **lateral horn**, which is only found in the thoracic, upper lumbar, and sacral regions, is the central component of the sympathetic division of the autonomic nervous system.

Some of the largest neurons of the spinal cord are the multipolar motor neurons in the anterior horn. The fibers that cause contraction of skeletal muscles are the axons of these neurons. The motor neuron that causes contraction of the big toe, for example, is located in the sacral spinal cord. The axon that has to reach all the way to the belly of that muscle may be a meter in length. The neuronal cell body that maintains that long fiber must be quite large, possibly several hundred micrometers in diameter, making it one of the largest cells in the body.
Cross-section of Spinal Cord

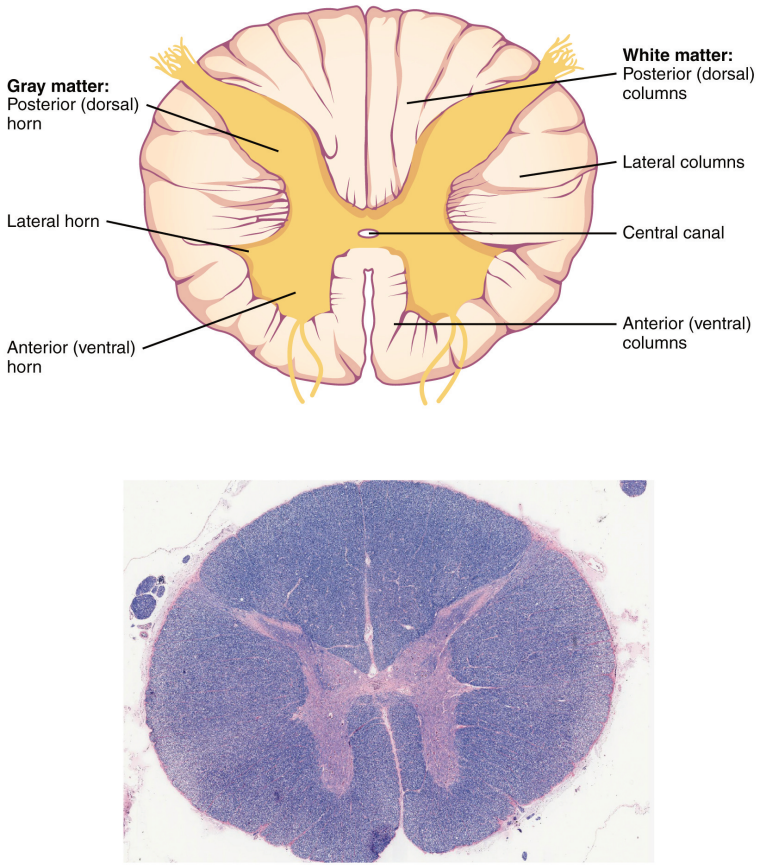


Figure 9. *The cross-section of a thoracic spinal cord segment shows the posterior, anterior, and lateral horns of gray matter, as well as the posterior, anterior, and lateral columns of white matter. LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

White Columns

Just as the gray matter is separated into horns, the white matter of the spinal cord is separated into columns. **Ascending tracts** of nervous system fibers in these columns carry sensory information up to the brain, whereas **descending tracts** carry motor commands from the brain. Looking at the spinal cord longitudinally, the columns extend along its length as continuous bands of white matter. Between the two posterior horns of gray matter are the **posterior columns**. Between the two anterior horns, and bounded by the axons of motor neurons emerging from that gray matter area, are the **anterior columns**. The white matter on either side of the spinal cord, between the posterior horn and the axons of the anterior horn neurons, are the **lateral columns**. The posterior columns are composed of axons of ascending tracts. The anterior and lateral columns are composed of many different groups of axons of both ascending and descending tracts–the latter carrying motor commands down from the brain to the spinal cord to control output to the periphery.

Watch this video to learn about the gray matter of the spinal cord that receives input from fibers of the dorsal (posterior) root and sends information out through the fibers of the ventral (anterior) root. As discussed in this video, these connections represent the interactions of the CNS with peripheral structures for both sensory and motor functions. The cervical and lumbar spinal cords have enlargements as a result of larger populations of neurons. What are these enlargements responsible for?

DISORDERS OF THE…

Basal Nuclei Parkinson's disease is a disorder of the basal nuclei, specifically of the substantia nigra, that demonstrates the effects of the direct and indirect pathways. Parkinson's disease is the result of neurons in the substantia nigra pars compacta dying. These neurons release dopamine into the striatum. Without that modulatory influence, the basal nuclei are stuck in the indirect pathway, without the direct pathway being activated. The direct pathway is responsible for increasing cortical movement commands. The increased activity of the indirect pathway results in the hypokinetic disorder of Parkinson's disease.

Parkinson's disease is neurodegenerative, meaning that neurons die that cannot be replaced, so there is no cure for the disorder. Treatments for Parkinson's disease are aimed at increasing dopamine levels in the striatum. Currently, the most common way of doing that is by providing the amino acid L-DOPA, which is a precursor to the neurotransmitter dopamine and can cross the blood-brain barrier. With levels of the precursor elevated, the remaining cells of the substantia nigra pars compacta can make more neurotransmitter and have a greater effect. Unfortunately, the patient will become less responsive to L-DOPA treatment as time progresses, and it can cause increased dopamine levels elsewhere in the brain, which are associated with psychosis or schizophrenia.

Visit this site for a thorough explanation of Parkinson's disease.

Compared with the nearest evolutionary relative, the chimpanzee, the human has a brain that is huge. At a point in the past, a common ancestor gave rise to the two species of humans and chimpanzees. That evolutionary history is long and is still an area of intense study. But something happened to increase the size of the human brain relative to the chimpanzee. Read this article in which the author explores the current understanding of why this happened.

According to one hypothesis about the expansion of brain size, what tissue might have been

sacrificed so energy was available to grow our larger brain? Based on what you know about that tissue and nervous tissue, why would there be a trade-off between them in terms of energy use?

Chapter Review

The adult brain is separated into four major regions: the cerebrum, the diencephalon, the brain stem, and the cerebellum. The cerebrum is the largest portion and contains the cerebral cortex and subcortical nuclei. It is divided into two halves by the longitudinal fissure.

The cortex is separated into the frontal, parietal, temporal, and occipital lobes. The frontal lobe is responsible for motor functions, from planning movements through executing commands to be sent to the spinal cord and periphery. The most anterior portion of the frontal lobe is the prefrontal cortex, which is associated with aspects of personality through its influence on motor responses in decision-making.

The other lobes are responsible for sensory functions. The parietal lobe is where somatosensation is processed. The occipital lobe is where visual processing begins, although the other parts of the brain can contribute to visual function. The temporal lobe contains the cortical area for auditory processing, but also has regions crucial for memory formation.

Nuclei beneath the cerebral cortex, known as the subcortical nuclei, are responsible for augmenting cortical functions. The basal nuclei receive input from cortical areas and compare it with the general state of the individual through the activity of a dopamine-releasing nucleus. The output influences the activity of part of the thalamus that can then increase or decrease cortical activity that often results in changes to motor commands. The basal forebrain is responsible for modulating cortical activity in attention and memory. The limbic system includes deep cerebral nuclei that are responsible for emotion and memory.

The diencephalon includes the thalamus and the hypothalamus, along with some other structures. The thalamus is a relay between the cerebrum and the rest of the nervous system. The hypothalamus coordinates homeostatic functions through the autonomic and endocrine systems.

The brain stem is composed of the midbrain, pons, and medulla. It controls the head and neck region of the body through the cranial nerves. There are control centers in the brain stem that regulate the cardiovascular and respiratory systems.

The cerebellum is connected to the brain stem, primarily at the pons, where it receives a copy of the descending input from the cerebrum to the spinal cord. It can compare this with sensory feedback input through the medulla and send output through the midbrain that can correct motor commands for coordination.

Circulation and the Central Nervous System

By the end of this section, you will be able to:

- Describe the vessels that supply the CNS with blood
- Name the components of the ventricular system and the regions of the brain in which each is located
- Explain the production of cerebrospinal fluid and its flow through the ventricles
- Explain how a disruption in circulation would result in a stroke

The CNS is crucial to the operation of the body, and any compromise in the brain and spinal cord can lead to severe difficulties. The CNS has a privileged blood supply, as suggested by the blood-brain barrier. The function of the tissue in the CNS is crucial to the survival of the organism, so the contents of the blood cannot simply pass into the central nervous tissue. To protect this region from the toxins and pathogens that may be traveling through the blood stream, there is strict control over what can move out of the general systems and into the brain and spinal cord. Because of this privilege, the CNS needs specialized structures for the maintenance of circulation. This begins with a unique arrangement of blood vessels carrying fresh blood into the CNS. Beyond the supply of blood, the CNS filters that blood into cerebrospinal fluid (CSF), which is then circulated through the cavities of the brain and spinal cord called ventricles.

Blood Supply to the Brain

A lack of oxygen to the CNS can be devastating, and the cardiovascular system has specific regulatory reflexes to ensure that the blood supply is not interrupted. There are multiple routes for blood to get into the CNS, with specializations to protect that blood supply and to maximize the ability of the brain to get an uninterrupted perfusion.

Arterial Supply

The major artery carrying recently oxygenated blood away from the heart is the aorta. The very first branches off the aorta supply the heart with nutrients and oxygen. The next branches give rise to the **common carotid arteries**, which further branch into the **internal carotid arteries**. The external carotid arteries supply blood to the tissues on the surface of the cranium. The bases of the common carotids contain stretch receptors that immediately respond to the drop in blood pressure upon standing. The **orthostatic reflex** is a reaction to this change in body position, so that blood pressure is maintained against the increasing effect of gravity (orthostatic means “standing up”). Heart rate increases—a reflex of the sympathetic division of the autonomic nervous system—and this raises blood pressure.

The internal carotid artery enters the cranium through the **carotid canal** in the temporal bone. A second set of vessels that supply the CNS are the **vertebral arteries**, which are protected as they pass through the neck region by the transverse foramina of the cervical vertebrae. The vertebral arteries enter the cranium through the **foramen magnum** of the occipital bone. Branches off the left and right vertebral arteries merge into the **anterior spinal artery** supplying the anterior aspect of the spinal cord, found along the anterior median fissure. The two vertebral arteries then merge into the **basilar artery**, which gives rise to branches to the brain stem and cerebellum. The left and right internal carotid arteries and branches of the basilar artery all become the **circle of Willis**, a confluence of arteries that can maintain perfusion of the brain even if narrowing or a blockage limits flow through one part (Figure 1. Circle of Willis).

Circle of Willis

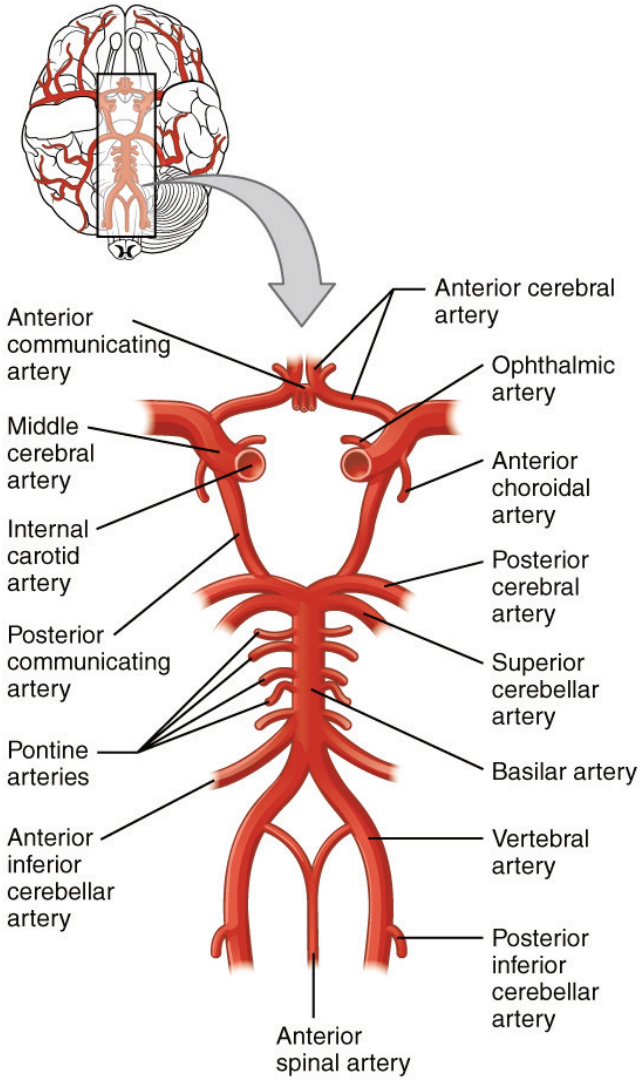


Figure 1. *The blood supply to the brain enters through the internal carotid arteries and the vertebral arteries, eventually giving rise to the circle of Willis.*

Watch this animation to see how blood flows to the brain and passes through the circle of Willis

before being distributed through the cerebrum. The circle of Willis is a specialized arrangement of arteries that ensure constant perfusion of the cerebrum even in the event of a blockage of one of the arteries in the circle. The animation shows the normal direction of flow through the circle of Willis to the middle cerebral artery. Where would the blood come from if there were a blockage just posterior to the middle cerebral artery on the left?

Venous Return

After passing through the CNS, blood returns to the circulation through a series of **dural sinuses** and veins (Figure 2. Dural Sinuses and Veins). The **superior sagittal sinus** runs in the groove of the longitudinal fissure, where it absorbs CSF from the meninges. The superior sagittal sinus drains to the confluence of sinuses, along with the **occipital sinuses** and **straight sinus**, to then drain into the **transverse sinuses**. The transverse sinuses connect to the **sigmoid sinuses**, which then connect to the **jugular veins**. From there, the blood continues toward the heart to be pumped to the lungs for reoxygenation.

Dural Sinuses and Veins

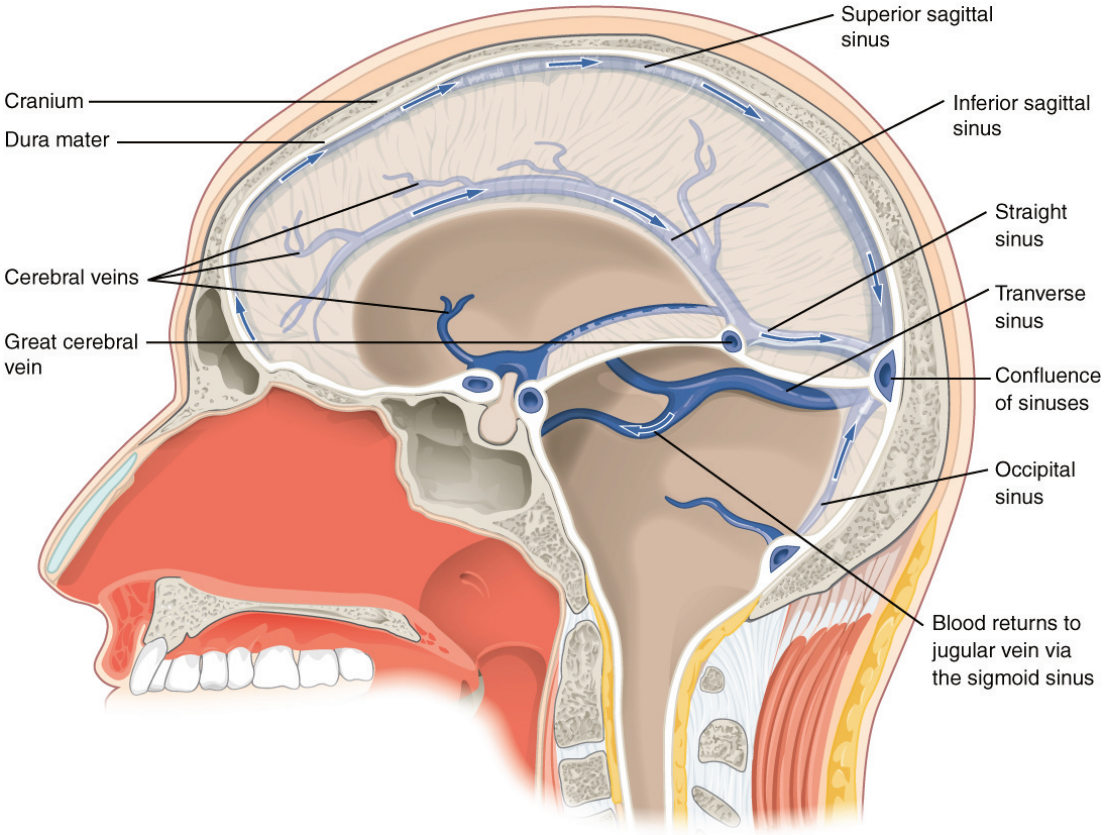


Figure 2. *Blood drains from the brain through a series of sinuses that connect to the jugular veins.*

Protective Coverings of the Brain and Spinal Cord

The outer surface of the CNS is covered by a series of membranes composed of connective tissue called the **meninges**, which protect the brain. The **dura mater** is a thick fibrous layer and a strong protective sheath over the entire brain and spinal cord. It is anchored to the inner surface of the cranium and vertebral cavity. The **arachnoid mater** is a membrane of thin fibrous tissue that forms a loose sac around the CNS. Beneath the arachnoid is a thin, filamentous mesh called the **arachnoid trabeculae**, which looks like a spider web, giving this layer its name. Directly adjacent to the surface of the CNS is the **pia mater**, a thin fibrous membrane that follows the convolutions of gyri and sulci in the cerebral cortex and fits into other grooves and indentations (Figure 3. Meningeal Layers of Superior Sagittal Sinus).

Meningeal Layers of Superior Sagittal Sinus

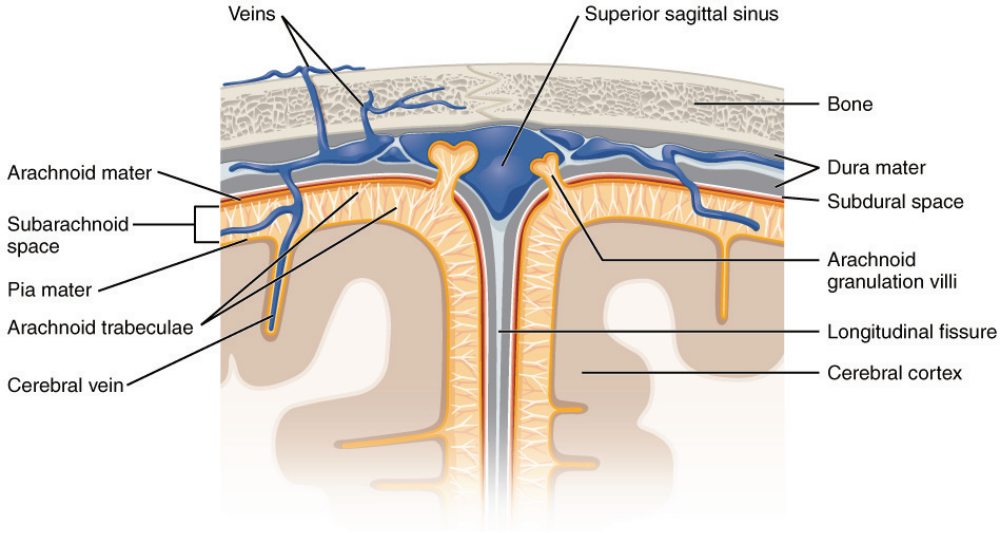


Figure 3. *The layers of the meninges in the longitudinal fissure of the superior sagittal sinus are shown, with the dura mater adjacent to the inner surface of the cranium, the pia mater adjacent to the surface of the brain, and the arachnoid and subarachnoid space between them. An arachnoid villus is shown emerging into the dural sinus to allow CSF to filter back into the blood for drainage.*

Dura Mater

Like a thick cap covering the brain, the dura mater is a tough outer covering. The name comes from the Latin for "tough mother" to represent its physically protective role. It encloses the entire CNS and the major blood vessels that enter the cranium and vertebral cavity. It is directly attached to the inner surface of the bones of the cranium and to the very end of the vertebral cavity.

There are infoldings of the dura that fit into large crevasses of the brain. Two infoldings go through the midline separations of the cerebrum and cerebellum; one forms a shelf-like tent between the occipital lobes of the cerebrum and the cerebellum, and the other surrounds the pituitary gland. The dura also surrounds and supports the venous sinuses.

Arachnoid Mater

The middle layer of the meninges is the arachnoid, named for the spider-web–like trabeculae between it and the pia mater. The arachnoid defines a sac-like enclosure around the CNS. The trabeculae are found in the **subarachnoid space**, which is filled with circulating CSF. The arachnoid emerges into the dural sinuses as the **arachnoid granulations**, where the CSF is filtered back into the blood for drainage from the nervous system.

The subarachnoid space is filled with circulating CSF, which also provides a liquid cushion to the brain and spinal cord. Similar to clinical blood work, a sample of CSF can be withdrawn to find chemical evidence of neuropathology or metabolic traces of the biochemical functions of nervous tissue.

Pia Mater

The outer surface of the CNS is covered in the thin fibrous membrane of the pia mater. It is thought to have a continuous layer of cells providing a fluid-impermeable membrane. The name pia mater comes from the Latin for "tender mother," suggesting the thin membrane is a gentle covering for the brain. The pia extends into every convolution of the CNS, lining the inside of the sulci in the cerebral and cerebellar cortices. At the end of the spinal cord, a thin filament extends from the inferior end of CNS at the upper lumbar region of the vertebral column to the sacral end of the vertebral column. Because the spinal cord does not extend through the lower lumbar region of the vertebral column, a needle can be inserted through the dura and arachnoid layers to withdraw CSF. This procedure is called a lumbar puncture and avoids the risk of damaging the central tissue of the spinal cord. Blood vessels that are nourishing the central nervous tissue are between the pia mater and the nervous tissue.

DISORDERS OF THE…

MeningesMeningitis is an inflammation of the meninges, the three layers of fibrous membrane that surround the CNS. Meningitis can be caused by infection by bacteria or viruses. The particular pathogens are not special to meningitis; it is just an inflammation of that specific set of tissues from what might be a broader infection. Bacterial meningitis can be caused by *Streptococcus*, *Staphylococcus*, or the tuberculosis pathogen, among many others. Viral meningitis is usually the result of common enteroviruses (such as those that cause intestinal disorders), but may be the result of the herpes virus or West Nile virus. Bacterial meningitis tends to be more severe.

The symptoms associated with meningitis can be fever, chills, nausea, vomiting, light sensitivity, soreness of the neck, or severe headache. More important are the neurological symptoms, such as changes in mental state (confusion, memory deficits, and other dementia-type symptoms). A serious risk of meningitis can be damage to peripheral structures because of the nerves that pass through the meninges. Hearing loss is a common result of meningitis.

The primary test for meningitis is a lumbar puncture. A needle inserted into the lumbar region of the spinal column through the dura mater and arachnoid membrane into the subarachnoid space can be used to withdraw the fluid for chemical testing. Fatality occurs in 5 to 40 percent of children and 20 to 50 percent of adults with bacterial meningitis. Treatment of bacterial meningitis is through

antibiotics, but viral meningitis cannot be treated with antibiotics because viruses do not respond to that type of drug. Fortunately, the viral forms are milder.

Watch this video that describes the procedure known as the lumbar puncture, a medical procedure used to sample the CSF. Because of the anatomy of the CNS, it is a relative safe location to insert a needle. Why is the lumbar puncture performed in the lower lumbar area of the vertebral column?

The Ventricular System

Cerebrospinal fluid (CSF) circulates throughout and around the CNS. In other tissues, water and small molecules are filtered through capillaries as the major contributor to the interstitial fluid. In the brain, CSF is produced in special structures to perfuse through the nervous tissue of the CNS and is continuous with the interstitial fluid. Specifically, CSF circulates to remove metabolic wastes from the interstitial fluids of nervous tissues and return them to the blood stream. The **ventricles** are the open spaces within the brain where CSF circulates. In some of these spaces, CSF is produced by filtering of the blood that is performed by a specialized membrane known as a choroid plexus. The CSF circulates through all of the ventricles to eventually emerge into the subarachnoid space where it will be reabsorbed into the blood.

The Ventricles

There are four ventricles within the brain, all of which developed from the original hollow space within the neural tube, the **central canal**. The first two are named the **lateral ventricles** and are deep within the cerebrum. These ventricles are connected to the **third ventricle** by two openings called the **interventricular foramina**. The third ventricle is the space between the left and right sides of the diencephalon, which opens into the **cerebral aqueduct** that passes through the midbrain. The aqueduct opens into the fourth ventricle, which is the space between the cerebellum and the pons and upper medulla (Figure 4. Cerebrospinal Fluid Circulation).
Cerebrospinal Fluid Circulation

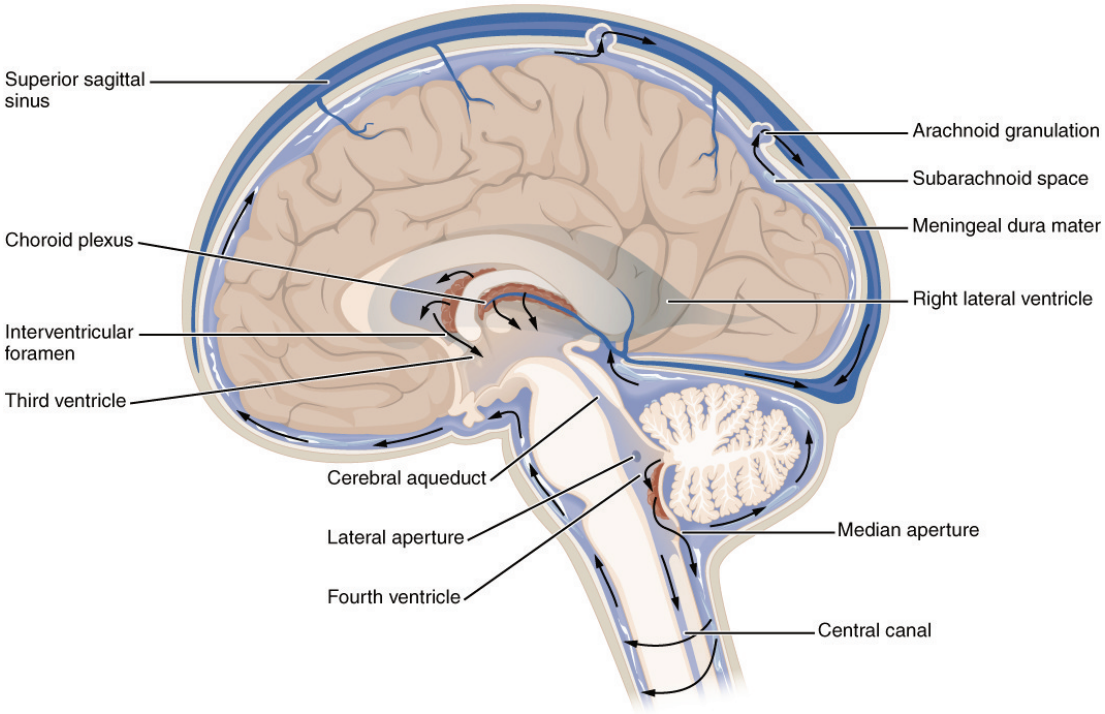


Figure 4. *The choroid plexus in the four ventricles produce CSF, which is circulated through the ventricular system and then enters the subarachnoid space through the median and lateral apertures. The CSF is then reabsorbed into the blood at the arachnoid granulations, where the arachnoid membrane emerges into the dural sinuses.*

As the telencephalon enlarges and grows into the cranial cavity, it is limited by the space within the skull. The telencephalon is the most anterior region of what was the neural tube, but cannot grow past the limit of the frontal bone of the skull. Because the cerebrum fits into this space, it takes on a C-shaped formation, through the frontal, parietal, occipital, and finally temporal regions. The space within the telencephalon is stretched into this same C-shape. The two ventricles are in the left and right sides, and were at one time referred to as the first and second ventricles. The interventricular foramina connect the frontal region of the lateral ventricles with the third ventricle.

The third ventricle is the space bounded by the medial walls of the hypothalamus and thalamus. The two thalami touch in the center in most brains as the massa intermedia, which is surrounded by the third ventricle. The cerebral aqueduct opens just inferior to the epithalamus and passes through the midbrain. The tectum and tegmentum of the midbrain are the roof and floor of the cerebral aqueduct, respectively. The aqueduct opens up into the fourth ventricle. The floor of the fourth ventricle is the dorsal surface of the pons and upper medulla (that gray matter making a continuation of the tegmentum of the midbrain). The fourth ventricle then narrows into the central canal of the spinal cord.

The ventricular system opens up to the subarachnoid space from the fourth ventricle. The **single median aperture** and the pair of **lateral apertures** connect to the subarachnoid space so that CSF can flow through the ventricles and around the outside of the CNS. Cerebrospinal fluid is produced within the ventricles by a type of specialized membrane called a **choroid plexus**. Ependymal cells (one of the types of glial cells described in the introduction to the nervous system) surround blood capillaries and filter the blood to make CSF. The fluid is a clear solution with a limited amount of the constituents of blood. It is essentially water, small molecules, and electrolytes. Oxygen and carbon dioxide are dissolved into the CSF, as they are in blood, and can diffuse between the fluid and the nervous tissue.

Cerebrospinal Fluid Circulation

The choroid plexuses are found in all four ventricles. Observed in dissection, they appear as soft, fuzzy structures that may still be pink, depending on how well the circulatory system is cleared in preparation of the tissue. The CSF is produced from components extracted from the blood, so its flow out of the ventricles is tied to the pulse of cardiovascular circulation.

From the lateral ventricles, the CSF flows into the third ventricle, where more CSF is produced, and then through the cerebral aqueduct into the fourth ventricle where even more CSF is produced. A very small amount of CSF is filtered at any one of the plexuses, for a total of about 500 milliliters daily, but it is continuously made and pulses through the ventricular system, keeping the fluid moving. From the fourth ventricle, CSF can continue down the central canal of the spinal cord, but this is essentially a cul-de-sac, so more of the fluid leaves the ventricular system and moves into the subarachnoid space through the median and lateral apertures.

Within the subarachnoid space, the CSF flows around all of the CNS, providing two important functions. As with elsewhere in its circulation, the CSF picks up metabolic wastes from the nervous tissue and moves it out of the CNS. It also acts as a liquid cushion for the brain and spinal cord. By surrounding the entire system in the subarachnoid space, it provides a thin buffer around the organs within the strong, protective dura mater. The arachnoid granulations are outpocketings of the arachnoid membrane into the dural sinuses so that CSF can be reabsorbed into the blood, along with the metabolic wastes. From the dural sinuses, blood drains out of the head and neck through the jugular veins, along with the rest of the circulation for blood, to be reoxygenated by the lungs and wastes to be filtered out by the kidneys (Table (Components of CSF Circulation)).

Watch this animation that shows the flow of CSF through the brain and spinal cord, and how it originates from the ventricles and then spreads into the space within the meninges, where the fluids then move into the venous sinuses to return to the cardiovascular circulation. What are the structures that produce CSF and where are they found? How are the structures indicated in this animation?

Components of CSF Circulation

	Lateral ventricles	**Third ventricle**	**Cerebral aqueduct**	**Fourth ventricle**	**Central canal**	**Subarachnoid space**
Location in CNS	Cerebrum	Diencephalon	Midbrain	Between pons/upper medulla and cerebellum	Spinal cord	External to entire CNS
Blood vessel structure	Choroid plexus	Choroid plexus	None	Choroid plexus	None	Arachnoid granulations

DISORDERS OF THE…

Central Nervous System

The supply of blood to the brain is crucial to its ability to perform many functions. Without a steady supply of oxygen, and to a lesser extent glucose, the nervous tissue in the brain cannot keep up its extensive electrical activity. These nutrients get into the brain through the blood, and if blood flow is interrupted, neurological function is compromised.

The common name for a disruption of blood supply to the brain is a stroke. It is caused by a blockage to an artery in the brain. The blockage is from some type of embolus: a blood clot, a fat embolus, or an air bubble. When the blood cannot travel through the artery, the surrounding tissue that is deprived starves and dies. Strokes will often result in the loss of very specific functions. A stroke in the lateral medulla, for example, can cause a loss in the ability to swallow. Sometimes, seemingly unrelated functions will be lost because they are dependent on structures in the same region. Along with the swallowing in the previous example, a stroke in that region could affect sensory functions from the face or extremities because important white matter pathways also pass through the lateral medulla. Loss of blood flow to specific regions of the cortex can lead to the loss of specific higher functions, from the ability to recognize faces to the ability to move a particular region of the body. Severe or limited memory loss can be the result of a temporal lobe stroke.

Related to strokes are transient ischemic attacks (TIAs), which can also be called "mini-strokes." These are events in which a physical blockage may be temporary, cutting off the blood supply and oxygen to a region, but not to the extent that it causes cell death in that region. While the neurons in that area are recovering from the event, neurological function may be lost. Function can return if the area is able to recover from the event.

Recovery from a stroke (or TIA) is strongly dependent on the speed of treatment. Often, the person who is present and notices something is wrong must then make a decision. The mnemonic **FAST** helps people remember what to look for when someone is dealing with sudden losses of neurological function. If someone complains of feeling "funny," check these things quickly: Look at the person's face. Does he or she have problems moving **F**ace muscles and making regular facial expressions? Ask the person to raise his or her **A**rms above the head. Can the person lift one arm but not the other? Has the person's **S**peech changed? Is he or she slurring words or having trouble saying things? If any of these things have happened, then it is **T**ime to call for help.

Sometimes, treatment with blood-thinning drugs can alleviate the problem, and recovery is possible. If the tissue is damaged, the amazing thing about the nervous system is that it is adaptable. With physical, occupational, and speech therapy, victims of strokes can recover, or more accurately relearn, functions.

Chapter Review

The CNS has a privileged blood supply established by the blood-brain barrier. Establishing this barrier are anatomical structures that help to protect and isolate the CNS. The arterial blood to the brain comes from the

internal carotid and vertebral arteries, which both contribute to the unique circle of Willis that provides constant perfusion of the brain even if one of the blood vessels is blocked or narrowed. That blood is eventually filtered to make a separate medium, the CSF, that circulates within the spaces of the brain and then into the surrounding space defined by the meninges, the protective covering of the brain and spinal cord.

The blood that nourishes the brain and spinal cord is behind the glial-cell–enforced blood-brain barrier, which limits the exchange of material from blood vessels with the interstitial fluid of the nervous tissue. Thus, metabolic wastes are collected in cerebrospinal fluid that circulates through the CNS. This fluid is produced by filtering blood at the choroid plexuses in the four ventricles of the brain. It then circulates through the ventricles and into the subarachnoid space, between the pia mater and the arachnoid mater. From the arachnoid granulations, CSF is reabsorbed into the blood, removing the waste from the privileged central nervous tissue.

The blood, now with the reabsorbed CSF, drains out of the cranium through the dural sinuses. The dura mater is the tough outer covering of the CNS, which is anchored to the inner surface of the cranial and vertebral cavities. It surrounds the venous space known as the dural sinuses, which connect to the jugular veins, where blood drains from the head and neck.

The Peripheral Nervous System

By the end of this section, you will be able to:

- Describe the structures found in the PNS
- Distinguish between somatic and autonomic structures, including the special peripheral structures of the enteric nervous system
- Name the twelve cranial nerves and explain the functions associated with each
- Describe the sensory and motor components of spinal nerves and the plexuses that they pass through

The PNS is not as contained as the CNS because it is defined as everything that is not the CNS. Some peripheral structures are incorporated into the other organs of the body. In describing the anatomy of the PNS, it is necessary to describe the common structures, the nerves and the ganglia, as they are found in various parts of the body. Many of the neural structures that are incorporated into other organs are features of the digestive system; these structures are known as the enteric nervous system and are a special subset of the PNS.

Ganglia

A ganglion is a group of neuron cell bodies in the periphery. Ganglia can be categorized, for the most part, as either sensory ganglia or autonomic ganglia, referring to their primary functions. The most common type of

sensory ganglion is a **dorsal (posterior) root ganglion**. These ganglia are the cell bodies of neurons with axons that are sensory endings in the periphery, such as in the skin, and that extend into the CNS through the dorsal nerve root. The ganglion is an enlargement of the nerve root. Under microscopic inspection, it can be seen to include the cell bodies of the neurons, as well as bundles of fibers that are the posterior nerve root (Figure 1. Dorsal Root Ganglion). The cells of the dorsal root ganglion are unipolar cells, classifying them by shape. Also, the small round nuclei of satellite cells can be seen surrounding—as if they were orbiting—the neuron cell bodies.

Dorsal Root Ganglion

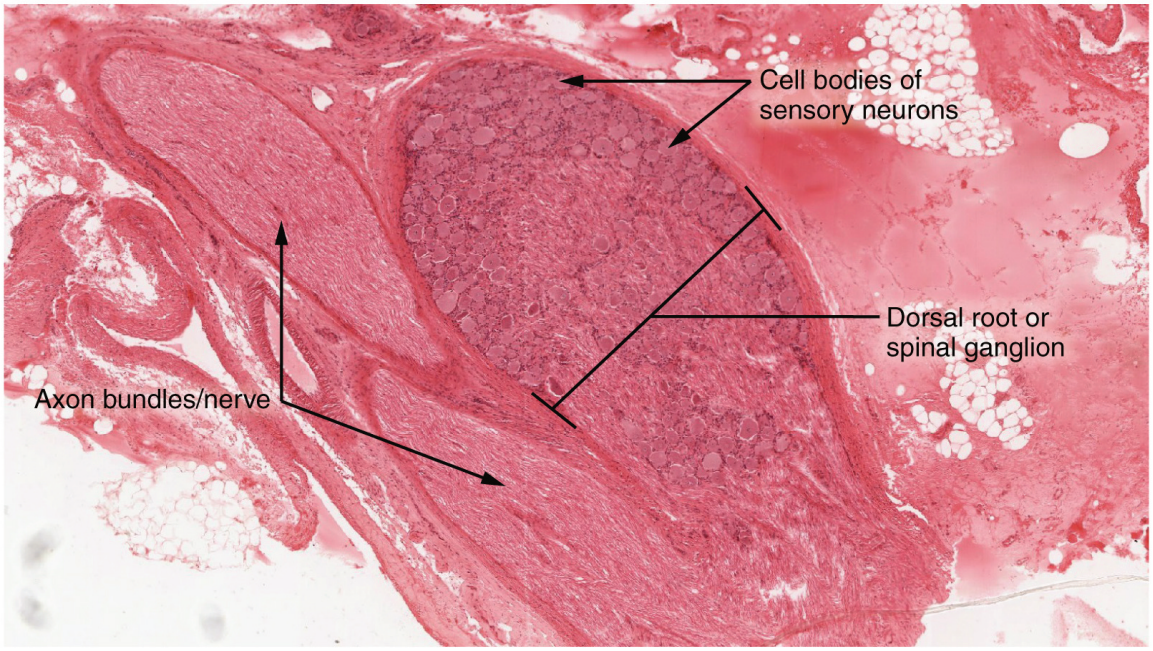


Figure 1. *The cell bodies of sensory neurons, which are unipolar neurons by shape, are seen in this photomicrograph. Also, the fibrous region is composed of the axons of these neurons that are passing through the ganglion to be part of the dorsal nerve root (tissue source: canine). LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

Spinal Cord and Root Ganglion

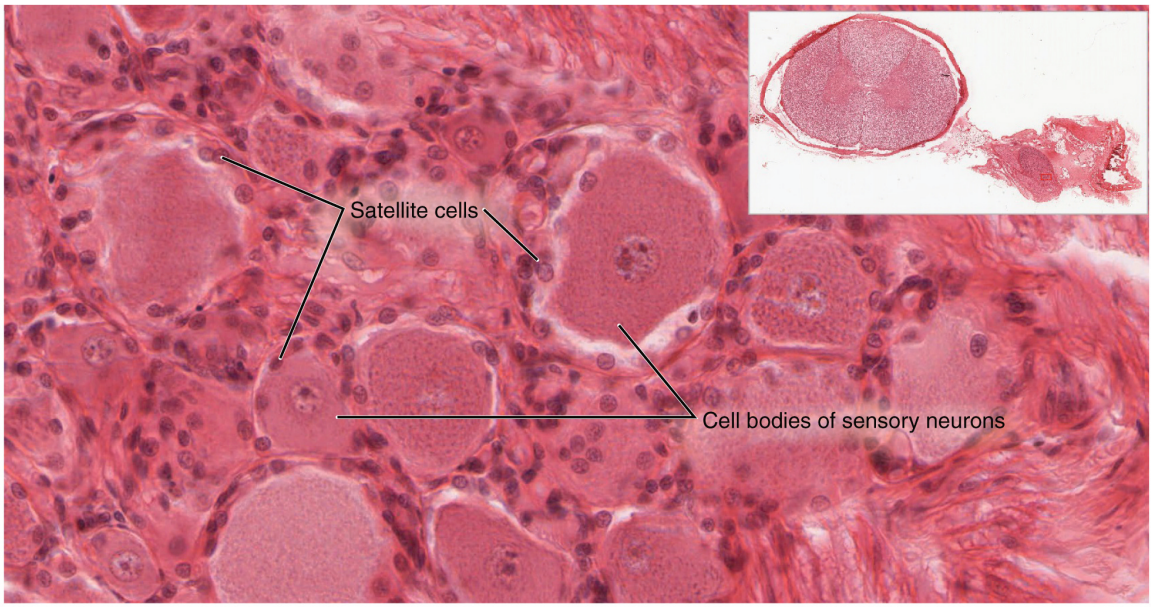


Figure 2. *The slide includes both a cross-section of the lumbar spinal cord and a section of the dorsal root ganglion (see also Figure) (tissue source: canine). LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://virtualslides.med.umich.edu/Histology/Basic%20Tissues/Nervous%20Tissue/065-2_HISTO_40X.svs/view.apml to explore the tissue sample in greater detail. If you zoom in on the dorsal root ganglion, you can see smaller satellite glial cells surrounding the large cell bodies of the sensory neurons. From what structure do satellite cells derive during embryologic development?

Another type of sensory ganglion is a **cranial nerve ganglion**. This is analogous to the dorsal root ganglion, except that it is associated with a **cranial nerve** instead of a **spinal nerve**. The roots of cranial nerves are within the cranium, whereas the ganglia are outside the skull. For example, the **trigeminal ganglion** is superficial to the temporal bone whereas its associated nerve is attached to the mid-pons region of the brain stem. The neurons of cranial nerve ganglia are also unipolar in shape with associated satellite cells.

The other major category of ganglia are those of the autonomic nervous system, which is divided into the sympathetic and parasympathetic nervous systems. The **sympathetic chain ganglia** constitute a row of ganglia along the vertebral column that receive central input from the lateral horn of the thoracic and upper lumbar spinal cord. Superior to the chain ganglia are three **paravertebral ganglia** in the cervical region. Three other autonomic ganglia that are related to the sympathetic chain are the **prevertebral ganglia**, which are located outside of the chain but have similar functions. They are referred to as prevertebral because they are anterior to the vertebral column. The neurons of these autonomic ganglia are multipolar in shape, with dendrites radiating out around the cell body where synapses from the spinal cord neurons are made. The neurons of the chain, paravertebral, and prevertebral ganglia then project to organs in the head and neck, thoracic, abdominal, and pelvic cavities to regulate the sympathetic aspect of homeostatic mechanisms.

Another group of autonomic ganglia are the **terminal ganglia** that receive input from cranial nerves or sacral

spinal nerves and are responsible for regulating the parasympathetic aspect of homeostatic mechanisms. These two sets of ganglia, sympathetic and parasympathetic, often project to the same organs—one input from the chain ganglia and one input from a terminal ganglion—to regulate the overall function of an organ. For example, the heart receives two inputs such as these; one increases heart rate, and the other decreases it. The terminal ganglia that receive input from cranial nerves are found in the head and neck, as well as the thoracic and upper abdominal cavities, whereas the terminal ganglia that receive sacral input are in the lower abdominal and pelvic cavities.

Terminal ganglia below the head and neck are often incorporated into the wall of the target organ as a **plexus**. A plexus, in a general sense, is a network of fibers or vessels. This can apply to nervous tissue (as in this instance) or structures containing blood vessels (such as a choroid plexus). For example, the **enteric plexus** is the extensive network of axons and neurons in the wall of the small and large intestines. The enteric plexus is actually part of the enteric nervous system, along with the **gastric plexuses** and the **esophageal plexus**. Though the enteric nervous system receives input originating from central neurons of the autonomic nervous system, it does not require CNS input to function. In fact, it operates independently to regulate the digestive system.

Nerves

Bundles of axons in the PNS are referred to as nerves. These structures in the periphery are different than the central counterpart, called a tract. Nerves are composed of more than just nervous tissue. They have connective tissues invested in their structure, as well as blood vessels supplying the tissues with nourishment. The outer surface of a nerve is a surrounding layer of fibrous connective tissue called the **epineurium**. Within the nerve, axons are further bundled into **fascicles**, which are each surrounded by their own layer of fibrous connective tissue called **perineurium**. Finally, individual axons are surrounded by loose connective tissue called the **endoneurium** (Figure 3. Nerve Structure). These three layers are similar to the connective tissue sheaths for muscles. Nerves are associated with the region of the CNS to which they are connected, either as cranial nerves connected to the brain or spinal nerves connected to the spinal cord.

Nerve Structure

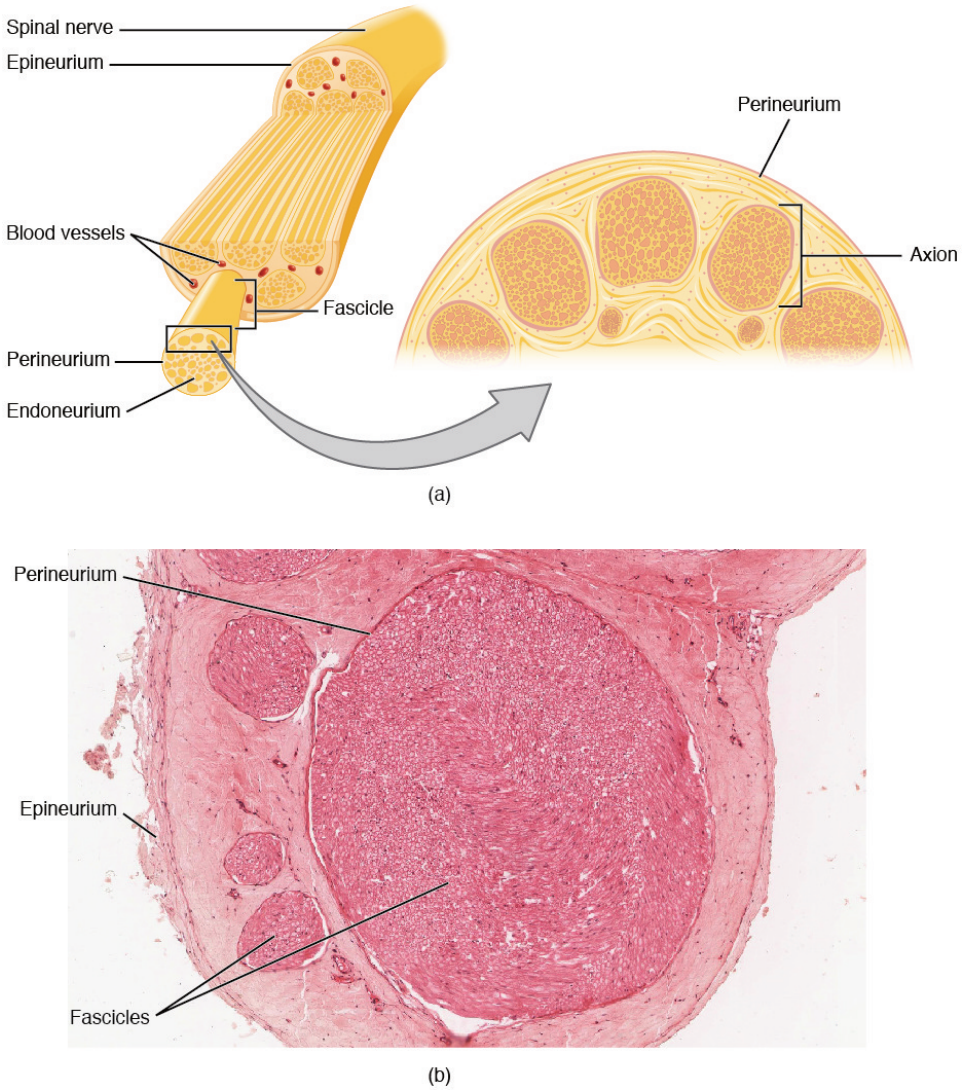


Figure 3. *The structure of a nerve is organized by the layers of connective tissue on the outside, around each fascicle, and surrounding the individual nerve fibers (tissue source: simian). LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

Close-Up of Nerve Trunk

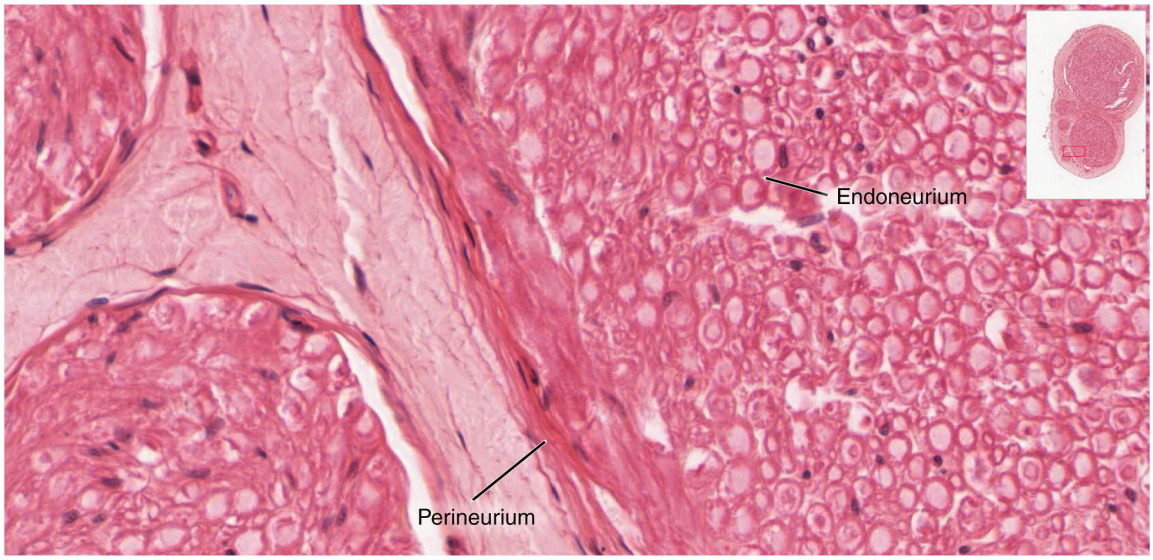


Figure 4. *Zoom in on this slide of a nerve trunk to examine the endoneurium, perineurium, and epineurium in greater detail (tissue source: simian). LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://virtualslides.med.umich.edu/Histology/Basic%20Tissues/Nervous%20Tissue/068_HISTO_40X.svs/view.apmlto explore the tissue sample in greater detail. With what structures in a skeletal muscle are the endoneurium, perineurium, and epineurium comparable?

Cranial Nerves

The nerves attached to the brain are the cranial nerves, which are primarily responsible for the sensory and motor functions of the head and neck (one of these nerves targets organs in the thoracic and abdominal cavities as part of the parasympathetic nervous system). There are twelve cranial nerves, which are designated CNI through CNXII for "Cranial Nerve," using Roman numerals for 1 through 12. They can be classified as sensory nerves, motor nerves, or a combination of both, meaning that the axons in these nerves originate out of sensory ganglia external to the cranium or motor nuclei within the brain stem. Sensory axons enter the brain to synapse in a nucleus. Motor axons connect to skeletal muscles of the head or neck. Three of the nerves are solely composed of sensory fibers; five are strictly motor; and the remaining four are mixed nerves.

Learning the cranial nerves is a tradition in anatomy courses, and students have always used mnemonic devices to remember the nerve names. A traditional mnemonic is the rhyming couplet, "On Old Olympus' Towering Tops/A Finn And German Viewed Some Hops," in which the initial letter of each word corresponds to the initial letter in the name of each nerve. The names of the nerves have changed over the years to reflect current usage and more accurate naming. An exercise to help learn this sort of information is to generate a mnemonic using words that have personal significance. The names of the cranial nerves are listed in Table (Cranial Nerves) along with a brief description of their function, their source (sensory ganglion or motor nucleus),

and their target (sensory nucleus or skeletal muscle). They are listed here with a brief explanation of each nerve (Figure 5. The Cranial Nerves).

The **olfactory nerve** and **optic nerve** are responsible for the sense of smell and vision, respectively. The **oculomotor nerve** is responsible for eye movements by controlling four of the **extraocular muscles**. It is also responsible for lifting the upper eyelid when the eyes point up, and for pupillary constriction. The **trochlear nerve** and the **abducens nerve** are both responsible for eye movement, but do so by controlling different extraocular muscles. The **trigeminal nerve** is responsible for cutaneous sensations of the face and controlling the muscles of mastication. The **facial nerve** is responsible for the muscles involved in facial expressions, as well as part of the sense of taste and the production of saliva. The **vestibulocochlear nerve** is responsible for the senses of hearing and balance. The **glossopharyngeal nerve** is responsible for controlling muscles in the oral cavity and upper throat, as well as part of the sense of taste and the production of saliva. The **vagus nerve** is responsible for contributing to homeostatic control of the organs of the thoracic and upper abdominal cavities. The **spinal accessory nerve** is responsible for controlling the muscles of the neck, along with cervical spinal nerves. The **hypoglossal nerve** is responsible for controlling the muscles of the lower throat and tongue.

The Cranial Nerves

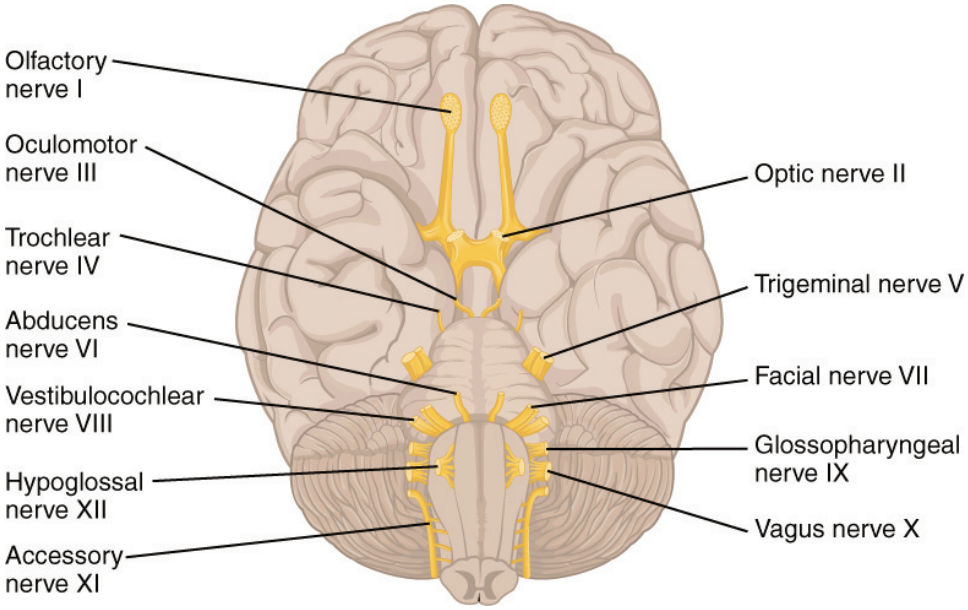


Figure 5. *The anatomical arrangement of the roots of the cranial nerves observed from an inferior view of the brain.*

Three of the cranial nerves also contain autonomic fibers, and a fourth is almost purely a component of the autonomic system. The oculomotor, facial, and glossopharyngeal nerves contain fibers that contact autonomic ganglia. The oculomotor fibers initiate pupillary constriction, whereas the facial and glossopharyngeal fibers both initiate salivation. The vagus nerve primarily targets autonomic ganglia in the thoracic and upper abdominal cavities.

Visit this site to read about a man who wakes with a headache and a loss of vision. His regular doctor sent him to an ophthalmologist to address the vision loss. The ophthalmologist recognizes a greater problem and immediately sends him to the emergency room. Once there, the patient undergoes a

large battery of tests, but a definite cause cannot be found. A specialist recognizes the problem as meningitis, but the question is what caused it originally. How can that be cured? The loss of vision comes from swelling around the optic nerve, which probably presented as a bulge on the inside of the eye. Why is swelling related to meningitis going to push on the optic nerve?

Another important aspect of the cranial nerves that lends itself to a mnemonic is the functional role each nerve plays. The nerves fall into one of three basic groups. They are sensory, motor, or both (see Table (Cranial Nerves)). The sentence, "Some Say Marry Money But My Brother Says Brains Beauty Matter More," corresponds to the basic function of each nerve. The first, second, and eighth nerves are purely sensory: the olfactory (CNI), optic (CNII), and vestibulocochlear (CNVIII) nerves. The three eye-movement nerves are all motor: the oculomotor (CNIII), trochlear (CNIV), and abducens (CNVI). The spinal accessory (CNXI) and hypoglossal (CNXII) nerves are also strictly motor. The remainder of the nerves contain both sensory and motor fibers. They are the trigeminal (CNV), facial (CNVII), glossopharyngeal (CNIX), and vagus (CNX) nerves. The nerves that convey both are often related to each other. The trigeminal and facial nerves both concern the face; one concerns the sensations and the other concerns the muscle movements. The facial and glossopharyngeal nerves are both responsible for conveying gustatory, or taste, sensations as well as controlling salivary glands. The vagus nerve is involved in visceral responses to taste, namely the gag reflex. This is not an exhaustive list of what these combination nerves do, but there is a thread of relation between them.

Cranial Nerves

Mnemonic	#	Name	Function (S/M/B)	Central connection (nuclei)	Peripheral connection (ganglion or muscle)
On	I	Olfactory	Smell (S)	Olfactory bulb	Olfactory epithelium
Old	II	Optic	Vision (S)	Hypothalamus/thalamus/midbrain	Retina (retinal ganglion cells)
Olympus'	III	Oculomotor	Eye movements (M)	Oculomotor nucleus	Extraocular muscles (other 4), levator palpebrae superioris, ciliary ganglion (autonomic)
Towering	IV	Trochlear	Eye movements (M)	Trochlear nucleus	Superior oblique muscle
Tops	V	Trigeminal	Sensory/motor – face (B)	Trigeminal nuclei in the midbrain, pons, and medulla	Trigeminal
A	VI	Abducens	Eye movements (M)	Abducens nucleus	Lateral rectus muscle
Finn	VII	Facial	Motor – face, Taste (B)	Facial nucleus, solitary nucleus, superior salivatory nucleus	Facial muscles, Geniculate ganglion, Pterygopalatine ganglion (autonomic)
And	VIII	Auditory (Vestibulocochlear)	Hearing/balance (S)	Cochlear nucleus, Vestibular nucleus/cerebellum	Spiral ganglion (hearing), Vestibular ganglion (balance)
German	IX	Glossopharyngeal	Motor – throat Taste (B)	Solitary nucleus, inferior salivatory nucleus, nucleus ambiguus	Pharyngeal muscles, Geniculate ganglion, Otic ganglion (autonomic)
Viewed	X	Vagus	Motor/sensory – viscera (autonomic) (B)	Medulla	Terminal ganglia serving thoracic and upper abdominal organs (heart and small intestines)
Some	XI	Spinal Accessory	Motor – head and neck (M)	Spinal accessory nucleus	Neck muscles
Hops	XII	Hypoglossal	Motor – lower throat (M)	Hypoglossal nucleus	Muscles of the larynx and lower pharynx

Spinal Nerves

The nerves connected to the spinal cord are the spinal nerves. The arrangement of these nerves is much more regular than that of the cranial nerves. All of the spinal nerves are combined sensory and motor axons that separate into two nerve roots. The sensory axons enter the spinal cord as the dorsal nerve root. The motor fibers, both somatic and autonomic, emerge as the ventral nerve root. The dorsal root ganglion for each nerve is an enlargement of the spinal nerve.

There are 31 spinal nerves, named for the level of the spinal cord at which each one emerges. There are eight pairs of cervical nerves designated C1 to C8, twelve thoracic nerves designated T1 to T12, five pairs of lumbar nerves designated L1 to L5, five pairs of sacral nerves designated S1 to S5, and one pair of coccygeal nerves. The nerves are numbered from the superior to inferior positions, and each emerges from the vertebral column through the intervertebral foramen at its level. The first nerve, C1, emerges between the first cervical vertebra and the occipital bone. The second nerve, C2, emerges between the first and second cervical vertebrae. The same occurs for C3 to C7, but C8 emerges between the seventh cervical vertebra and the first thoracic vertebra. For the thoracic and lumbar nerves, each one emerges between the vertebra that has the same designation and the

next vertebra in the column. The sacral nerves emerge from the sacral foramina along the length of that unique vertebra.

Spinal nerves extend outward from the vertebral column to enervate the periphery. The nerves in the periphery are not straight continuations of the spinal nerves, but rather the reorganization of the axons in those nerves to follow different courses. Axons from different spinal nerves will come together into a **systemic nerve**. This occurs at four places along the length of the vertebral column, each identified as a **nerve plexus**, whereas the other spinal nerves directly correspond to nerves at their respective levels. In this instance, the word plexus is used to describe networks of nerve fibers with no associated cell bodies.

Of the four nerve plexuses, two are found at the cervical level, one at the lumbar level, and one at the sacral level (Figure 6. Nerve Plexuses of the Body). The **cervical plexus** is composed of axons from spinal nerves C1 through C5 and branches into nerves in the posterior neck and head, as well as the **phrenic nerve**, which connects to the diaphragm at the base of the thoracic cavity. The other plexus from the cervical level is the **brachial plexus**. Spinal nerves C4 through T1 reorganize through this plexus to give rise to the nerves of the arms, as the name brachial suggests. A large nerve from this plexus is the **radial nerve** from which the **axillary nerve** branches to go to the armpit region. The radial nerve continues through the arm and is paralleled by the **ulnar nerve** and the median nerve. The **lumbar plexus** arises from all the lumbar spinal nerves and gives rise to nerves enervating the pelvic region and the anterior leg. The **femoral nerve** is one of the major nerves from this plexus, which gives rise to the **saphenous nerve** as a branch that extends through the anterior lower leg. The **sacral plexus** comes from the lower lumbar nerves L4 and L5 and the sacral nerves S1 to S4. The most significant systemic nerve to come from this plexus is the **sciatic nerve**, which is a combination of the **tibial nerve** and the **fibular nerve**. The sciatic nerve extends across the hip joint and is most commonly associated with the condition **sciatica**, which is the result of compression or irritation of the nerve or any of the spinal nerves giving rise to it.

These plexuses are described as arising from spinal nerves and giving rise to certain systemic nerves, but they contain fibers that serve sensory functions or fibers that serve motor functions. This means that some fibers extend from cutaneous or other peripheral sensory surfaces and send action potentials into the CNS. Those are axons of sensory neurons in the dorsal root ganglia that enter the spinal cord through the dorsal nerve root. Other fibers are the axons of motor neurons of the anterior horn of the spinal cord, which emerge in the ventral nerve root and send action potentials to cause skeletal muscles to contract in their target regions. For example, the radial nerve contains fibers of cutaneous sensation in the arm, as well as motor fibers that move muscles in the arm.

Spinal nerves of the thoracic region, T2 through T11, are not part of the plexuses but rather emerge and give rise to the **intercostal nerves** found between the ribs, which articulate with the vertebrae surrounding the spinal nerve.

Nerve Plexuses of the Body

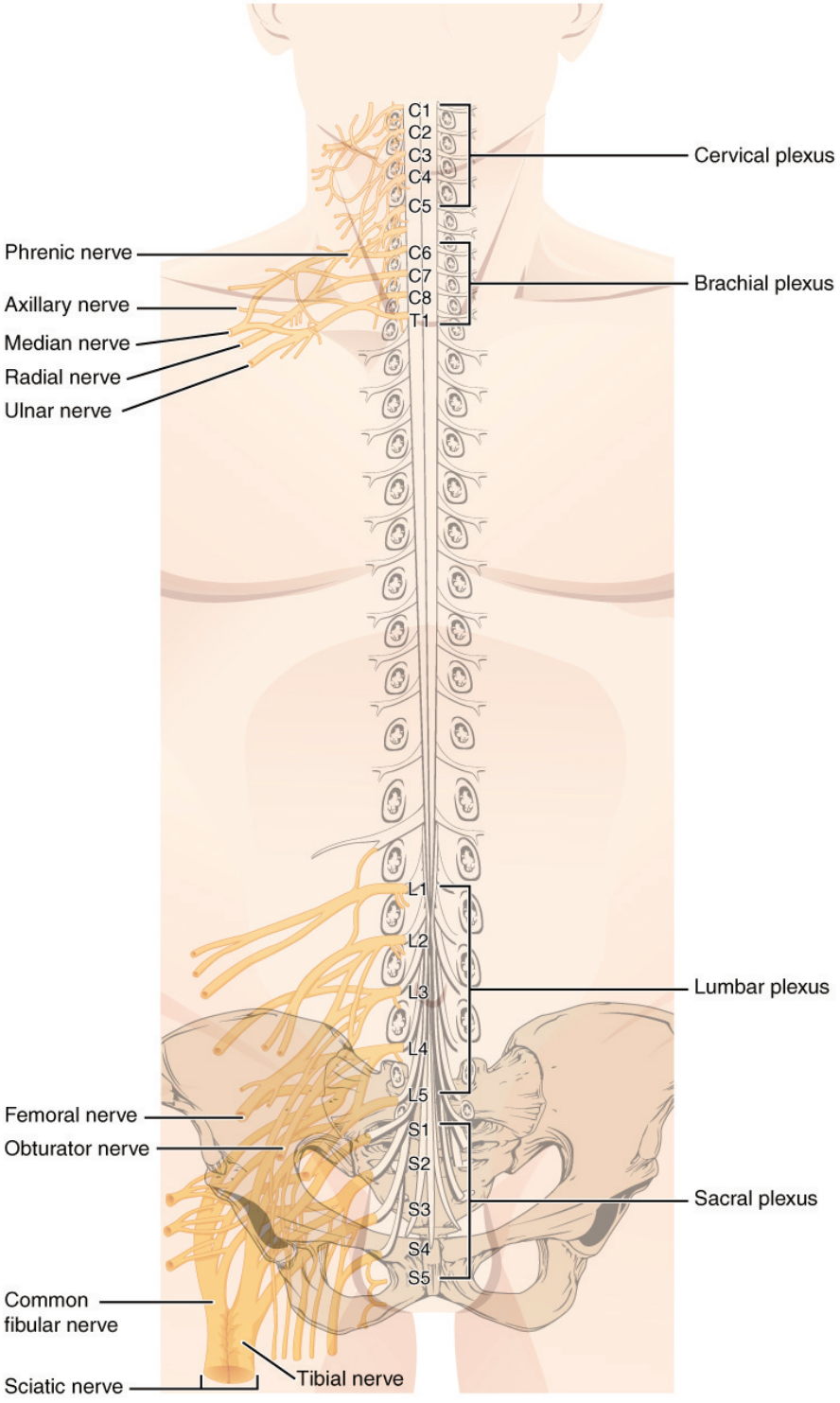


Figure 6. *There are four main nerve plexuses in the human body. The cervical plexus supplies nerves to the posterior head and neck, as well as to the diaphragm. The brachial plexus supplies nerves to the arm. The lumbar plexus supplies nerves to the anterior leg. The sacral plexus supplies nerves to the posterior leg.*

AGING AND THE...

Nervous System

Anosmia is the loss of the sense of smell. It is often the result of the olfactory nerve being severed, usually because of blunt force trauma to the head. The sensory neurons of the olfactory epithelium have a limited lifespan of approximately one to four months, and new ones are made on a regular basis. The new neurons extend their axons into the CNS by growing along the existing fibers of the olfactory nerve. The ability of these neurons to be replaced is lost with age. Age-related anosmia is not the result of impact trauma to the head, but rather a slow loss of the sensory neurons with no new neurons born to replace them.

Smell is an important sense, especially for the enjoyment of food. There are only five tastes sensed by the tongue, and two of them are generally thought of as unpleasant tastes (sour and bitter). The rich sensory experience of food is the result of odor molecules associated with the food, both as food is moved into the mouth, and therefore passes under the nose, and when it is chewed and molecules are released to move up the pharynx into the posterior nasal cavity. Anosmia results in a loss of the enjoyment of food.

As the replacement of olfactory neurons declines with age, anosmia can set in. Without the sense of smell, many sufferers complain of food tasting bland. Often, the only way to enjoy food is to add seasoning that can be sensed on the tongue, which usually means adding table salt. The problem with this solution, however, is that this increases sodium intake, which can lead to cardiovascular problems through water retention and the associated increase in blood pressure.

Chapter Review

The PNS is composed of the groups of neurons (ganglia) and bundles of axons (nerves) that are outside of the brain and spinal cord. Ganglia are of two types, sensory or autonomic. Sensory ganglia contain unipolar sensory neurons and are found on the dorsal root of all spinal nerves as well as associated with many of the cranial nerves. Autonomic ganglia are in the sympathetic chain, the associated paravertebral or prevertebral ganglia, or in terminal ganglia near or within the organs controlled by the autonomic nervous system.

Nerves are classified as cranial nerves or spinal nerves on the basis of their connection to the brain or spinal cord, respectively. The twelve cranial nerves can be strictly sensory in function, strictly motor in function, or a combination of the two functions. Sensory fibers are axons of sensory ganglia that carry sensory information into the brain and target sensory nuclei. Motor fibers are axons of motor neurons in motor nuclei of the brain stem and target skeletal muscles of the head and neck. Spinal nerves are all mixed nerves with both sensory and motor fibers. Spinal nerves emerge from the spinal cord and reorganize through plexuses, which then give rise to systemic nerves. Thoracic spinal nerves are not part of any plexus, but give rise to the intercostal nerves directly.

License

1.4 The Somatic Nervous System

Introduction

Too Hot to Touch

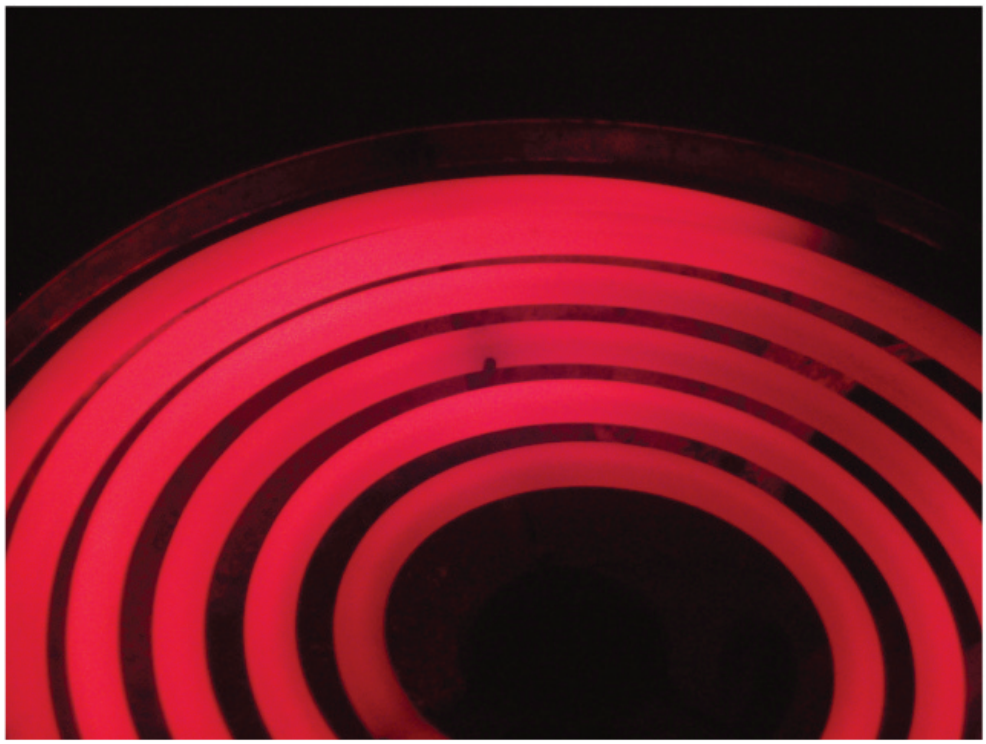


Figure 1. *When high temperature is sensed in the skin, a reflexive withdrawal is initiated by the muscles of the arm. Sensory neurons are activated by a stimulus, which is sent to the central nervous system, and a motor response is sent out to the skeletal muscles that control this movement.*

After studying this chapter, you will be able to

- Describe the components of the somatic nervous system
- Name the modalities and submodalities of the sensory systems
- Distinguish between general and special senses
- Describe regions of the central nervous system that contribute to somatic functions
- Explain the stimulus-response motor pathway

The somatic nervous system is traditionally considered a division within the peripheral nervous system.

However, this misses an important point: somatic refers to a functional division, whereas peripheral refers to an anatomic division. The somatic nervous system is responsible for our conscious perception of the environment and for our voluntary responses to that perception by means of skeletal muscles. Peripheral sensory neurons receive input from environmental stimuli, but the neurons that produce motor responses originate in the central nervous system. The distinction between the structures (i.e., anatomy) of the peripheral and central nervous systems and functions (i.e., physiology) of the somatic and autonomic systems can most easily be demonstrated through a simple reflex action. When you touch a hot stove, you pull your hand away. Sensory receptors in the skin sense extreme temperature and the early signs of tissue damage. This triggers an action potential, which travels along the sensory fiber from the skin, through the dorsal spinal root to the spinal cord, and directly activates a ventral horn motor neuron. That neuron sends a signal along its axon to excite the biceps brachii, causing contraction of the muscle and flexion of the forearm at the elbow to withdraw the hand from the hot stove. The withdrawal reflex has more components, such as inhibiting the opposing muscle and balancing posture while the arm is forcefully withdrawn, which will be further explored at the end of this chapter.

The basic withdrawal reflex explained above includes sensory input (the painful stimulus), central processing (the synapse in the spinal cord), and motor output (activation of a ventral motor neuron that causes contraction of the biceps brachii). Expanding the explanation of the withdrawal reflex can include inhibition of the opposing muscle, or cross extension, either of which increase the complexity of the example by involving more central neurons. A collateral branch of the sensory axon would inhibit another ventral horn motor neuron so that the triceps brachii do not contract and slow the withdrawal down. The cross extensor reflex provides a counterbalancing movement on the other side of the body, which requires another collateral of the sensory axon to activate contraction of the extensor muscles in the contralateral limb.

A more complex example of somatic function is conscious muscle movement. For example, reading of this text starts with visual sensory input to the retina, which then projects to the thalamus, and on to the cerebral cortex. A sequence of regions of the cerebral cortex process the visual information, starting in the primary visual cortex of the occipital lobe, and resulting in the conscious perception of these letters. Subsequent cognitive processing results in understanding of the content. As you continue reading, regions of the cerebral cortex in the frontal lobe plan how to move the eyes to follow the lines of text. The output from the cortex causes activity in motor neurons in the brain stem that cause movement of the extraocular muscles through the third, fourth, and sixth cranial nerves. This example also includes sensory input (the retinal projection to the thalamus), central processing (the thalamus and subsequent cortical activity), and motor output (activation of neurons in the brain stem that lead to coordinated contraction of extraocular muscles).

The Sensory Perception

By the end of this section, you will be able to:

- Describe different types of sensory receptors
- Describe the structures responsible for the special senses of taste, smell, hearing, balance, and vision

- Distinguish how different tastes are transduced
- Describe the means of mechanoreception for hearing and balance
- List the supporting structures around the eye and describe the structure of the eyeball
- Describe the processes of phototransduction

A major role of sensory receptors is to help us learn about the environment around us, or about the state of our internal environment. Stimuli from varying sources, and of different types, are received and changed into the electrochemical signals of the nervous system. This occurs when a stimulus changes the cell membrane potential of a sensory neuron. The stimulus causes the sensory cell to produce an action potential that is relayed into the central nervous system (CNS), where it is integrated with other sensory information—or sometimes higher cognitive functions—to become a conscious perception of that stimulus. The central integration may then lead to a motor response.

Describing sensory function with the term sensation or perception is a deliberate distinction. Sensation is the activation of sensory receptor cells at the level of the stimulus. Perception is the central processing of sensory stimuli into a meaningful pattern. Perception is dependent on sensation, but not all sensations are perceived. Receptors are the cells or structures that detect sensations. A receptor cell is changed directly by a stimulus. A transmembrane protein receptor is a protein in the cell membrane that mediates a physiological change in a neuron, most often through the opening of ion channels or changes in the cell signaling processes. Transmembrane receptors are activated by chemicals called ligands. For example, a molecule in food can serve as a ligand for taste receptors. Other transmembrane proteins, which are not accurately called receptors, are sensitive to mechanical or thermal changes. Physical changes in these proteins increase ion flow across the membrane, and can generate an action potential or a graded potential in the sensory neurons.

Sensory Receptors

Stimuli in the environment activate specialized receptor cells in the peripheral nervous system. Different types of stimuli are sensed by different types of receptor cells. Receptor cells can be classified into types on the basis of three different criteria: cell type, position, and function. Receptors can be classified structurally on the basis of cell type and their position in relation to stimuli they sense. They can also be classified functionally on the basis of the **transduction** of stimuli, or how the mechanical stimulus, light, or chemical changed the cell membrane potential.

Structural Receptor Types

The cells that interpret information about the environment can be either (1) a neuron that has a **free nerve ending**, with dendrites embedded in tissue that would receive a sensation; (2) a neuron that has an **encapsulated ending** in which the sensory nerve endings are encapsulated in connective tissue that enhances their sensitivity; or (3) a specialized **receptor cell**, which has distinct structural components that interpret a specific type of stimulus (Figure 1. Receptor Classification by Cell Type). The pain and temperature receptors in the dermis of the

skin are examples of neurons that have free nerve endings. Also located in the dermis of the skin are lamellated corpuscles, neurons with encapsulated nerve endings that respond to pressure and touch. The cells in the retina that respond to light stimuli are an example of a specialized receptor, a **photoreceptor**.

Receptor Classification by Cell Type

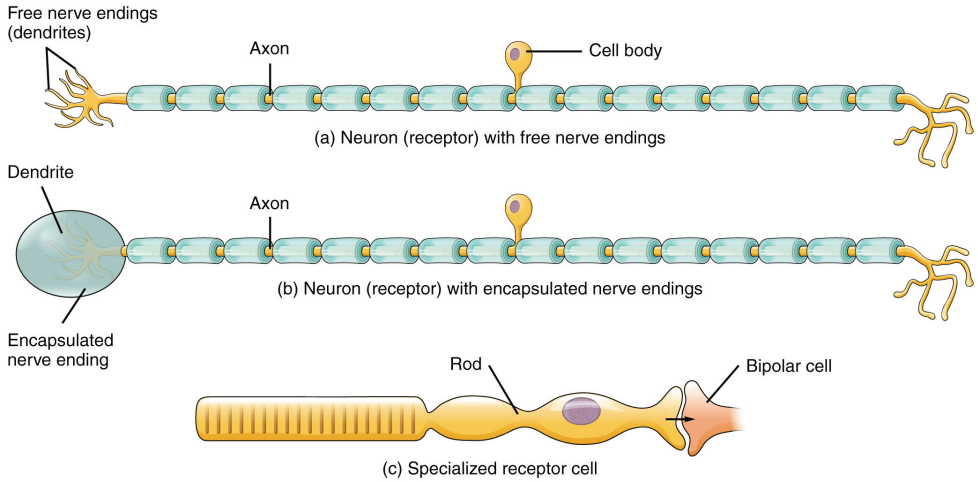


Figure 1. *Receptor cell types can be classified on the basis of their structure. Sensory neurons can have either (a) free nerve endings or (b) encapsulated endings. Photoreceptors in the eyes, such as rod cells, are examples of (c) specialized receptor cells. These cells release neurotransmitters onto a bipolar cell, which then synapses with the optic nerve neurons.*

Another way that receptors can be classified is based on their location relative to the stimuli. An **exteroceptor** is a receptor that is located near a stimulus in the external environment, such as the somatosensory receptors that are located in the skin. An **interoceptor** is one that interprets stimuli from internal organs and tissues, such as the receptors that sense the increase in blood pressure in the aorta or carotid sinus. Finally, a **proprioceptor** is a receptor located near a moving part of the body, such as a muscle, that interprets the positions of the tissues as they move.

Functional Receptor Types

A third classification of receptors is by how the receptor transduces stimuli into membrane potential changes. Stimuli are of three general types. Some stimuli are ions and macromolecules that affect transmembrane receptor proteins when these chemicals diffuse across the cell membrane. Some stimuli are physical variations in the environment that affect receptor cell membrane potentials. Other stimuli include the electromagnetic radiation from visible light. For humans, the only electromagnetic energy that is perceived by our eyes is visible light. Some other organisms have receptors that humans lack, such as the heat sensors of snakes, the ultraviolet light sensors of bees, or magnetic receptors in migratory birds.

Receptor cells can be further categorized on the basis of the type of stimuli they transduce. Chemical stimuli can be interpreted by a **chemoreceptor** that interprets chemical stimuli, such as an object's taste or smell. **Osmoreceptors** respond to solute concentrations of body fluids. Additionally, pain is primarily a chemical sense that interprets the presence of chemicals from tissue damage, or similar intense stimuli, through a **nociceptor**. Physical stimuli, such as pressure and vibration, as well as the sensation of sound and body position (balance), are interpreted through a **mechanoreceptor**. Another physical stimulus that has its own type

of receptor is temperature, which is sensed through a **thermoreceptor** that is either sensitive to temperatures above (heat) or below (cold) normal body temperature.

Sensory Modalities

Ask anyone what the senses are, and they are likely to list the five major senses—taste, smell, touch, hearing, and sight. However, these are not all of the senses. The most obvious omission from this list is balance. Also, what is referred to simply as touch can be further subdivided into pressure, vibration, stretch, and hair-follicle position, on the basis of the type of mechanoreceptors that perceive these touch sensations. Other overlooked senses include temperature perception by thermoreceptors and pain perception by nociceptors.

Within the realm of physiology, senses can be classified as either general or specific. A **general sense** is one that is distributed throughout the body and has receptor cells within the structures of other organs. Mechanoreceptors in the skin, muscles, or the walls of blood vessels are examples of this type. General senses often contribute to the sense of touch, as described above, or to **proprioception** (body movement) and **kinesthesia** (body movement), or to a **visceral sense**, which is most important to autonomic functions. A **special sense** is one that has a specific organ devoted to it, namely the eye, inner ear, tongue, or nose.

Each of the senses is referred to as a **sensory modality**. Modality refers to the way that information is encoded, which is similar to the idea of transduction. The main sensory modalities can be described on the basis of how each is transduced. The chemical senses are taste and smell. The general sense that is usually referred to as touch includes chemical sensation in the form of nociception, or pain. Pressure, vibration, muscle stretch, and the movement of hair by an external stimulus, are all sensed by mechanoreceptors. Hearing and balance are also sensed by mechanoreceptors. Finally, vision involves the activation of photoreceptors.

Listing all the different sensory modalities, which can number as many as 17, involves separating the five major senses into more specific categories, or **submodalities**, of the larger sense. An individual sensory modality represents the sensation of a specific type of stimulus. For example, the general sense of touch, which is known as **somatosensation**, can be separated into light pressure, deep pressure, vibration, itch, pain, temperature, or hair movement.

Gustation (Taste)

Only a few recognized submodalities exist within the sense of taste, or **gustation**. Until recently, only four tastes were recognized: sweet, salty, sour, and bitter. Research at the turn of the 20th century led to recognition of the fifth taste, umami, during the mid-1980s. **Umami** is a Japanese word that means "delicious taste," and is often translated to mean savory. Very recent research has suggested that there may also be a sixth taste for fats, or lipids.

Gustation is the special sense associated with the tongue. The surface of the tongue, along with the rest of the oral cavity, is lined by a stratified squamous epithelium. Raised bumps called **papillae** (singular = papilla) contain the structures for gustatory transduction. There are four types of papillae, based on their appearance (Figure 2. The Tongue): circumvallate, foliate, filiform, and fungiform. Within the structure of the papillae are **taste buds** that contain specialized **gustatory receptor cells** for the transduction of taste stimuli. These receptor cells are sensitive to the chemicals contained within foods that are ingested, and they release neurotransmitters

based on the amount of the chemical in the food. Neurotransmitters from the gustatory cells can activate sensory neurons in the facial, glossopharyngeal, and vagus cranial nerves.

The Tongue

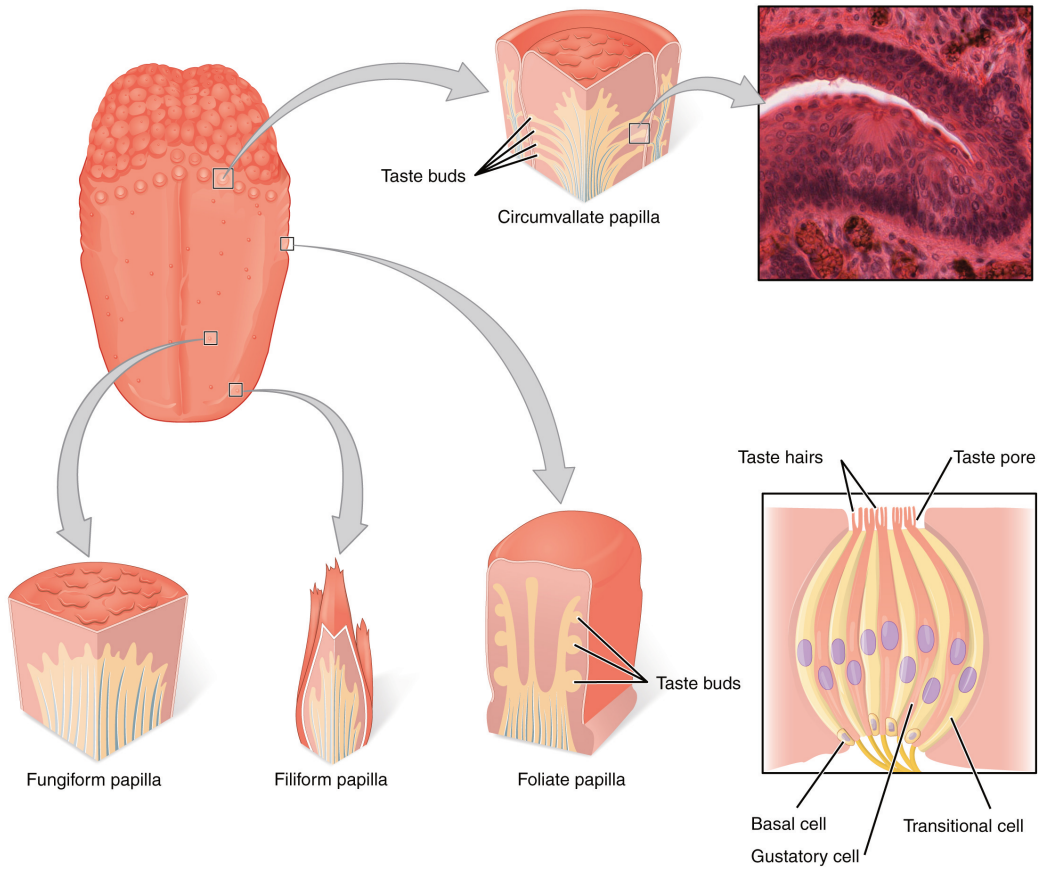


Figure 2. *The tongue is covered with small bumps, called papillae, which contain taste buds that are sensitive to chemicals in ingested food or drink. Different types of papillae are found in different regions of the tongue. The taste buds contain specialized gustatory receptor cells that respond to chemical stimuli dissolved in the saliva. These receptor cells activate sensory neurons that are part of the facial and glossopharyngeal nerves. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

Salty taste is simply the perception of sodium ions (Na^+) in the saliva. When you eat something salty, the salt crystals dissociate into the component ions Na^+ and Cl^-, which dissolve into the saliva in your mouth. The Na^+ concentration becomes high outside the gustatory cells, creating a strong concentration gradient that drives the diffusion of the ion into the cells. The entry of Na^+into these cells results in the depolarization of the cell membrane and the generation of a receptor potential.

Sour taste is the perception of H^+ concentration. Just as with sodium ions in salty flavors, these hydrogen ions enter the cell and trigger depolarization. Sour flavors are, essentially, the perception of acids in our food. Increasing hydrogen ion concentrations in the saliva (lowering saliva pH) triggers progressively stronger graded potentials in the gustatory cells. For example, orange juice—which contains citric acid—will taste sour because it has a pH value of approximately 3. Of course, it is often sweetened so that the sour taste is masked.

The first two tastes (salty and sour) are triggered by the cations Na^+ and H^+. The other tastes result from food molecules binding to a G protein–coupled receptor. A G protein signal transduction system ultimately leads to depolarization of the gustatory cell. The sweet taste is the sensitivity of gustatory cells to the presence of glucose

dissolved in the saliva. Other monosaccharides such as fructose, or artificial sweeteners such as aspartame (NutraSweet™), saccharine, or sucralose (Splenda™) also activate the sweet receptors. The affinity for each of these molecules varies, and some will taste sweeter than glucose because they bind to the G protein–coupled receptor differently.

Bitter taste is similar to sweet in that food molecules bind to G protein–coupled receptors. However, there are a number of different ways in which this can happen because there are a large diversity of bitter-tasting molecules. Some bitter molecules depolarize gustatory cells, whereas others hyperpolarize gustatory cells. Likewise, some bitter molecules increase G protein activation within the gustatory cells, whereas other bitter molecules decrease G protein activation. The specific response depends on which molecule is binding to the receptor.

One major group of bitter-tasting molecules are alkaloids. **Alkaloids** are nitrogen containing molecules that are commonly found in bitter-tasting plant products, such as coffee, hops (in beer), tannins (in wine), tea, and aspirin. By containing toxic alkaloids, the plant is less susceptible to microbe infection and less attractive to herbivores.

Therefore, the function of bitter taste may primarily be related to stimulating the gag reflex to avoid ingesting poisons. Because of this, many bitter foods that are normally ingested are often combined with a sweet component to make them more palatable (cream and sugar in coffee, for example). The highest concentration of bitter receptors appear to be in the posterior tongue, where a gag reflex could still spit out poisonous food.

The taste known as umami is often referred to as the savory taste. Like sweet and bitter, it is based on the activation of G protein–coupled receptors by a specific molecule. The molecule that activates this receptor is the amino acid L-glutamate. Therefore, the umami flavor is often perceived while eating protein-rich foods. Not surprisingly, dishes that contain meat are often described as savory.

Once the gustatory cells are activated by the taste molecules, they release neurotransmitters onto the dendrites of sensory neurons. These neurons are part of the facial and glossopharyngeal cranial nerves, as well as a component within the vagus nerve dedicated to the gag reflex. The facial nerve connects to taste buds in the anterior third of the tongue. The glossopharyngeal nerve connects to taste buds in the posterior two thirds of the tongue. The vagus nerve connects to taste buds in the extreme posterior of the tongue, verging on the pharynx, which are more sensitive to noxious stimuli such as bitterness.

Watch this video to learn about Dr. Danielle Reed of the Monell Chemical Senses Center in Philadelphia, Pennsylvania, who became interested in science at an early age because of her sensory experiences. She recognized that her sense of taste was unique compared with other people she knew. Now, she studies the genetic differences between people and their sensitivities to taste stimuli. In the video, there is a brief image of a person sticking out their tongue, which has been covered with a colored dye. This is how Dr. Reed is able to visualize and count papillae on the surface of the tongue. People fall into two groups known as “tasters” and “non-tasters” based on the density of papillae on their tongue, which also indicates the number of taste buds. Non-tasters can taste food, but they are not as sensitive to certain tastes, such as bitterness. Dr. Reed discovered that she is a non-taster, which explains why she perceived bitterness differently than other people she knew. Are you very sensitive to tastes? Can you see any similarities among the members of your family?

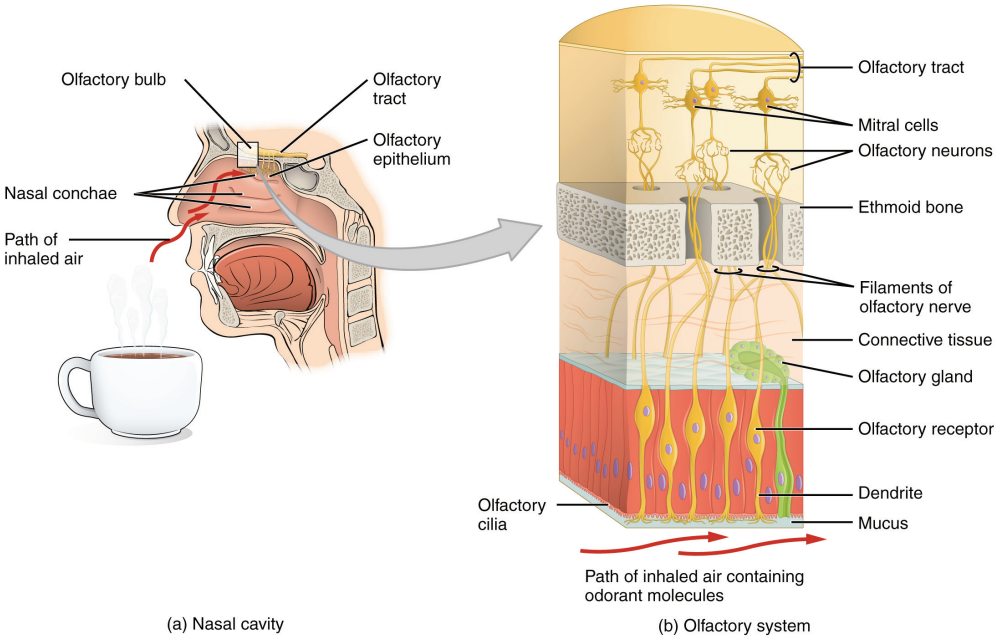
Olfaction (Smell)

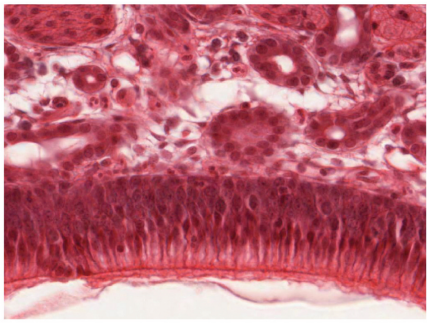
Like taste, the sense of smell, or **olfaction**, is also responsive to chemical stimuli. The olfactory receptor neurons are located in a small region within the superior nasal cavity (Figure 3. The Olfactory System). This region is referred to as the **olfactory epithelium** and contains bipolar sensory neurons. Each **olfactory sensory neuron** has dendrites that extend from the apical surface of the epithelium into the mucus lining the cavity. As airborne molecules are inhaled through the nose, they pass over the olfactory epithelial region and dissolve into the mucus. These **odorant molecules** bind to proteins that keep them dissolved in the mucus and help transport them to the olfactory dendrites. The odorant–protein complex binds to a receptor protein within the cell membrane of an olfactory dendrite. These receptors are G protein–coupled, and will produce a graded membrane potential in the olfactory neurons.

The axon of an olfactory neuron extends from the basal surface of the epithelium, through an olfactory foramen in the cribriform plate of the ethmoid bone, and into the brain. The group of axons called the olfactory tract connect to the **olfactory bulb** on the ventral surface of the frontal lobe. From there, the axons split to travel to several brain regions. Some travel to the cerebrum, specifically to the primary olfactory cortex that is located in the inferior and medial areas of the temporal lobe. Others project to structures within the limbic system and hypothalamus, where smells become associated with long-term memory and emotional responses. This is how certain smells trigger emotional memories, such as the smell of food associated with one's birthplace. Smell is the one sensory modality that does not synapse in the thalamus before connecting to the cerebral cortex. This intimate connection between the olfactory system and the cerebral cortex is one reason why smell can be a potent trigger of memories and emotion.

The nasal epithelium, including the olfactory cells, can be harmed by airborne toxic chemicals. Therefore, the olfactory neurons are regularly replaced within the nasal epithelium, after which the axons of the new neurons must find their appropriate connections in the olfactory bulb. These new axons grow along the axons that are already in place in the cranial nerve.

The Olfactory System





(c) Olfactory epithelium

Figure 3. *(a) The olfactory system begins in the peripheral structures of the nasal cavity. (b) The olfactory receptor neurons are within the olfactory epithelium. (c) Axons of the olfactory receptor neurons project through the cribriform plate of the ethmoid bone and synapse with the neurons of the olfactory bulb (tissue source: simian). LM × 812. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

DISORDERS OF THE...

Olfactory System: Anosmia

Blunt force trauma to the face, such as that common in many car accidents, can lead to the loss of the olfactory nerve, and subsequently, loss of the sense of smell. This condition is known as **anosmia**. When the frontal lobe of the brain moves relative to the ethmoid bone, the olfactory tract axons may be sheared apart. Professional fighters often experience anosmia because of repeated trauma to face and head. In addition, certain pharmaceuticals, such as antibiotics, can cause anosmia by killing all

the olfactory neurons at once. If no axons are in place within the olfactory nerve, then the axons from newly formed olfactory neurons have no guide to lead them to their connections within the olfactory bulb. There are temporary causes of anosmia, as well, such as those caused by inflammatory responses related to respiratory infections or allergies.

Loss of the sense of smell can result in food tasting bland. A person with an impaired sense of smell may require additional spice and seasoning levels for food to be tasted. Anosmia may also be related to some presentations of mild depression, because the loss of enjoyment of food may lead to a general sense of despair.

The ability of olfactory neurons to replace themselves decreases with age, leading to age-related anosmia. This explains why some elderly people salt their food more than younger people do. However, this increased sodium intake can increase blood volume and blood pressure, increasing the risk of cardiovascular diseases in the elderly.

Audition (Hearing)

Hearing, or **audition**, is the transduction of sound waves into a neural signal that is made possible by the structures of the ear (Figure 4. Structures of the Ear). The large, fleshy structure on the lateral aspect of the head is known as the **auricle**. Some sources will also refer to this structure as the pinna, though that term is more appropriate for a structure that can be moved, such as the external ear of a cat. The C-shaped curves of the auricle direct sound waves toward the auditory canal. The canal enters the skull through the external auditory meatus of the temporal bone. At the end of the auditory canal is the **tympanic membrane**, or ear drum, which vibrates after it is struck by sound waves. The auricle, ear canal, and tympanic membrane are often referred to as the **external ear**. The **middle ear** consists of a space spanned by three small bones called the ossicles. The three ossicles are the **malleus**, **incus**, and **stapes**, which are Latin names that roughly translate to hammer, anvil, and stirrup. The malleus is attached to the tympanic membrane and articulates with the incus. The incus, in turn, articulates with the stapes. The stapes is then attached to the **inner ear**, where the sound waves will be transduced into a neural signal. The middle ear is connected to the pharynx through the Eustachian tube, which helps equilibrate air pressure across the tympanic membrane. The tube is normally closed but will pop open when the muscles of the pharynx contract during swallowing or yawning.

Structures of the Ear

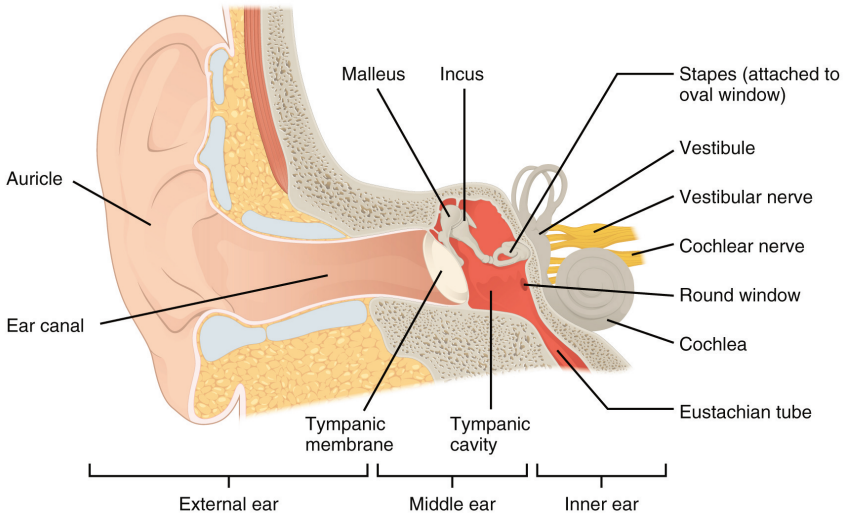


Figure 4. *The external ear contains the auricle, ear canal, and tympanic membrane. The middle ear contains the ossicles and is connected to the pharynx by the Eustachian tube. The inner ear contains the cochlea and vestibule, which are responsible for audition and equilibrium, respectively.*

The inner ear is often described as a bony labyrinth, as it is composed of a series of canals embedded within the temporal bone. It has two separate regions, the **cochlea** and the **vestibule**, which are responsible for hearing and balance, respectively. The neural signals from these two regions are relayed to the brain stem through separate fiber bundles. However, these two distinct bundles travel together from the inner ear to the brain stem as the vestibulocochlear nerve. Sound is transduced into neural signals within the cochlear region of the inner ear, which contains the sensory neurons of the **spiral ganglia**. These ganglia are located within the spiral-shaped cochlea of the inner ear. The cochlea is attached to the stapes through the **oval window**.

The oval window is located at the beginning of a fluid-filled tube within the cochlea called the **scala vestibuli**. The scala vestibuli extends from the oval window, travelling above the **cochlear duct**, which is the central cavity of the cochlea that contains the sound-transducing neurons. At the uppermost tip of the cochlea, the scala vestibuli curves over the top of the cochlear duct. The fluid-filled tube, now called the **scala tympani**, returns to the base of the cochlea, this time travelling under the cochlear duct. The scala tympani ends at the **round windo**w, which is covered by a membrane that contains the fluid within the scala. As vibrations of the ossicles travel through the oval window, the fluid of the scala vestibuli and scala tympani moves in a wave-like motion. The frequency of the fluid waves match the frequencies of the sound waves (Figure 5. Transmission of Sound Waves to Cochlea). The membrane covering the round window will bulge out or pucker in with the movement of the fluid within the scala tympani.

Transmission of Sound Waves to Cochlea

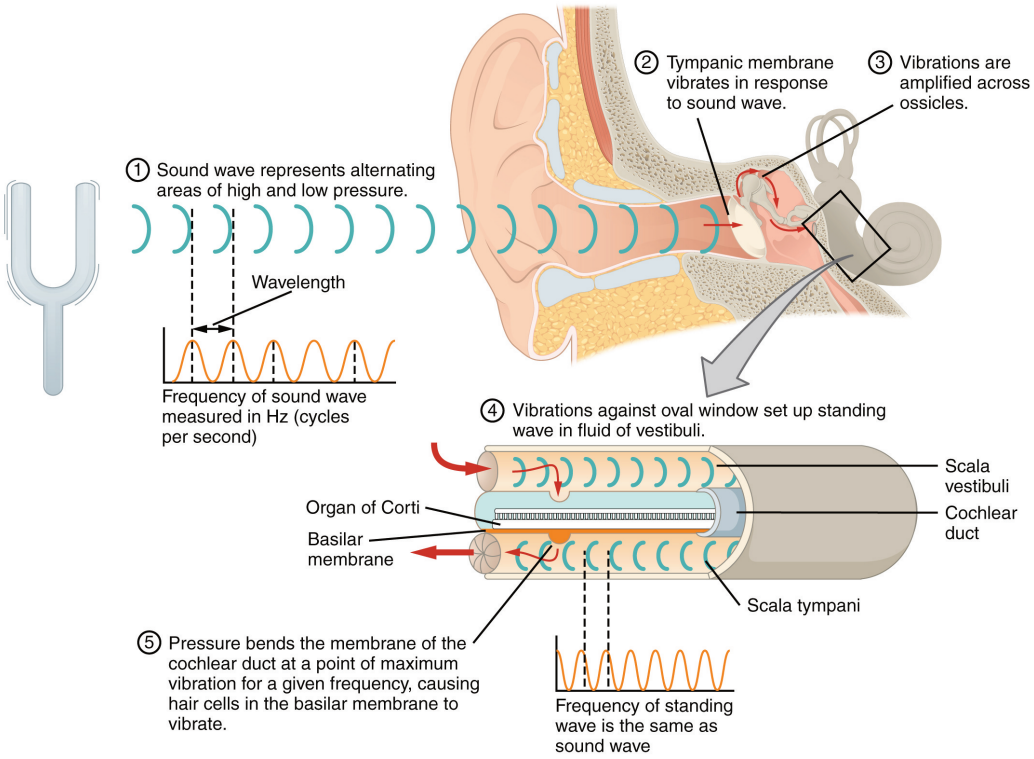


Figure 5. *A sound wave causes the tympanic membrane to vibrate. This vibration is amplified as it moves across the malleus, incus, and stapes. The amplified vibration is picked up by the oval window causing pressure waves in the fluid of the scala vestibuli and scala tympani. The complexity of the pressure waves is determined by the changes in amplitude and frequency of the sound waves entering the ear.*

A cross-sectional view of the cochlea shows that the scala vestibuli and scala tympani run along both sides of the cochlear duct (Figure 6. Cross Section of the Cochlea). The cochlear duct contains several **organs of Corti**, which tranduce the wave motion of the two scala into neural signals. The organs of Corti lie on top of the **basilar membrane**, which is the side of the cochlear duct located between the organs of Corti and the scala tympani. As the fluid waves move through the scala vestibuli and scala tympani, the basilar membrane moves at a specific spot, depending on the frequency of the waves. Higher frequency waves move the region of the basilar membrane that is close to the base of the cochlea. Lower frequency waves move the region of the basilar membrane that is near the tip of the cochlea.

Cross Section of the Cochlea

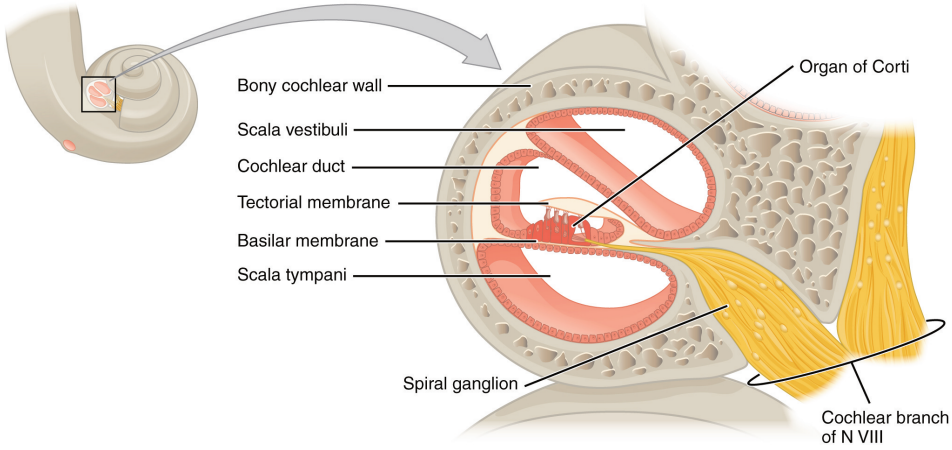


Figure 6. *The three major spaces within the cochlea are highlighted. The scala tympani and scala vestibuli lie on either side of the cochlear duct. The organ of Corti, containing the mechanoreceptor hair cells, is adjacent to the scala tympani, where it sits atop the basilar membrane.*

The organs of Corti contain **hair cells**, which are named for the hair-like **stereocilia** extending from the cell's apical surfaces (Figure 7. Hair Cell). The stereocilia are an array of microvilli-like structures arranged from tallest to shortest. Protein fibers tether adjacent hairs together within each array, such that the array will bend in response to movements of the basilar membrane. The stereocilia extend up from the hair cells to the overlying **tectorial membrane**, which is attached medially to the organ of Corti. When the pressure waves from the scala move the basilar membrane, the tectorial membrane slides across the stereocilia. This bends the stereocilia either toward or away from the tallest member of each array. When the stereocilia bend toward the tallest member of their array, tension in the protein tethers opens ion channels in the hair cell membrane. This will depolarize the hair cell membrane, triggering nerve impulses that travel down the afferent nerve fibers attached to the hair cells. When the stereocilia bend toward the shortest member of their array, the tension on the tethers slackens and the ion channels close. When no sound is present, and the stereocilia are standing straight, a small amount of tension still exists on the tethers, keeping the membrane potential of the hair cell slightly depolarized.

Hair Cell

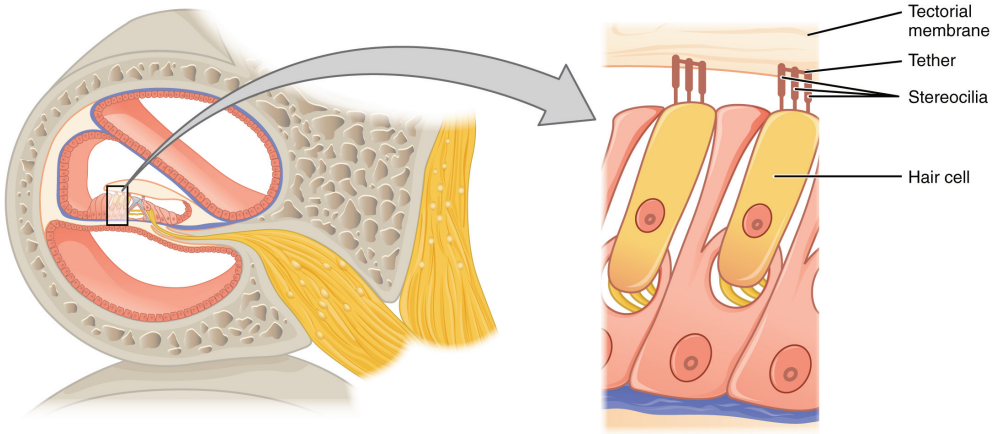


Figure 7. *The hair cell is a mechanoreceptor with an array of stereocilia emerging from its apical surface. The stereocilia are tethered together by proteins that open ion channels when the array is bent toward the tallest member of their array, and closed when the array is bent toward the shortest member of their array.*

Cochlea and Organ of Corti

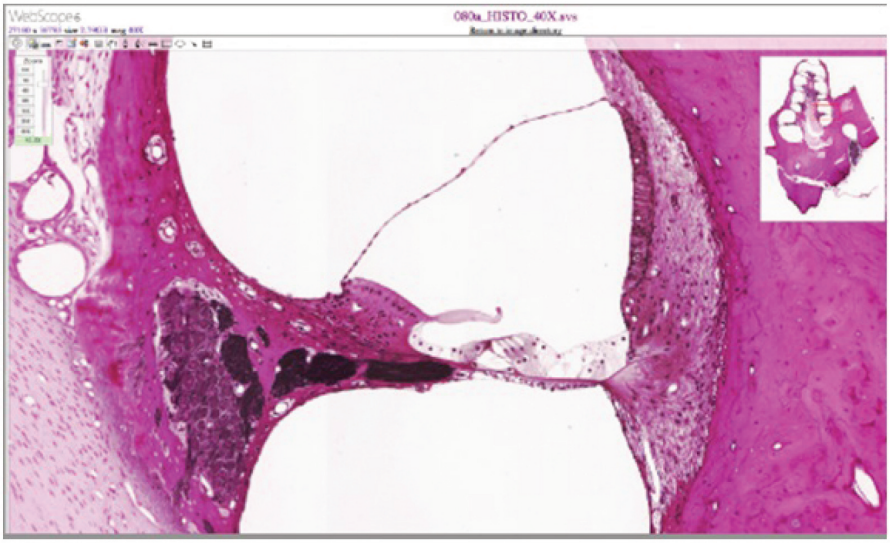


Figure 8. *LM × 412. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope athttp://virtualslides.med.umich.edu/Histology/Central%20Nervous%20System/080a_HISTO_40X.svs/view.apmlto explore the tissue sample in greater detail. The basilar membrane is the thin membrane that extends from the central core of the cochlea to the edge. What is anchored to this membrane so that they can be activated by movement of the fluids within the cochlea?

As stated above, a given region of the basilar membrane will only move if the incoming sound is at a specific frequency. Because the tectorial membrane only moves where the basilar membrane moves, the hair cells in this region will also only respond to sounds of this specific frequency. Therefore, as the frequency of a sound changes, different hair cells are activated all along the basilar membrane. The cochlea encodes auditory stimuli for frequencies between 20 and 20,000 Hz, which is the range of sound that human ears can detect. The unit of Hertz measures the frequency of sound waves in terms of cycles produced per second. Frequencies as low as 20 Hz are detected by hair cells at the apex, or tip, of the cochlea. Frequencies in the higher ranges of 20 KHz are encoded by hair cells at the base of the cochlea, close to the round and oval windows (Figure 9. Frequency Coding in the Cochlea). Most auditory stimuli contain a mixture of sounds at a variety of frequencies and intensities (represented by the amplitude of the sound wave). The hair cells along the length of the cochlear duct, which are each sensitive to a particular frequency, allow the cochlea to separate auditory stimuli by frequency, just as a prism separates visible light into its component colors.

Frequency Coding in the Cochlea

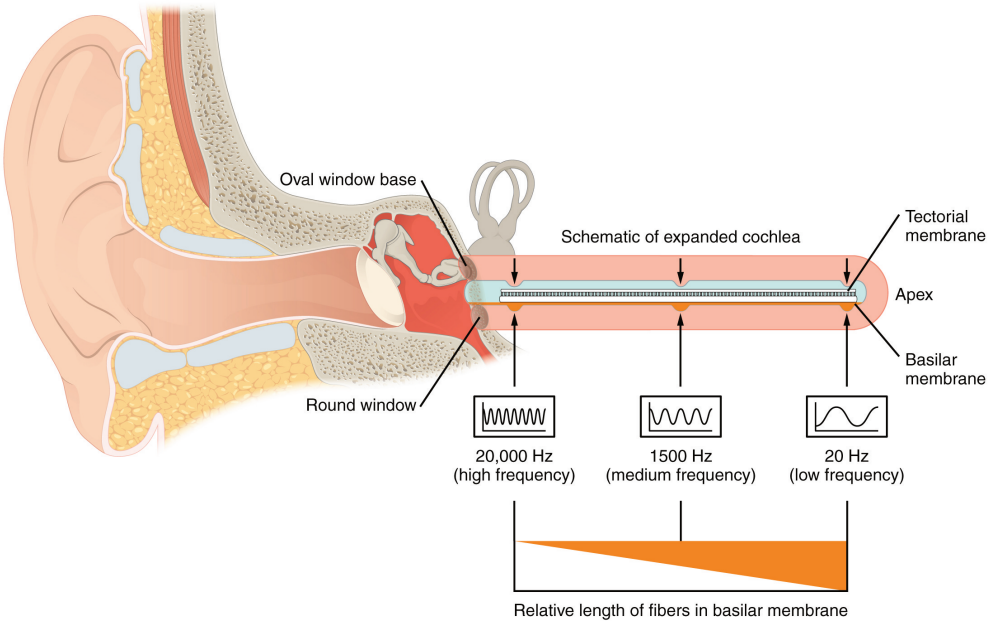


Figure 9. *The standing sound wave generated in the cochlea by the movement of the oval window deflects the basilar membrane on the basis of the frequency of sound. Therefore, hair cells at the base of the cochlea are activated only by high frequencies, whereas those at the apex of the cochlea are activated only by low frequencies.*

Watch this video to learn more about how the structures of the ear convert sound waves into a neural signal by moving the "hairs," or stereocilia, of the cochlear duct. Specific locations along the length of the duct encode specific frequencies, or pitches. The brain interprets the meaning of the sounds we hear as music, speech, noise, etc. Which ear structures are responsible for the amplification and transfer of sound from the external ear to the inner ear?

Watch this animation to learn more about the inner ear and to see the cochlea unroll, with the base at the back of the image and the apex at the front. Specific wavelengths of sound cause specific regions of the basilar membrane to vibrate, much like the keys of a piano produce sound at different frequencies. Based on the animation, where do frequencies—from high to low pitches—cause activity in the hair cells within the cochlear duct?

Equilibrium (Balance)

Along with audition, the inner ear is responsible for encoding information about **equilibrium**, the sense of balance. A similar mechanoreceptor—a hair cell with stereocilia—senses head position, head movement, and whether our bodies are in motion. These cells are located within the vestibule of the inner ear. Head position

is sensed by the **utricle** and **saccule**, whereas head movement is sensed by the **semicircular canals**. The neural signals generated in the **vestibular ganglion** are transmitted through the vestibulocochlear nerve to the brain stem and cerebellum.

The utricle and saccule are both largely composed of **macula** tissue (plural = maculae). The macula is composed of hair cells surrounded by support cells. The stereocilia of the hair cells extend into a viscous gel called the **otolithic membrane** (Figure 10. Linear Acceleration Coding by Maculae). On top of the otolithic membrane is a layer of calcium carbonate crystals, called otoliths. The otoliths essentially make the otolithic membrane top-heavy. The otolithic membrane moves separately from the macula in response to head movements. Tilting the head causes the otolithic membrane to slide over the macula in the direction of gravity. The moving otolithic membrane, in turn, bends the sterocilia, causing some hair cells to depolarize as others hyperpolarize. The exact position of the head is interpreted by the brain based on the pattern of hair-cell depolarization.

Linear Acceleration Coding by Maculae

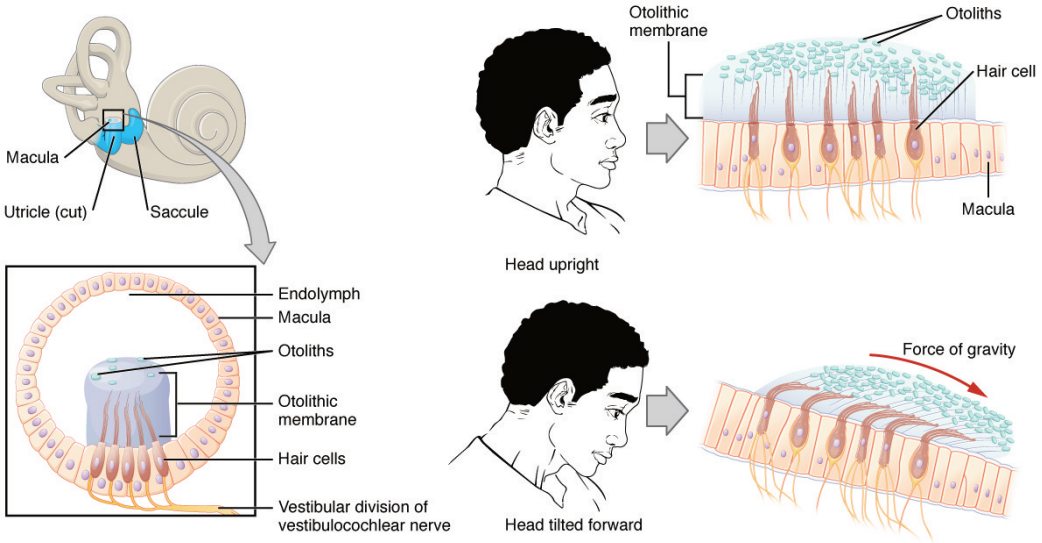


Figure 10. *The maculae are specialized for sensing linear acceleration, such as when gravity acts on the tilting head, or if the head starts moving in a straight line. The difference in inertia between the hair cell stereocilia and the otolithic membrane in which they are embedded leads to a shearing force that causes the stereocilia to bend in the direction of that linear acceleration.*

The semicircular canals are three ring-like extensions of the vestibule. One is oriented in the horizontal plane, whereas the other two are oriented in the vertical plane. The anterior and posterior vertical canals are oriented at approximately 45 degrees relative to the sagittal plane (Figure 11. Rotational Coding by Semicircular Canals). The base of each semicircular canal, where it meets with the vestibule, connects to an enlarged region known as the **ampulla**. The ampulla contains the hair cells that respond to rotational movement, such as turning the head while saying "no." The stereocilia of these hair cells extend into the **cupula**, a membrane that attaches to the top of the ampulla. As the head rotates in a plane parallel to the semicircular canal, the fluid lags, deflecting the cupula in the direction opposite to the head movement. The semicircular canals contain several ampullae, with some oriented horizontally and others oriented vertically. By comparing the relative movements of both the horizontal and vertical ampullae, the vestibular system can detect the direction of most head movements within three-dimensional (3-D) space.

Rotational Coding by Semicircular Canals

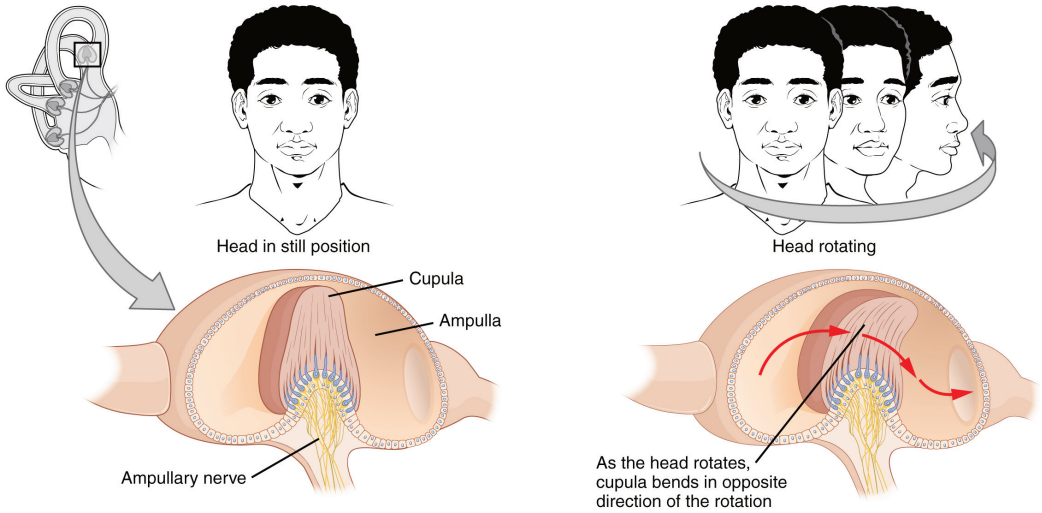


Figure 11. *Rotational movement of the head is encoded by the hair cells in the base of the semicircular canals. As one of the canals moves in an arc with the head, the internal fluid moves in the opposite direction, causing the cupula and stereocilia to bend. The movement of two canals within a plane results in information about the direction in which the head is moving, and activation of all six canals can give a very precise indication of head movement in three dimensions.*

Somatosensation (Touch)

Somatosensation is considered a general sense, as opposed to the special senses discussed in this section. Somatosensation is the group of sensory modalities that are associated with touch, proprioception, and interoception. These modalities include pressure, vibration, light touch, tickle, itch, temperature, pain, proprioception, and kinesthesia. This means that its receptors are not associated with a specialized organ, but are instead spread throughout the body in a variety of organs. Many of the somatosensory receptors are located in the skin, but receptors are also found in muscles, tendons, joint capsules, ligaments, and in the walls of visceral organs.

Two types of somatosensory signals that are transduced by free nerve endings are pain and temperature. These two modalities use thermoreceptors and nociceptors to transduce temperature and pain stimuli, respectively. Temperature receptors are stimulated when local temperatures differ from body temperature. Some thermoreceptors are sensitive to just cold and others to just heat. Nociception is the sensation of potentially damaging stimuli. Mechanical, chemical, or thermal stimuli beyond a set threshold will elicit painful sensations. Stressed or damaged tissues release chemicals that activate receptor proteins in the nociceptors. For example, the sensation of heat associated with spicy foods involves capsaicin, the active molecule in hot peppers. Capsaicin molecules bind to a transmembrane ion channel in nociceptors that is sensitive to temperatures above 37°C. The dynamics of capsaicin binding with this transmembrane ion channel is unusual in that the molecule remains bound for a long time. Because of this, it will decrease the ability of other stimuli to elicit pain sensations through the activated nociceptor. For this reason, capsaicin can be used as a topical analgesic, such as in products such as Icy Hot™.

If you drag your finger across a textured surface, the skin of your finger will vibrate. Such low frequency vibrations are sensed by mechanoreceptors called Merkel cells, also known as type I cutaneous mechanoreceptors. Merkel cells are located in the stratum basale of the epidermis. Deep pressure and vibration

is transduced by lamellated (Pacinian) corpuscles, which are receptors with encapsulated endings found deep in the dermis, or subcutaneous tissue. Light touch is transduced by the encapsulated endings known as tactile (Meissner) corpuscles. Follicles are also wrapped in a plexus of nerve endings known as the hair follicle plexus. These nerve endings detect the movement of hair at the surface of the skin, such as when an insect may be walking along the skin. Stretching of the skin is transduced by stretch receptors known as bulbous corpuscles. Bulbous corpuscles are also known as Ruffini corpuscles, or type II cutaneous mechanoreceptors.

Other somatosensory receptors are found in the joints and muscles. Stretch receptors monitor the stretching of tendons, muscles, and the components of joints. For example, have you ever stretched your muscles before or after exercise and noticed that you can only stretch so far before your muscles spasm back to a less stretched state? This spasm is a reflex that is initiated by stretch receptors to avoid muscle tearing. Such stretch receptors can also prevent over-contraction of a muscle. In skeletal muscle tissue, these stretch receptors are called muscle spindles. Golgi tendon organs similarly transduce the stretch levels of tendons. Bulbous corpuscles are also present in joint capsules, where they measure stretch in the components of the skeletal system within the joint. The types of nerve endings, their locations, and the stimuli they transduce are presented in Table (Mechanoreceptors of Somatosensation).

Mechanoreceptors of Somatosensation

Name	Historical (eponymous) name	Location(s)	Stimuli
Free nerve endings	*	Dermis, cornea, tongue, joint capsules, visceral organs	Pain, temperature, mechanical deformation
Mechanoreceptors	Merkel's discs	Epidermal–dermal junction, mucosal membranes	Low frequency vibration (5–15 Hz)
Bulbous corpuscle	Ruffini's corpuscle	Dermis, joint capsules	Stretch
Tactile corpuscle	Meissner's corpuscle	Papillary dermis, especially in the fingertips and lips	Light touch, vibrations below 50 Hz
Lamellated corpuscle	Pacinian corpuscle	Deep dermis, subcutaneous tissue	Deep pressure, high-frequency vibration (around 250 Hz)
Hair follicle plexus	*	Wrapped around hair follicles in the dermis	Movement of hair
Muscle spindle	*	In line with skeletal muscle fibers	Muscle contraction and stretch
Tendon stretch organ	Golgi tendon organ	In line with tendons	Stretch of tendons

*No *corresponding eponymous name.*

Vision

Vision is the special sense of sight that is based on the transduction of light stimuli received through the eyes. The eyes are located within either orbit in the skull. The bony orbits surround the eyeballs, protecting them and anchoring the soft tissues of the eye (Figure 12. The Eye in the Orbit). The eyelids, with lashes at their leading edges, help to protect the eye from abrasions by blocking particles that may land on the surface of the eye. The inner surface of each lid is a thin membrane known as the **palpebral conjunctiva**. The conjunctiva extends over the white areas of the eye (the sclera), connecting the eyelids to the eyeball. Tears are produced by the **lacrimal**

gland, located beneath the lateral edges of the nose. Tears produced by this gland flow through the **lacrimal duct** to the medial corner of the eye, where the tears flow over the conjunctiva, washing away foreign particles.

The Eye in the Orbit

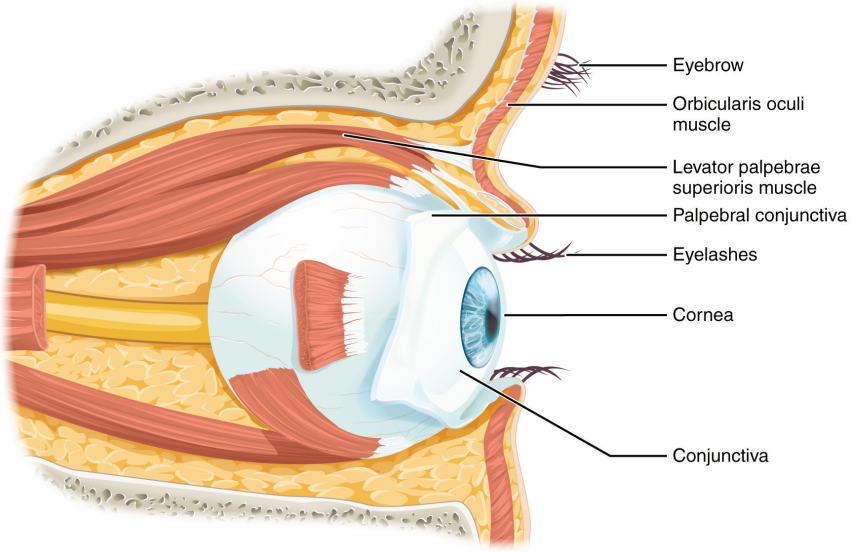


Figure 12. *The eye is located within the orbit and surrounded by soft tissues that protect and support its function. The orbit is surrounded by cranial bones of the skull.*

Movement of the eye within the orbit is accomplished by the contraction of six **extraocular muscles** that originate from the bones of the orbit and insert into the surface of the eyeball (Figure 13. Extraocular Muscles). Four of the muscles are arranged at the cardinal points around the eye and are named for those locations. They are the **superior rectus**, **medial rectus**, **inferior rectus**, and **lateral rectus**. When each of these muscles contract, the eye to moves toward the contracting muscle. For example, when the superior rectus contracts, the eye rotates to look up. The **superior oblique** originates at the posterior orbit, near the origin of the four rectus muscles. However, the tendon of the oblique muscles threads through a pulley-like piece of cartilage known as the **trochlea**. The tendon inserts obliquely into the superior surface of the eye. The angle of the tendon through the trochlea means that contraction of the superior oblique rotates the eye medially. The **inferior oblique** muscle originates from the floor of the orbit and inserts into the inferolateral surface of the eye. When it contracts, it laterally rotates the eye, in opposition to the superior oblique. Rotation of the eye by the two oblique muscles is necessary because the eye is not perfectly aligned on the sagittal plane. When the eye looks up or down, the eye must also rotate slightly to compensate for the superior rectus pulling at approximately a 20-degree angle, rather than straight up. The same is true for the inferior rectus, which is compensated by contraction of the inferior oblique. A seventh muscle in the orbit is the **levator palpebrae superioris**, which is responsible for elevating and retracting the upper eyelid, a movement that usually occurs in concert with elevation of the eye by the superior rectus (see Figure 12. The Eye in the Orbit).

The extraocular muscles are innervated by three cranial nerves. The lateral rectus, which causes abduction of the eye, is innervated by the abducens nerve. The superior oblique is innervated by the trochlear nerve. All of the other muscles are innervated by the oculomotor nerve, as is the levator palpebrae superioris. The motor nuclei of these cranial nerves connect to the brain stem, which coordinates eye movements.

Extraocular Muscles

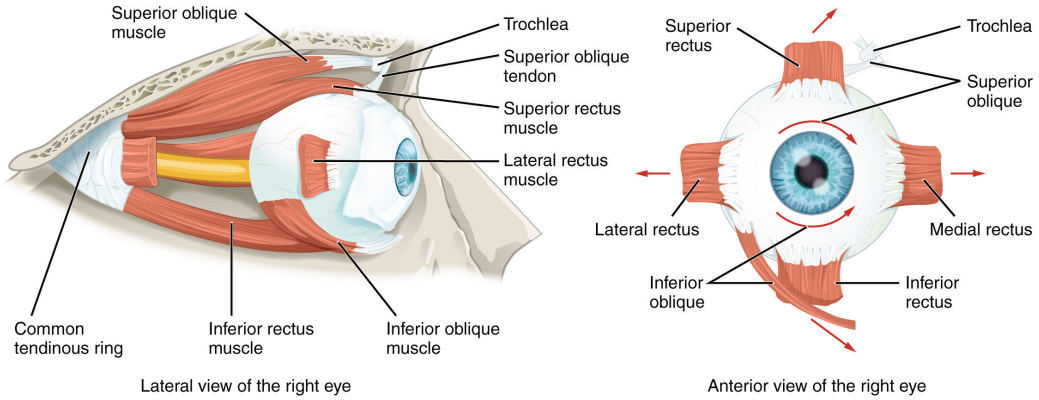


Figure 13. *The extraocular muscles move the eye within the orbit.*

The eye itself is a hollow sphere composed of three layers of tissue. The outermost layer is the **fibrous tunic**, which includes the white **sclera** and clear **cornea**. The sclera accounts for five sixths of the surface of the eye, most of which is not visible, though humans are unique compared with many other species in having so much of the "white of the eye" visible (Figure 14. Structure of the Eye). The transparent cornea covers the anterior tip of the eye and allows light to enter the eye. The middle layer of the eye is the **vascular tunic**, which is mostly composed of the choroid, ciliary body, and iris. The **choroid** is a layer of highly vascularized connective tissue that provides a blood supply to the eyeball. The choroid is posterior to the ciliary body, a muscular structure that is attached to the **lens** by suspensory ligaments, or **zonule fibers**. These two structures bend the lens, allowing it to focus light on the back of the eye. Overlaying the ciliary body, and visible in the anterior eye, is the iris—the colored part of the eye. The iris is a smooth muscle that opens or closes the **pupil**, which is the hole at the center of the eye that allows light to enter. The iris constricts the pupil in response to bright light and dilates the pupil in response to dim light. The innermost layer of the eye is the **neural tunic**, or **retina**, which contains the nervous tissue responsible for photoreception.

The eye is also divided into two cavities: the anterior cavity and the posterior cavity. The anterior cavity is the space between the cornea and lens, including the iris and ciliary body. It is filled with a watery fluid called the **aqueous humor**. The posterior cavity is the space behind the lens that extends to the posterior side of the interior eyeball, where the retina is located. The posterior cavity is filled with a more viscous fluid called the **vitreous humor**.

The retina is composed of several layers and contains specialized cells for the initial processing of visual stimuli. The photoreceptors (rods and cones) change their membrane potential when stimulated by light energy. The change in membrane potential alters the amount of neurotransmitter that the photoreceptor cells release onto **bipolar cells** in the **outer synaptic layer**. It is the bipolar cell in the retina that connects a photoreceptor to a **retinal ganglion cell (RGC)** in the **inner synaptic layer**. There, **amacrine cells** additionally contribute to retinal processing before an action potential is produced by the RGC. The axons of RGCs, which lie at the innermost layer of the retina, collect at the **optic disc** and leave the eye as the **optic nerve** (see Figure 14. Structure of the Eye). Because these axons pass through the retina, there are no photoreceptors at the very back of the eye, where the optic nerve begins. This creates a "blind spot" in the retina, and a corresponding blind spot in our visual field.
Structure of the Eye

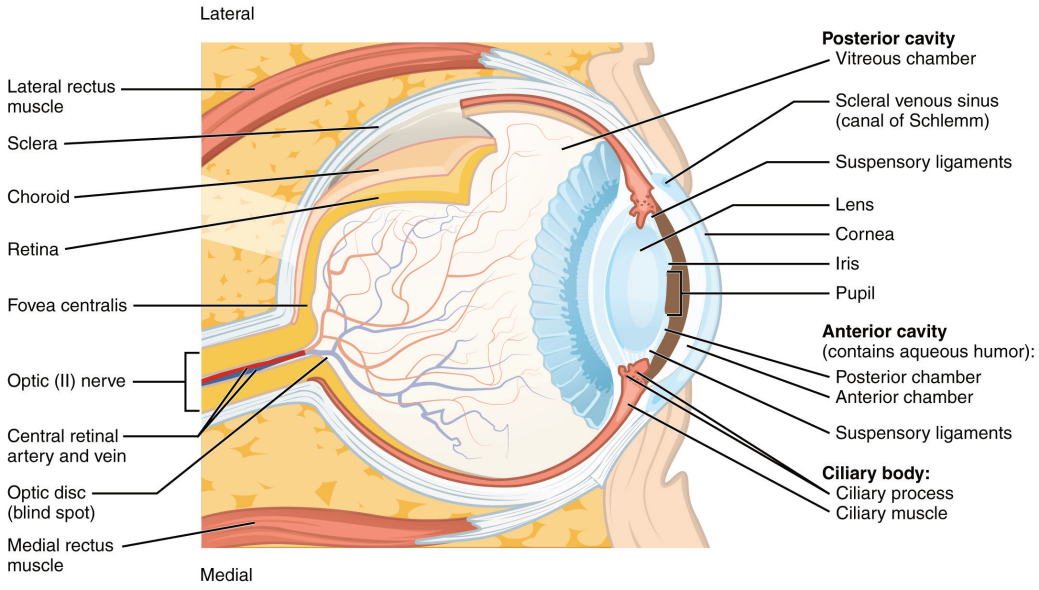


Figure 14. *The sphere of the eye can be divided into anterior and posterior chambers. The wall of the eye is composed of three layers: the fibrous tunic, vascular tunic, and neural tunic. Within the neural tunic is the retina, with three layers of cells and two synaptic layers in between. The center of the retina has a small indentation known as the fovea.*

Note that the photoreceptors in the retina (rods and cones) are located behind the axons, RGCs, bipolar cells, and retinal blood vessels. A significant amount of light is absorbed by these structures before the light reaches the photoreceptor cells. However, at the exact center of the retina is a small area known as the **fovea**. At the fovea, the retina lacks the supporting cells and blood vessels, and only contains photoreceptors. Therefore, **visual acuity**, or the sharpness of vision, is greatest at the fovea. This is because the fovea is where the least amount of incoming light is absorbed by other retinal structures (see Figure 14. Structure of the Eye). As one moves in either direction from this central point of the retina, visual acuity drops significantly. In addition, each photoreceptor cell of the fovea is connected to a single RGC. Therefore, this RGC does not have to integrate inputs from multiple photoreceptors, which reduces the accuracy of visual transduction. Toward the edges of the retina, several photoreceptors converge on RGCs (through the bipolar cells) up to a ratio of 50 to 1. The difference in visual acuity between the fovea and peripheral retina is easily evidenced by looking directly at a word in the middle of this paragraph. The visual stimulus in the middle of the field of view falls on the fovea and is in the sharpest focus. Without moving your eyes off that word, notice that words at the beginning or end of the paragraph are not in focus. The images in your peripheral vision are focused by the peripheral retina, and have vague, blurry edges and words that are not as clearly identified. As a result, a large part of the neural function of the eyes is concerned with moving the eyes and head so that important visual stimuli are centered on the fovea.

Light falling on the retina causes chemical changes to pigment molecules in the photoreceptors, ultimately leading to a change in the activity of the RGCs. Photoreceptor cells have two parts, the **inner segment** and the **outer segment** (Figure 15. Photoreceptor). The inner segment contains the nucleus and other common organelles of a cell, whereas the outer segment is a specialized region in which photoreception takes place. There are two types of photoreceptors—rods and cones—which differ in the shape of their outer segment. The rod-shaped outer segments of the **rod photoreceptor** contain a stack of membrane-bound discs that contain the photosensitive pigment **rhodopsin**. The cone-shaped outer segments of the cone photoreceptor contain their photosensitive pigments in infoldings of the cell membrane. There are three cone photopigments, called opsins,

which are each sensitive to a particular wavelength of light. The wavelength of visible light determines its color. The pigments in human eyes are specialized in perceiving three different primary colors: red, green, and blue.

Photoreceptor

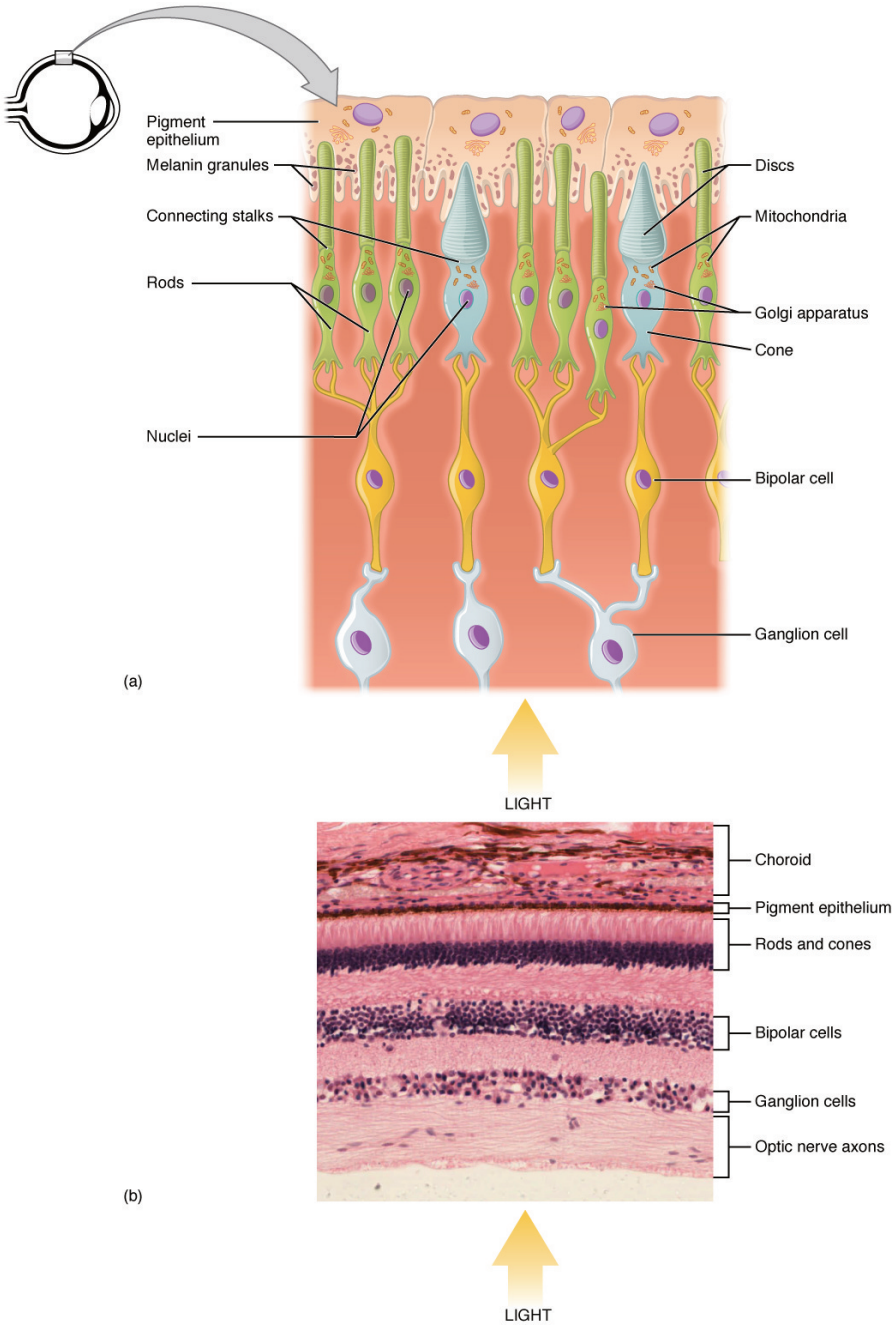


Figure 15. *(a) All photoreceptors have inner segments containing the nucleus and other important organelles and outer segments with membrane arrays containing the photosensitive opsin molecules. Rod outer segments are long columnar shapes with stacks of membrane-bound discs that contain the rhodopsin pigment. Cone outer segments are short, tapered shapes with folds of membrane in place of the discs in the rods. (b) Tissue of the retina shows a dense layer of nuclei of the rods and cones. LM × 800. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

At the molecular level, visual stimuli cause changes in the photopigment molecule that lead to changes in membrane potential of the photoreceptor cell. A single unit of light is called a **photon**, which is described in physics as a packet of energy with properties of both a particle and a wave. The energy of a photon is represented by its wavelength, with each wavelength of visible light corresponding to a particular color. Visible light is electromagnetic radiation with a wavelength between 380 and 720 nm. Wavelengths of electromagnetic radiation longer than 720 nm fall into the infrared range, whereas wavelengths shorter than 380 nm fall into the ultraviolet range. Light with a wavelength of 380 nm is blue whereas light with a wavelength of 720 nm is dark red. All other colors fall between red and blue at various points along the wavelength scale.

Opsin pigments are actually transmembrane proteins that contain a cofactor known as **retinal**. Retinal is a hydrocarbon molecule related to vitamin A. When a photon hits retinal, the long hydrocarbon chain of the molecule is biochemically altered. Specifically, photons cause some of the double-bonded carbons within the chain to switch from a *cis* to a *trans* conformation. This process is called **photoisomerization**. Before interacting with a photon, retinal's flexible double-bonded carbons are in the *cis* conformation. This molecule is referred to as 11-*cis*-retinal. A photon interacting with the molecule causes the flexible double-bonded carbons to change to the *trans*– conformation, forming all-*trans*-retinal, which has a straight hydrocarbon chain (Figure 16. Retinal Isomers).

The shape change of retinal in the photoreceptors initiates visual transduction in the retina. Activation of retinal and the opsin proteins result in activation of a G protein. The G protein changes the membrane potential of the photoreceptor cell, which then releases less neurotransmitter into the outer synaptic layer of the retina. Until the retinal molecule is changed back to the 11-*cis*-retinal shape, the opsin cannot respond to light energy, which is called bleaching. When a large group of photopigments is bleached, the retina will send information as if opposing visual information is being perceived. After a bright flash of light, afterimages are usually seen in negative. The photoisomerization is reversed by a series of enzymatic changes so that the retinal responds to more light energy.

Retinal Isomers

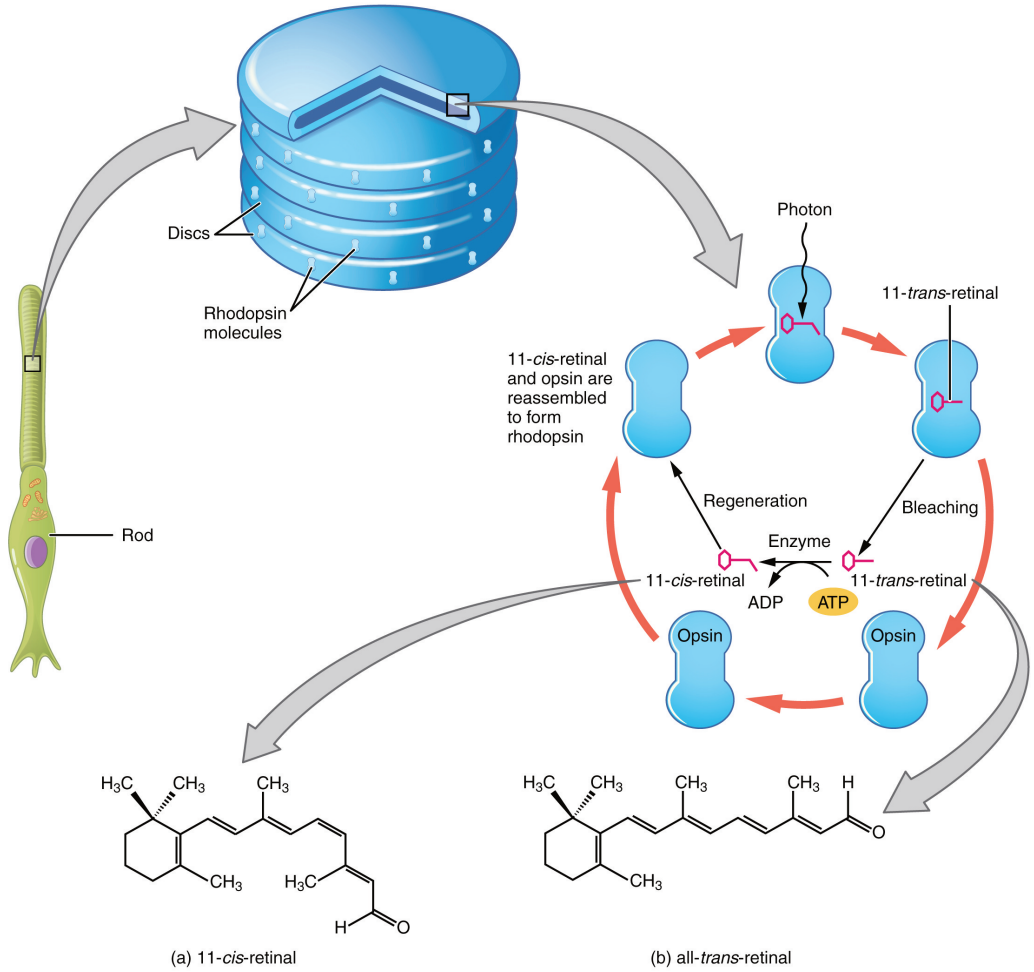


Figure 16. *The retinal molecule has two isomers, (a) one before a photon interacts with it and (b) one that is altered through photoisomerization.*

The opsins are sensitive to limited wavelengths of light. Rhodopsin, the photopigment in rods, is most sensitive to light at a wavelength of 498 nm. The three color opsins have peak sensitivities of 564 nm, 534 nm, and 420 nm corresponding roughly to the primary colors of red, green, and blue (Figure 17. Comparison of Color Sensitivity of Photopigments). The absorbance of rhodopsin in the rods is much more sensitive than in the cone opsins; specifically, rods are sensitive to vision in low light conditions, and cones are sensitive to brighter conditions. In normal sunlight, rhodopsin will be constantly bleached while the cones are active. In a darkened room, there is not enough light to activate cone opsins, and vision is entirely dependent on rods. Rods are so sensitive to light that a single photon can result in an action potential from a rod's corresponding RGC.

The three types of cone opsins, being sensitive to different wavelengths of light, provide us with color vision. By comparing the activity of the three different cones, the brain can extract color information from visual stimuli. For example, a bright blue light that has a wavelength of approximately 450 nm would activate the "red" cones minimally, the "green" cones marginally, and the "blue" cones predominantly. The relative activation of the three different cones is calculated by the brain, which perceives the color as blue. However, cones cannot react to low-intensity light, and rods do not sense the color of light. Therefore, our low-light vision is—in essence—in grayscale. In other words, in a dark room, everything appears as a shade of gray. If you think that you can see

colors in the dark, it is most likely because your brain knows what color something is and is relying on that memory.

Comparison of Color Sensitivity of Photopigments

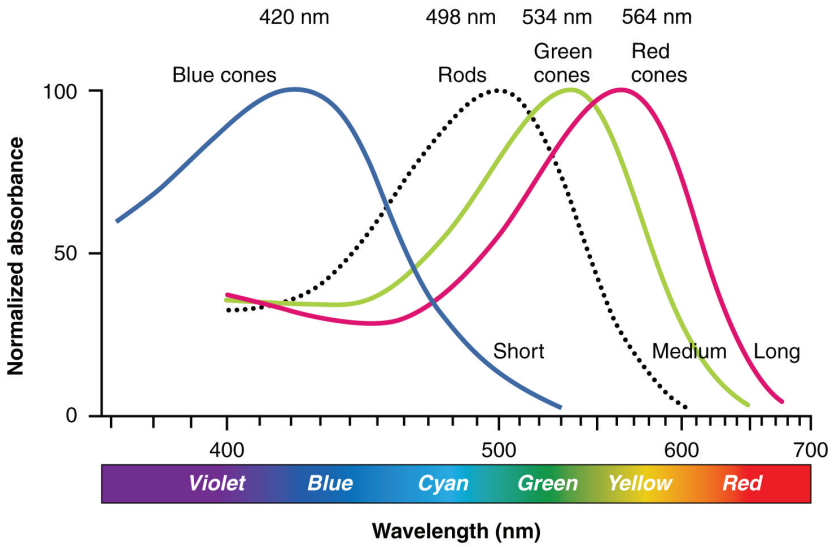


Figure 17. *Comparing the peak sensitivity and absorbance spectra of the four photopigments suggests that they are most sensitive to particular wavelengths.*

Watch this video to learn more about a transverse section through the brain that depicts the visual pathway from the eye to the occipital cortex. The first half of the pathway is the projection from the RGCs through the optic nerve to the lateral geniculate nucleus in the thalamus on either side. This first fiber in the pathway synapses on a thalamic cell that then projects to the visual cortex in the occipital lobe where "seeing," or visual perception, takes place. This video gives an abbreviated overview of the visual system by concentrating on the pathway from the eyes to the occipital lobe. The video makes the statement (at 0:45) that "specialized cells in the retina called ganglion cells convert the light rays into electrical signals." What aspect of retinal processing is simplified by that statement? Explain your answer.

Sensory Nerves

Once any sensory cell transduces a stimulus into a nerve impulse, that impulse has to travel along axons to reach the CNS. In many of the special senses, the axons leaving the sensory receptors have a **topographical** arrangement, meaning that the location of the sensory receptor relates to the location of the axon in the nerve. For example, in the retina, axons from RGCs in the fovea are located at the center of the optic nerve, where they are surrounded by axons from the more peripheral RGCs.

Spinal Nerves

Generally, spinal nerves contain afferent axons from sensory receptors in the periphery, such as from the skin, mixed with efferent axons travelling to the muscles or other effector organs. As the spinal nerve nears the spinal cord, it splits into dorsal and ventral roots. The dorsal root contains only the axons of sensory neurons, whereas the ventral roots contain only the axons of the motor neurons. Some of the branches will synapse with local neurons in the dorsal root ganglion, posterior (dorsal) horn, or even the anterior (ventral) horn, at the level of the spinal cord where they enter. Other branches will travel a short distance up or down the spine to interact with neurons at other levels of the spinal cord. A branch may also turn into the posterior (dorsal) column of the white matter to connect with the brain. For the sake of convenience, we will use the terms ventral and dorsal in reference to structures within the spinal cord that are part of these pathways. This will help to underscore the relationships between the different components. Typically, spinal nerve systems that connect to the brain are **contralateral**, in that the right side of the body is connected to the left side of the brain and the left side of the body to the right side of the brain.

Cranial Nerves

Cranial nerves convey specific sensory information from the head and neck directly to the brain. For sensations below the neck, the right side of the body is connected to the left side of the brain and the left side of the body to the right side of the brain. Whereas spinal information is contralateral, cranial nerve systems are mostly **ipsilateral**, meaning that a cranial nerve on the right side of the head is connected to the right side of the brain. Some cranial nerves contain only sensory axons, such as the olfactory, optic, and vestibulocochlear nerves. Other cranial nerves contain both sensory and motor axons, including the trigeminal, facial, glossopharyngeal, and vagus nerves (however, the vagus nerve is not associated with the somatic nervous system). The general senses of somatosensation for the face travel through the trigeminal system.

Chapter Review

The senses are olfaction (smell), gustation (taste), somatosensation (sensations associated with the skin and body), audition (hearing), equilibrium (balance), and vision. With the exception of somatosensation, this list represents the special senses, or those systems of the body that are associated with specific organs such as the tongue or eye. Somatosensation belongs to the general senses, which are those sensory structures that are distributed throughout the body and in the walls of various organs. The special senses are all primarily part of the somatic nervous system in that they are consciously perceived through cerebral processes, though some special senses contribute to autonomic function. The general senses can be divided into somatosensation, which is commonly considered touch, but includes tactile, pressure, vibration, temperature, and pain perception. The general senses also include the visceral senses, which are separate from the somatic nervous system function in that they do not normally rise to the level of conscious perception.

The cells that transduce sensory stimuli into the electrochemical signals of the nervous system are classified on the basis of structural or functional aspects of the cells. The structural classifications are either based on the anatomy of the cell that is interacting with the stimulus (free nerve endings, encapsulated endings,

or specialized receptor cell), or where the cell is located relative to the stimulus (interoceptor, exteroceptor, proprioceptor). Thirdly, the functional classification is based on how the cell transduces the stimulus into a neural signal. Chemoreceptors respond to chemical stimuli and are the basis for olfaction and gustation. Related to chemoreceptors are osmoreceptors and nociceptors for fluid balance and pain reception, respectively. Mechanoreceptors respond to mechanical stimuli and are the basis for most aspects of somatosensation, as well as being the basis of audition and equilibrium in the inner ear. Thermoreceptors are sensitive to temperature changes, and photoreceptors are sensitive to light energy.

The nerves that convey sensory information from the periphery to the CNS are either spinal nerves, connected to the spinal cord, or cranial nerves, connected to the brain. Spinal nerves have mixed populations of fibers; some are motor fibers and some are sensory. The sensory fibers connect to the spinal cord through the dorsal root, which is attached to the dorsal root ganglion. Sensory information from the body that is conveyed through spinal nerves will project to the opposite side of the brain to be processed by the cerebral cortex. The cranial nerves can be strictly sensory fibers, such as the olfactory, optic, and vestibulocochlear nerves, or mixed sensory and motor nerves, such as the trigeminal, facial, glossopharyngeal, and vagus nerves. The cranial nerves are connected to the same side of the brain from which the sensory information originates.

Central Processing

By the end of this section, you will be able to:

- Describe the pathways that sensory systems follow into the central nervous system
- Differentiate between the two major ascending pathways in the spinal cord
- Describe the pathway of somatosensory input from the face and compare it to the ascending pathways in the spinal cord
- Explain topographical representations of sensory information in at least two systems
- Describe two pathways of visual processing and the functions associated with each

Sensory Pathways

Specific regions of the CNS coordinate different somatic processes using sensory inputs and motor outputs of peripheral nerves. A simple case is a reflex caused by a synapse between a dorsal sensory neuron axon and a motor neuron in the ventral horn. More complex arrangements are possible to integrate peripheral sensory information with higher processes. The important regions of the CNS that play a role in somatic processes can be separated into the spinal cord brain stem, diencephalon, cerebral cortex, and subcortical structures.

Spinal Cord and Brain Stem

A sensory pathway that carries peripheral sensations to the brain is referred to as an **ascending pathway**, or ascending tract. The various sensory modalities each follow specific pathways through the CNS. Tactile and other somatosensory stimuli activate receptors in the skin, muscles, tendons, and joints throughout the entire body. However, the somatosensory pathways are divided into two separate systems on the basis of the location of the receptor neurons. Somatosensory stimuli from below the neck pass along the sensory pathways of the spinal cord, whereas somatosensory stimuli from the head and neck travel through the cranial nerves—specifically, the trigeminal system.

The **dorsal column system** (sometimes referred to as the dorsal column–medial lemniscus) and the **spinothalamic tract** are two major pathways that bring sensory information to the brain (Figure 1. Ascending Sensory Pathways of the Spinal Cord). The sensory pathways in each of these systems are composed of three successive neurons.

The dorsal column system begins with the axon of a dorsal root ganglion neuron entering the dorsal root and joining the dorsal column white matter in the spinal cord. As axons of this pathway enter the dorsal column, they take on a positional arrangement so that axons from lower levels of the body position themselves medially, whereas axons from upper levels of the body position themselves laterally. The dorsal column is separated into two component tracts, the **fasciculus gracilis** that contains axons from the legs and lower body, and the **fasciculus cuneatus** that contains axons from the upper body and arms.

The axons in the dorsal column terminate in the nuclei of the medulla, where each synapses with the second neuron in their respective pathway. The **nucleus gracilis** is the target of fibers in the fasciculus gracilis, whereas the **nucleus cuneatus** is the target of fibers in the fasciculus cuneatus. The second neuron in the system projects from one of the two nuclei and then **decussates**, or crosses the midline of the medulla. These axons then continue to ascend the brain stem as a bundle called the **medial lemniscus**. These axons terminate in the thalamus, where each synapses with the third neuron in their respective pathway. The third neuron in the system projects its axons to the postcentral gyrus of the cerebral cortex, where somatosensory stimuli are initially processed and the conscious perception of the stimulus occurs.

The spinothalamic tract also begins with neurons in a dorsal root ganglion. These neurons extend their axons to the dorsal horn, where they synapse with the second neuron in their respective pathway. The name "spinothalamic" comes from this second neuron, which has its cell body in the spinal cord gray matter and connects to the thalamus. Axons from these second neurons then decussate within the spinal cord and ascend to the brain and enter the thalamus, where each synapses with the third neuron in its respective pathway. The neurons in the thalamus then project their axons to the spinothalamic tract, which synapses in the postcentral gyrus of the cerebral cortex.

These two systems are similar in that they both begin with dorsal root ganglion cells, as with most general sensory information. The dorsal column system is primarily responsible for touch sensations and proprioception, whereas the spinothalamic tract pathway is primarily responsible for pain and temperature sensations. Another similarity is that the second neurons in both of these pathways are contralateral, because they project across the midline to the other side of the brain or spinal cord. In the dorsal column system, this decussation takes place in the brain stem; in the spinothalamic pathway, it takes place in the spinal cord at the same spinal cord level at which the information entered. The third neurons in the two pathways are essentially the same. In both, the second neuron synapses in the thalamus, and the thalamic neuron projects to the somatosensory cortex.

Ascending Sensory Pathways of the Spinal Cord

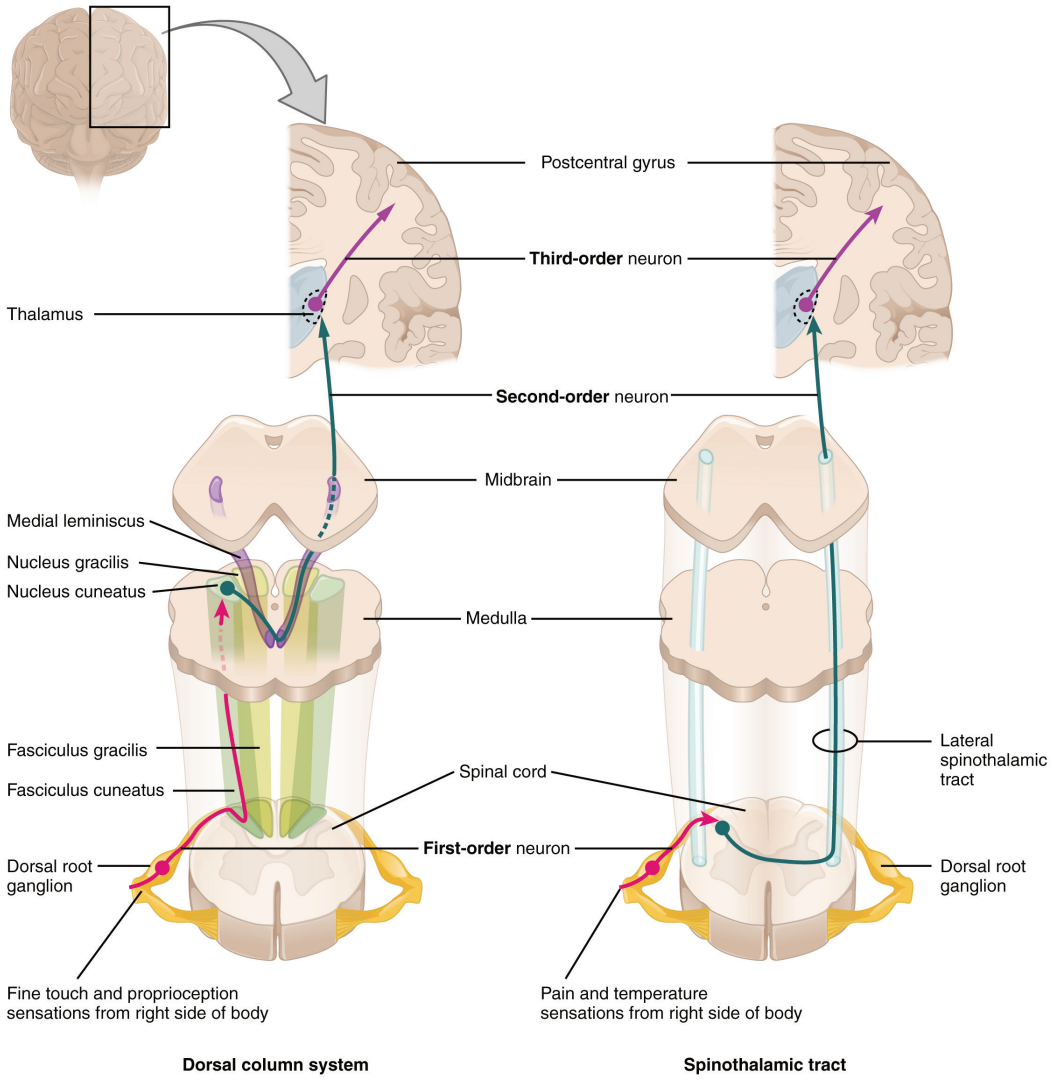


Figure 1. *The dorsal column system and spinothalamic tract are the major ascending pathways that connect the periphery with the brain.*

The trigeminal pathway carries somatosensory information from the face, head, mouth, and nasal cavity. As with the previously discussed nerve tracts, the sensory pathways of the trigeminal pathway each involve three successive neurons. First, axons from the trigeminal ganglion enter the brain stem at the level of the pons. These axons project to one of three locations. The **spinal trigeminal nucleus** of the medulla receives information similar to that carried by spinothalamic tract, such as pain and temperature sensations. Other axons go to either the **chief sensory nucleus** in the pons or the **mesencephalic nuclei** in the midbrain. These nuclei receive information like that carried by the dorsal column system, such as touch, pressure, vibration, and proprioception. Axons from the second neuron decussate and ascend to the thalamus along the trigeminothalamic tract. In the thalamus, each axon synapses with the third neuron in its respective pathway. Axons from the third neuron then project from the thalamus to the primary somatosensory cortex of the cerebrum.

The sensory pathway for gustation travels along the facial and glossopharyngeal cranial nerves, which synapse with neurons of the **solitary nucleus** in the brain stem. Axons from the solitary nucleus then project to the **ventral posterior nucleus** of the thalamus. Finally, axons from the ventral posterior nucleus project to the gustatory cortex of the cerebral cortex, where taste is processed and consciously perceived.

The sensory pathway for audition travels along the vestibulocochlear nerve, which synapses with neurons in the cochlear nuclei of the superior medulla. Within the brain stem, input from either ear is combined to extract location information from the auditory stimuli. Whereas the initial auditory stimuli received at the cochlea strictly represent the frequency—or pitch—of the stimuli, the locations of sounds can be determined by comparing information arriving at both ears.

Sound localization is a feature of central processing in the auditory nuclei of the brain stem. Sound localization is achieved by the brain calculating the **interaural time difference** and the **interaural intensity difference**. A sound originating from a specific location will arrive at each ear at different times, unless the sound is directly in front of the listener. If the sound source is slightly to the left of the listener, the sound will arrive at the left ear microseconds before it arrives at the right ear (Figure 2. Auditory Brain Stem Mechanisms of Sound Localizations). This time difference is an example of an interaural time difference. Also, the sound will be slightly louder in the left ear than in the right ear because some of the sound waves reaching the opposite ear are blocked by the head. This is an example of an interaural intensity difference.

Auditory Brain Stem Mechanisms of Sound Localization

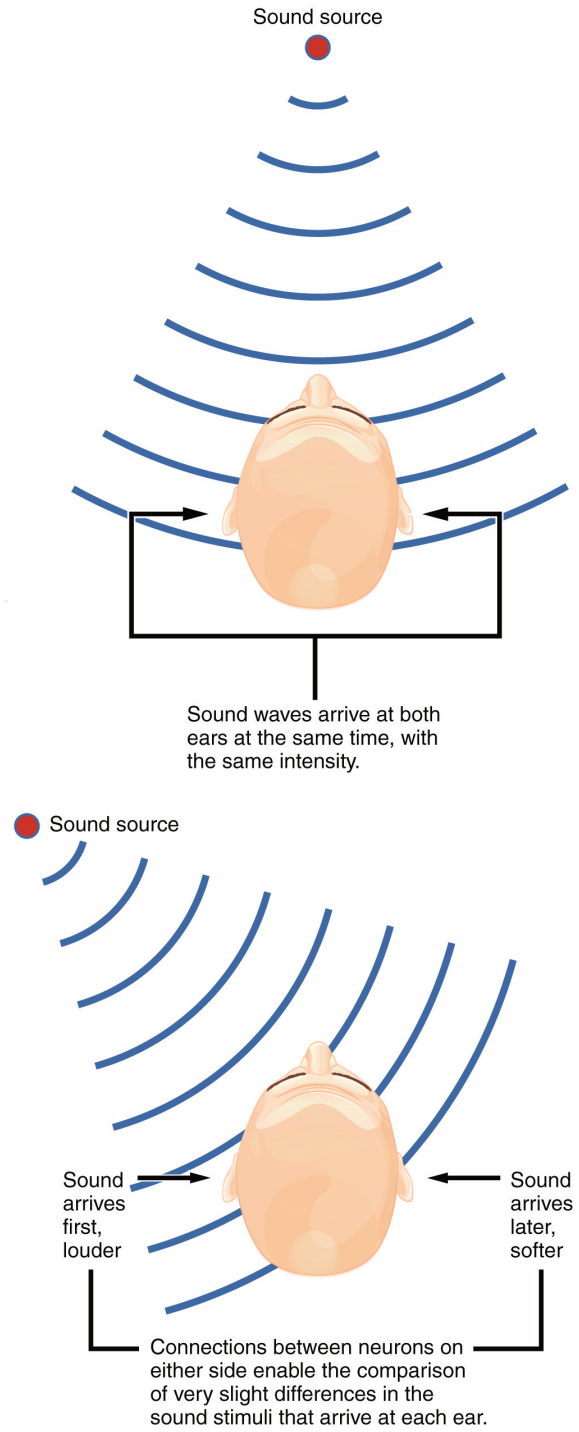


Figure 2. *Localizing sound in the horizontal plane is achieved by processing in the medullary nuclei of the auditory system. Connections between neurons on either side are able to compare very slight differences in sound stimuli that arrive at either ear and represent interaural time and intensity differences.*

Auditory processing continues on to a nucleus in the midbrain called the **inferior colliculus**. Axons from the inferior colliculus project to two locations, the thalamus and the **superior colliculus**. The **medial geniculate nucleus** of the thalamus receives the auditory information and then projects that information to the auditory

cortex in the temporal lobe of the cerebral cortex. The superior colliculus receives input from the visual and somatosensory systems, as well as the ears, to initiate stimulation of the muscles that turn the head and neck toward the auditory stimulus.

Balance is coordinated through the vestibular system, the nerves of which are composed of axons from the vestibular ganglion that carries information from the utricle, saccule, and semicircular canals. The system contributes to controlling head and neck movements in response to vestibular signals. An important function of the vestibular system is coordinating eye and head movements to maintain visual attention. Most of the axons terminate in the **vestibular nuclei** of the medulla. Some axons project from the vestibular ganglion directly to the cerebellum, with no intervening synapse in the vestibular nuclei. The cerebellum is primarily responsible for initiating movements on the basis of equilibrium information.

Neurons in the vestibular nuclei project their axons to targets in the brain stem. One target is the reticular formation, which influences respiratory and cardiovascular functions in relation to body movements. A second target of the axons of neurons in the vestibular nuclei is the spinal cord, which initiates the spinal reflexes involved with posture and balance. To assist the visual system, fibers of the vestibular nuclei project to the oculomotor, trochlear, and abducens nuclei to influence signals sent along the cranial nerves. These connections constitute the pathway of the **vestibulo-ocular reflex (VOR)**, which compensates for head and body movement by stabilizing images on the retina (Figure 3. Vestibulo-ocular Reflex). Finally, the vestibular nuclei project to the thalamus to join the proprioceptive pathway of the dorsal column system, allowing conscious perception of equilibrium.

Vestibulo-ocular Reflex

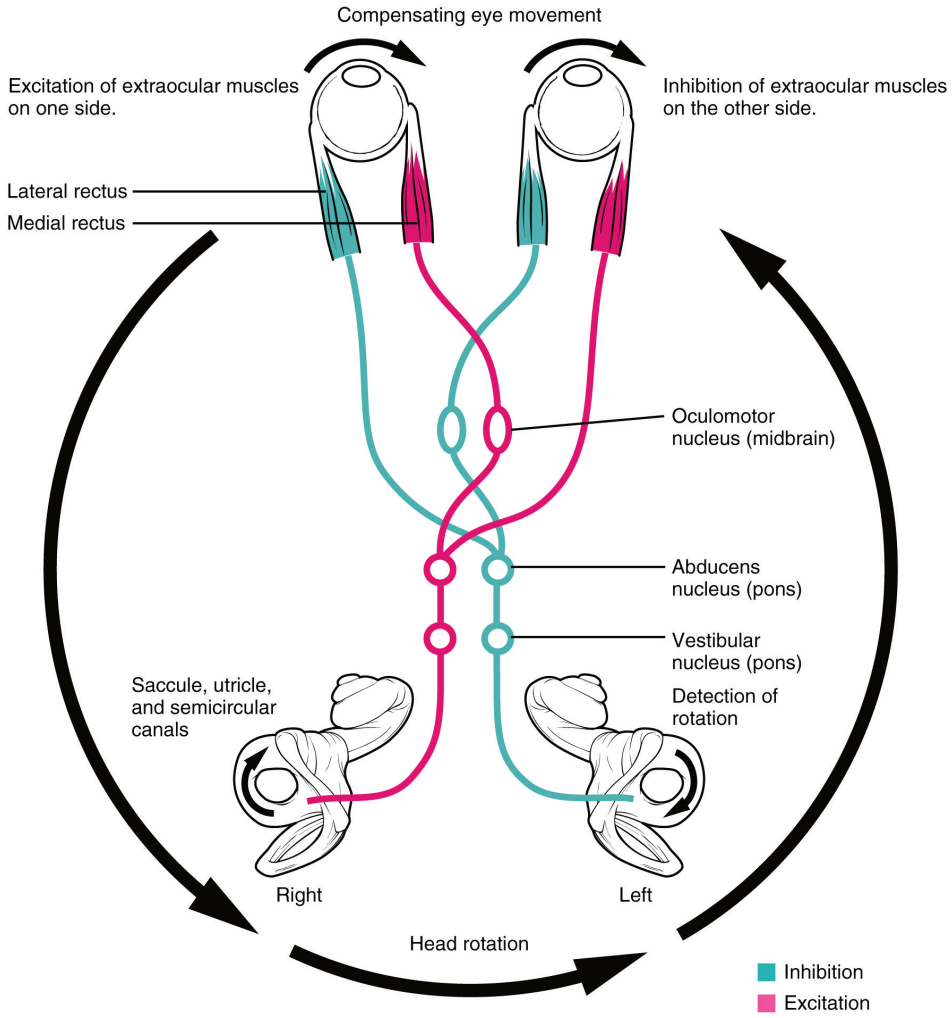


Figure 3. *Connections between the vestibular system and the cranial nerves controlling eye movement keep the eyes centered on a visual stimulus, even though the head is moving. During head movement, the eye muscles move the eyes in the opposite direction as the head movement, keeping the visual stimulus centered in the field of view.*

The connections of the optic nerve are more complicated than those of other cranial nerves. Instead of the connections being between each eye and the brain, visual information is segregated between the left and right sides of the visual field. In addition, some of the information from one side of the visual field projects to the opposite side of the brain. Within each eye, the axons projecting from the medial side of the retina decussate at the **optic chiasm**. For example, the axons from the medial retina of the left eye cross over to the right side of the brain at the optic chiasm. However, within each eye, the axons projecting from the lateral side of the retina do not decussate. For example, the axons from the lateral retina of the right eye project back to the right side of the brain. Therefore the left field of view of each eye is processed on the right side of the brain, whereas the right field of view of each eye is processed on the left side of the brain (Figure 4. Segregation of Visual Field Information).

Segregation of Visual Field Information at the Optic Chiasm

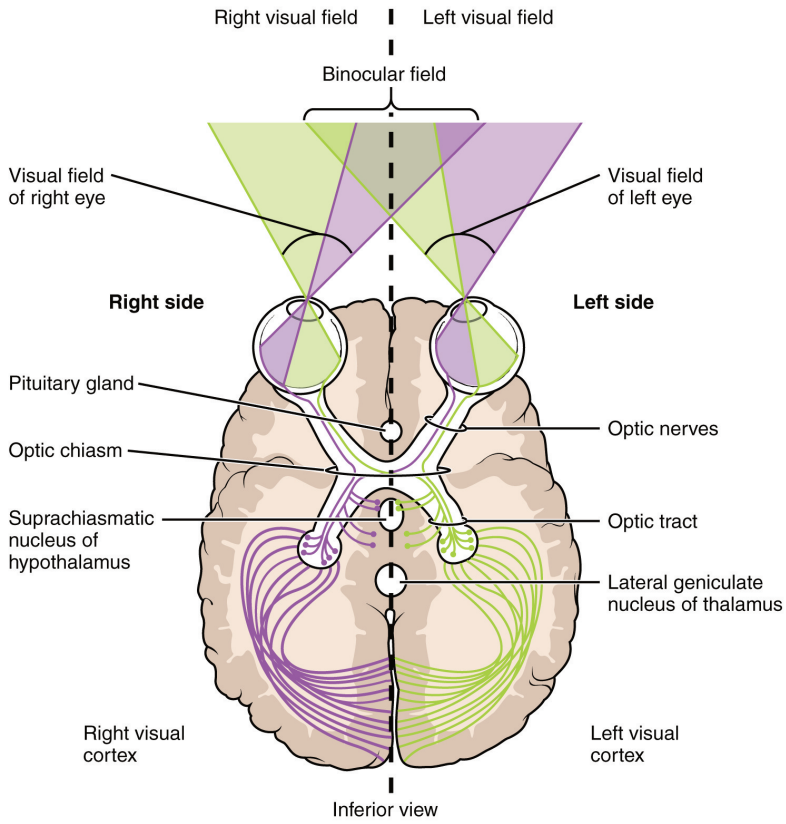


Figure 4. *Contralateral visual field information from the lateral retina projects to the ipsilateral brain, whereas ipsilateral visual field information has to decussate at the optic chiasm to reach the opposite side of the brain. (Note that this is an inferior view.)*

A unique clinical presentation that relates to this anatomic arrangement is the loss of lateral peripheral vision, known as bilateral hemianopia. This is different from "tunnel vision" because the superior and inferior peripheral fields are not lost. Visual field deficits can be disturbing for a patient, but in this case, the cause is not within the visual system itself. A growth of the pituitary gland presses against the optic chiasm and interferes with signal transmission. However, the axons projecting to the same side of the brain are unaffected. Therefore, the patient loses the outermost areas of their field of vision and cannot see objects to their right and left.

Extending from the optic chiasm, the axons of the visual system are referred to as the **optic tract** instead of the optic nerve. The optic tract has three major targets, two in the diencephalon and one in the midbrain. The connection between the eyes and diencephalon is demonstrated during development, in which the neural tissue of the retina differentiates from that of the diencephalon by the growth of the secondary vesicles. The connections of the retina into the CNS are a holdover from this developmental association. The majority of the connections of the optic tract are to the thalamus—specifically, the **lateral geniculate nucleus**. Axons from this nucleus then project to the visual cortex of the cerebrum, located in the occipital lobe. Another target of the optic tract is the superior colliculus.

In addition, a very small number of RGC axons project from the optic chiasm to the **suprachiasmatic nucleus** of the hypothalamus. These RGCs are photosensitive, in that they respond to the presence or absence of light. Unlike the photoreceptors, however, these photosensitive RGCs cannot be used to perceive images. By simply responding to the absence or presence of light, these RGCs can send information about day length. The

perceived proportion of sunlight to darkness establishes the **circadian rhythm** of our bodies, allowing certain physiological events to occur at approximately the same time every day.

Diencephalon

The diencephalon is beneath the cerebrum and includes the thalamus and hypothalamus. In the somatic nervous system, the thalamus is an important relay for communication between the cerebrum and the rest of the nervous system. The hypothalamus has both somatic and autonomic functions. In addition, the hypothalamus communicates with the limbic system, which controls emotions and memory functions.

Sensory input to the thalamus comes from most of the special senses and ascending somatosensory tracts. Each sensory system is relayed through a particular nucleus in the thalamus. The thalamus is a required transfer point for most sensory tracts that reach the cerebral cortex, where conscious sensory perception begins. The one exception to this rule is the olfactory system. The olfactory tract axons from the olfactory bulb project directly to the cerebral cortex, along with the limbic system and hypothalamus.

The thalamus is a collection of several nuclei that can be categorized into three anatomical groups. White matter running through the thalamus defines the three major regions of the thalamus, which are an anterior nucleus, a medial nucleus, and a lateral group of nuclei. The anterior nucleus serves as a relay between the hypothalamus and the emotion and memory-producing limbic system. The medial nuclei serve as a relay for information from the limbic system and basal ganglia to the cerebral cortex. This allows memory creation during learning, but also determines alertness. The special and somatic senses connect to the lateral nuclei, where their information is relayed to the appropriate sensory cortex of the cerebrum.

Cortical Processing

As described earlier, many of the sensory axons are positioned in the same way as their corresponding receptor cells in the body. This allows identification of the position of a stimulus on the basis of which receptor cells are sending information. The cerebral cortex also maintains this sensory topography in the particular areas of the cortex that correspond to the position of the receptor cells. The somatosensory cortex provides an example in which, in essence, the locations of the somatosensory receptors in the body are mapped onto the somatosensory cortex. This mapping is often depicted using a **sensory homunculus** (Figure 5. The Sensory Homunculus).

The term homunculus comes from the Latin word for “little man” and refers to a map of the human body that is laid across a portion of the cerebral cortex. In the somatosensory cortex, the external genitals, feet, and lower legs are represented on the medial face of the gyrus within the longitudinal fissure. As the gyrus curves out of the fissure and along the surface of the parietal lobe, the body map continues through the thighs, hips, trunk, shoulders, arms, and hands. The head and face are just lateral to the fingers as the gyrus approaches the lateral sulcus. The representation of the body in this topographical map is medial to lateral from the lower to upper body. It is a continuation of the topographical arrangement seen in the dorsal column system, where axons from the lower body are carried in the fasciculus gracilis, whereas axons from the upper body are carried in the fasciculus cuneatus. As the dorsal column system continues into the medial lemniscus, these relationships are maintained. Also, the head and neck axons running from the trigeminal nuclei to the thalamus run adjacent to the upper body fibers. The connections through the thalamus maintain topography such that the anatomic information is preserved. Note that this correspondence does not result in a perfectly miniature scale version of

the body, but rather exaggerates the more sensitive areas of the body, such as the fingers and lower face. Less sensitive areas of the body, such as the shoulders and back, are mapped to smaller areas on the cortex.

The Sensory Homunculus

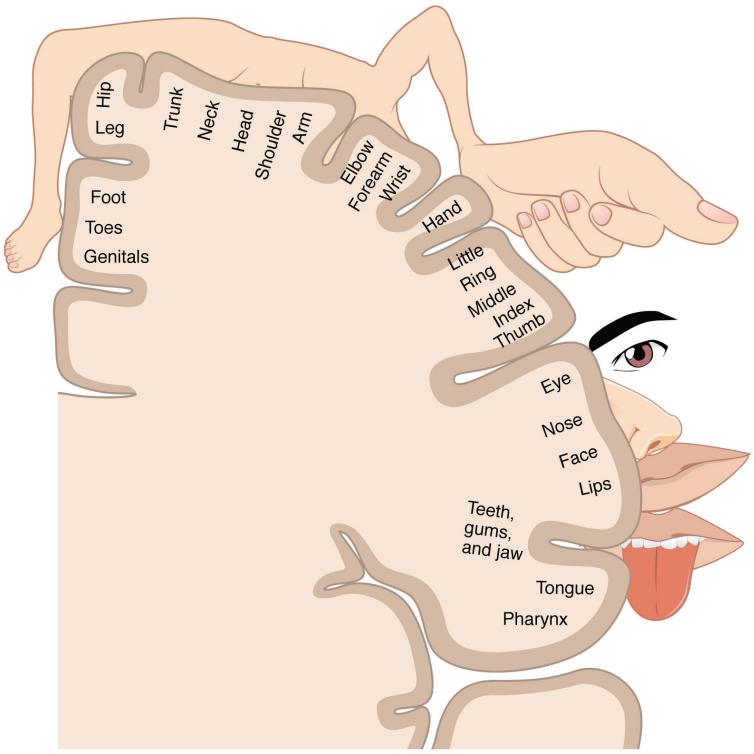


Figure 5. *A cartoon representation of the sensory homunculus arranged adjacent to the cortical region in which the processing takes place.*

Likewise, the topographic relationship between the retina and the visual cortex is maintained throughout the visual pathway. The visual field is projected onto the two retinae, as described above, with sorting at the optic chiasm. The right peripheral visual field falls on the medial portion of the right retina and the lateral portion of the left retina. The right medial retina then projects across the midline through the optic chiasm. This results in the right visual field being processed in the left visual cortex. Likewise, the left visual field is processed in the right visual cortex (see Figure 4. Segregation of Visual Field Information at the Optic Chiasm). Though the chiasm is helping to sort right and left visual information, superior and inferior visual information is maintained topographically in the visual pathway. Light from the superior visual field falls on the inferior retina, and light from the inferior visual field falls on the superior retina. This topography is maintained such that the superior region of the visual cortex processes the inferior visual field and vice versa. Therefore, the visual field information is inverted and reversed as it enters the visual cortex—up is down, and left is right. However, the cortex processes the visual information such that the final conscious perception of the visual field is correct. The topographic relationship is evident in that information from the foveal region of the retina is processed in the center of the primary visual cortex. Information from the peripheral regions of the retina are correspondingly processed toward the edges of the visual cortex. Similar to the exaggerations in the sensory homunculus of the somatosensory cortex, the foveal-processing area of the visual cortex is disproportionately larger than the areas processing peripheral vision.

In an experiment performed in the 1960s, subjects wore prism glasses so that the visual field was inverted before reaching the eye. On the first day of the experiment, subjects would duck when walking up to a table,

thinking it was suspended from the ceiling. However, after a few days of acclimation, the subjects behaved as if everything were represented correctly. Therefore, the visual cortex is somewhat flexible in adapting to the information it receives from our eyes (Figure 6. Topographic Mapping of the Retina onto the Visual Cortex).

Topographic Mapping of the Retina onto the Visual Cortex

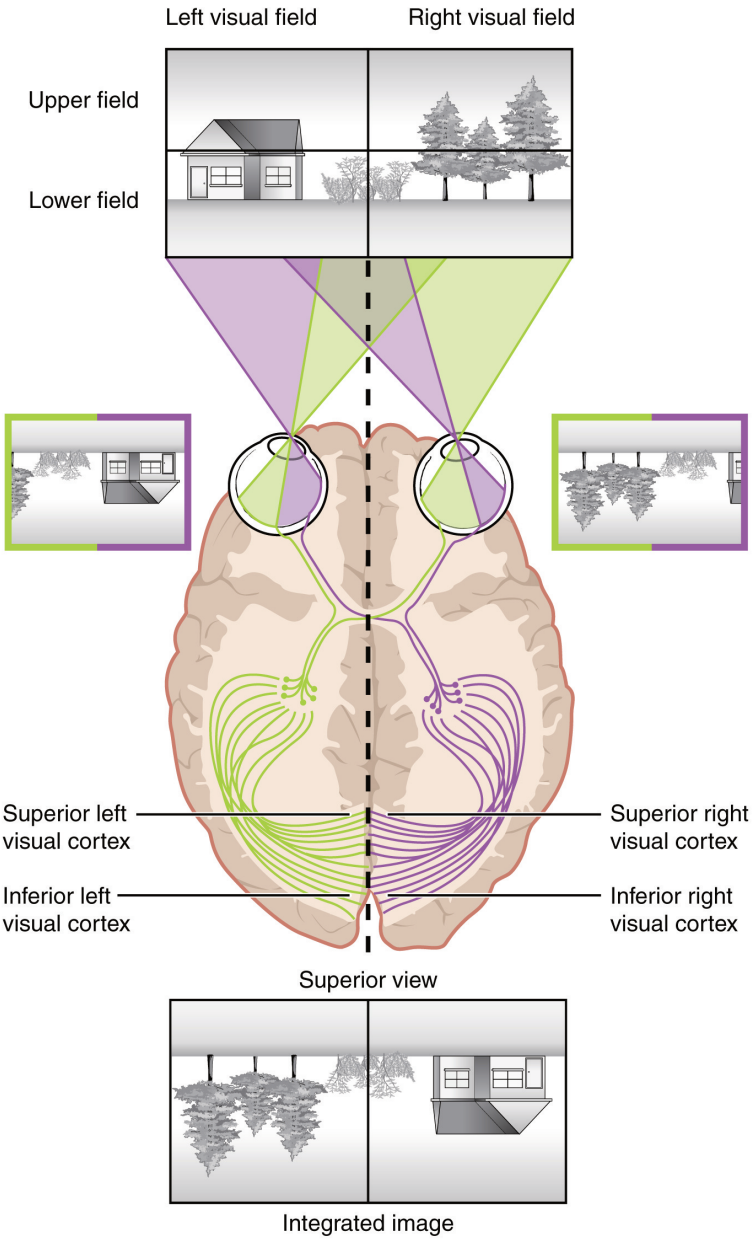


Figure 6. *The visual field projects onto the retina through the lenses and falls on the retinae as an inverted, reversed image. The topography of this image is maintained as the visual information travels through the visual pathway to the cortex.*

The cortex has been described as having specific regions that are responsible for processing specific information; there is the visual cortex, somatosensory cortex, gustatory cortex, etc. However, our experience of these senses is not divided. Instead, we experience what can be referred to as a seamless percept. Our

perceptions of the various sensory modalities—though distinct in their content—are integrated by the brain so that we experience the world as a continuous whole.

In the cerebral cortex, sensory processing begins at the **primary sensory cortex**, then proceeds to an **association area**, and finally, into a **multimodal integration area**. For example, the visual pathway projects from the retinae through the thalamus to the primary visual cortex in the occipital lobe. This area is primarily in the medial wall within the longitudinal fissure. Here, visual stimuli begin to be recognized as basic shapes. Edges of objects are recognized and built into more complex shapes. Also, inputs from both eyes are compared to extract depth information. Because of the overlapping field of view between the two eyes, the brain can begin to estimate the distance of stimuli based on **binocular depth cues**.

Watch this video to learn more about how the brain perceives 3-D motion. Similar to how retinal disparity offers 3-D moviegoers a way to extract 3-D information from the two-dimensional visual field projected onto the retina, the brain can extract information about movement in space by comparing what the two eyes see. If movement of a visual stimulus is leftward in one eye and rightward in the opposite eye, the brain interprets this as movement toward (or away) from the face along the midline. If both eyes see an object moving in the same direction, but at different rates, what would that mean for spatial movement?

EVERYDAY CONNECTIONS

Depth Perception, 3-D Movies, and Optical Illusions The visual field is projected onto the retinal surface, where photoreceptors transduce light energy into neural signals for the brain to interpret. The retina is a two-dimensional surface, so it does not encode three-dimensional information. However, we can perceive depth. How is that accomplished?

Two ways in which we can extract depth information from the two-dimensional retinal signal are based on monocular cues and binocular cues, respectively. Monocular depth cues are those that are the result of information within the two-dimensional visual field. One object that overlaps another object has to be in front. Relative size differences are also a cue. For example, if a basketball appears larger than the basket, then the basket must be further away. On the basis of experience, we can estimate how far away the basket is. Binocular depth cues compare information represented in the two retinae because they do not see the visual field exactly the same.

The centers of the two eyes are separated by a small distance, which is approximately 6 to 6.5 cm in most people. Because of this offset, visual stimuli do not fall on exactly the same spot on both retinae unless we are fixated directly on them and they fall on the fovea of each retina. All other objects in the visual field, either closer or farther away than the fixated object, will fall on different spots on the retina. When vision is fixed on an object in space, closer objects will fall on the lateral retina of each eye, and more distant objects will fall on the medial retina of either eye (Figure). This is easily observed by holding a finger up in front of your face as you look at a more distant object. You will see two images of your finger that represent the two disparate images that are falling on either retina.

These depth cues, both monocular and binocular, can be exploited to make the brain think there

are three dimensions in two-dimensional information. This is the basis of 3-D movies. The projected image on the screen is two dimensional, but it has disparate information embedded in it. The 3-D glasses that are available at the theater filter the information so that only one eye sees one version of what is on the screen, and the other eye sees the other version. If you take the glasses off, the image on the screen will have varying amounts of blur because both eyes are seeing both layers of information, and the third dimension will not be evident. Some optical illusions can take advantage of depth cues as well, though those are more often using monocular cues to fool the brain into seeing different parts of the scene as being at different depths.

Retinal Disparity

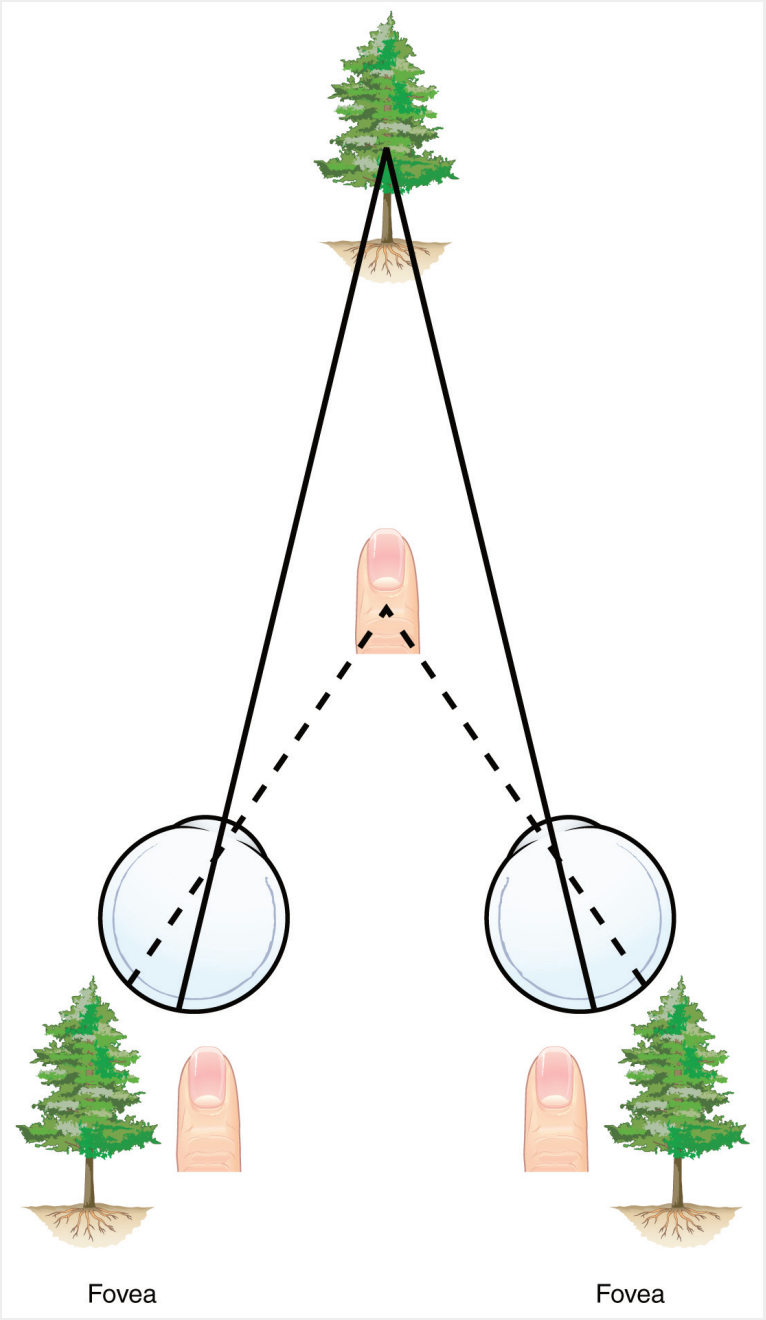


Figure 7. *Because of the interocular distance, which results in objects of different distances falling on different spots of the two retinae, the brain can extract depth perception from the two-dimensional information of the visual field.*

There are two main regions that surround the primary cortex that are usually referred to as areas V2 and V3 (the primary visual cortex is area V1). These surrounding areas are the visual association cortex. The visual association regions develop more complex visual perceptions by adding color and motion information. The

information processed in these areas is then sent to regions of the temporal and parietal lobes. Visual processing has two separate streams of processing: one into the temporal lobe and one into the parietal lobe. These are the ventral and dorsal streams, respectively (Figure 8. Ventral and Dorsal Visual Streams). The **ventral stream** identifies visual stimuli and their significance. Because the ventral stream uses temporal lobe structures, it begins to interact with the non-visual cortex and may be important in visual stimuli becoming part of memories. The **dorsal stream** locates objects in space and helps in guiding movements of the body in response to visual inputs. The dorsal stream enters the parietal lobe, where it interacts with somatosensory cortical areas that are important for our perception of the body and its movements. The dorsal stream can then influence frontal lobe activity where motor functions originate.

Ventral and Dorsal Visual Streams

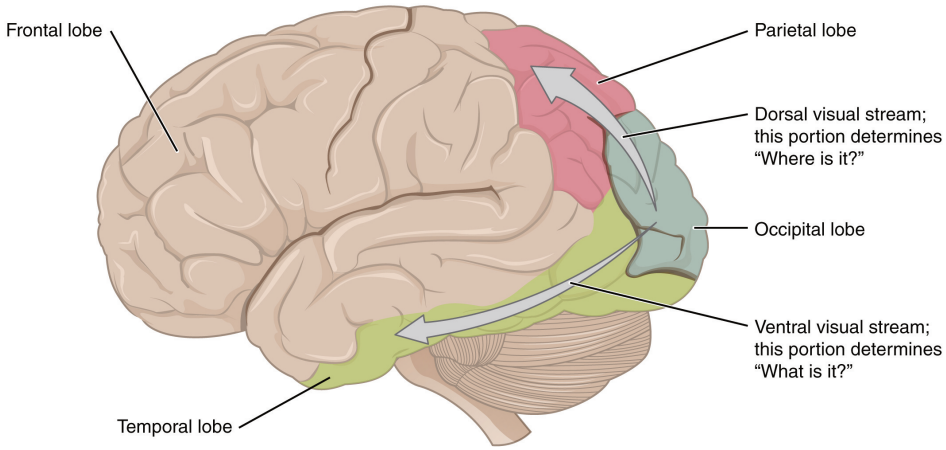


Figure 8. *From the primary visual cortex in the occipital lobe, visual processing continues in two streams—one into the temporal lobe and one into the parietal lobe.*

DISORDERS OF THE...

Brain: Prosopagnosia The failures of sensory perception can be unusual and debilitating. A particular sensory deficit that inhibits an important social function of humans is prosopagnosia, or face blindness. The word comes from the Greek words prosopa, that means "faces," and agnosia, that means "not knowing." Some people may feel that they cannot recognize people easily by their faces. However, a person with prosopagnosia cannot recognize the most recognizable people in their respective cultures. They would not recognize the face of a celebrity, an important historical figure, or even a family member like their mother. They may not even recognize their own face.

Prosopagnosia can be caused by trauma to the brain, or it can be present from birth. The exact cause of proposagnosia and the reason that it happens to some people is unclear. A study of the brains of people born with the deficit found that a specific region of the brain, the anterior fusiform gyrus of the temporal lobe, is often underdeveloped. This region of the brain is concerned with the recognition of visual stimuli and its possible association with memories. Though the evidence is not yet definitive, this region is likely to be where facial recognition occurs.

Though this can be a devastating condition, people who suffer from it can get by—often by using other cues to recognize the people they see. Often, the sound of a person's voice, or the presence of unique cues such as distinct facial features (a mole, for example) or hair color can help the sufferer

recognize a familiar person. In the video on prosopagnosia provided in this section, a woman is shown having trouble recognizing celebrities, family members, and herself. In some situations, she can use other cues to help her recognize faces.

The inability to recognize people by their faces is a troublesome problem. It can be caused by trauma, or it may be inborn. Watch this video to learn more about a person who lost the ability to recognize faces as the result of an injury. She cannot recognize the faces of close family members or herself. What other information can a person suffering from prosopagnosia use to figure out whom they are seeing?

Chapter Review

Sensory input to the brain enters through pathways that travel through either the spinal cord (for somatosensory input from the body) or the brain stem (for everything else, except the visual and olfactory systems) to reach the diencephalon. In the diencephalon, sensory pathways reach the thalamus. This is necessary for all sensory systems to reach the cerebral cortex, except for the olfactory system that is directly connected to the frontal and temporal lobes.

The two major tracts in the spinal cord, originating from sensory neurons in the dorsal root ganglia, are the dorsal column system and the spinothalamic tract. The major differences between the two are in the type of information that is relayed to the brain and where the tracts decussate. The dorsal column system primarily carries information about touch and proprioception and crosses the midline in the medulla. The spinothalamic tract is primarily responsible for pain and temperature sensation and crosses the midline in the spinal cord at the level at which it enters. The trigeminal nerve adds similar sensation information from the head to these pathways.

The auditory pathway passes through multiple nuclei in the brain stem in which additional information is extracted from the basic frequency stimuli processed by the cochlea. Sound localization is made possible through the activity of these brain stem structures. The vestibular system enters the brain stem and influences activity in the cerebellum, spinal cord, and cerebral cortex.

The visual pathway segregates information from the two eyes so that one half of the visual field projects to the other side of the brain. Within visual cortical areas, the perception of the stimuli and their location is passed along two streams, one ventral and one dorsal. The ventral visual stream connects to structures in the temporal lobe that are important for long-term memory formation. The dorsal visual stream interacts with the somatosensory cortex in the parietal lobe, and together they can influence the activity in the frontal lobe to generate movements of the body in relation to visual information.

Motor Responses

By the end of this section, you will be able to:

- List the components of the basic processing stream for the motor system
- Describe the pathway of descending motor commands from the cortex to the skeletal muscles
- Compare different descending pathways, both by structure and function
- Explain the initiation of movement from the neurological connections
- Describe several reflex arcs and their functional roles

The defining characteristic of the somatic nervous system is that it controls skeletal muscles. Somatic senses inform the nervous system about the external environment, but the response to that is through voluntary muscle movement. The term "voluntary" suggests that there is a conscious decision to make a movement. However, some aspects of the somatic system use voluntary muscles without conscious control. One example is the ability of our breathing to switch to unconscious control while we are focused on another task. However, the muscles that are responsible for the basic process of breathing are also utilized for speech, which is entirely voluntary.

Cortical Responses

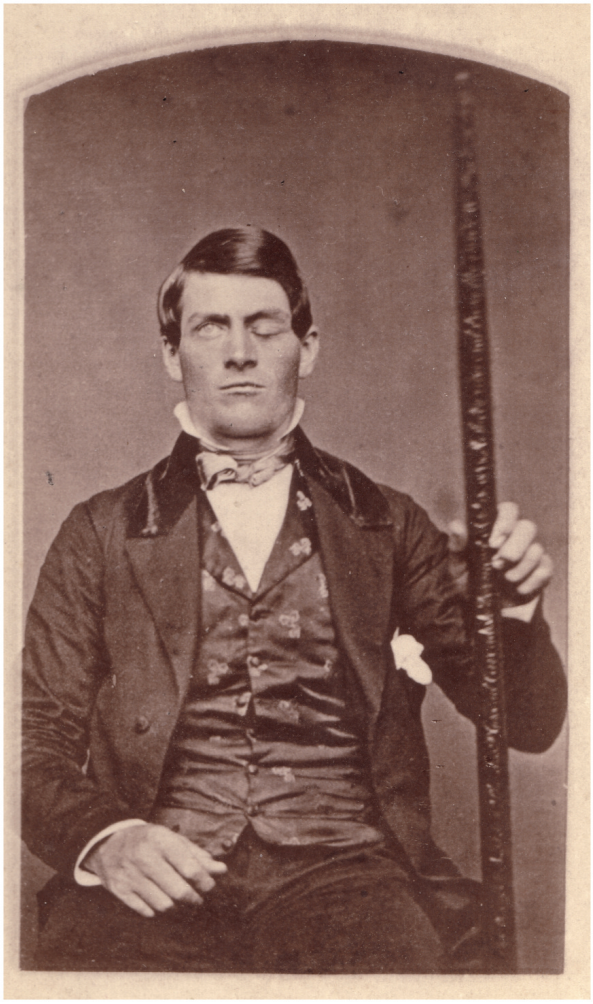
Let's start with sensory stimuli that have been registered through receptor cells and the information relayed to the CNS along ascending pathways. In the cerebral cortex, the initial processing of sensory perception progresses to associative processing and then integration in multimodal areas of cortex. These levels of processing can lead to the incorporation of sensory perceptions into memory, but more importantly, they lead to a response. The completion of cortical processing through the primary, associative, and integrative sensory areas initiates a similar progression of motor processing, usually in different cortical areas.

Whereas the sensory cortical areas are located in the occipital, temporal, and parietal lobes, motor functions are largely controlled by the frontal lobe. The most anterior regions of the frontal lobe—the prefrontal areas—are important for **executive functions**, which are those cognitive functions that lead to goal-directed behaviors. These higher cognitive processes include **working memory**, which has been called a "mental scratch pad," that can help organize and represent information that is not in the immediate environment. The prefrontal lobe is responsible for aspects of attention, such as inhibiting distracting thoughts and actions so that a person can focus on a goal and direct behavior toward achieving that goal.

The functions of the prefrontal cortex are integral to the personality of an individual, because it is largely responsible for what a person intends to do and how they accomplish those plans. A famous case of damage to the prefrontal cortex is that of Phineas Gage, dating back to 1848. He was a railroad worker who had a metal spike impale his prefrontal cortex (Figure 1. Phineas Gage). He survived the accident, but according to second-hand accounts, his personality changed drastically. Friends described him as no longer acting like himself. Whereas he was a hardworking, amiable man before the accident, he turned into an irritable, temperamental, and lazy man after the accident. Many of the accounts of his change may have been inflated in the retelling, and some behavior

was likely attributable to alcohol used as a pain medication. However, the accounts suggest that some aspects of his personality did change. Also, there is new evidence that though his life changed dramatically, he was able to become a functioning stagecoach driver, suggesting that the brain has the ability to recover even from major trauma such as this.

Phineas Gage



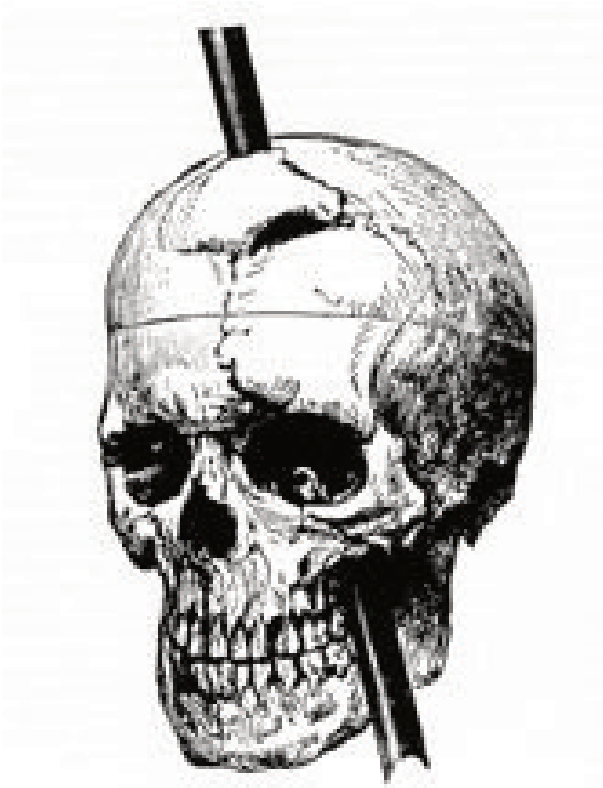


Figure 1. *The victim of an accident while working on a railroad in 1848, Phineas Gage had a large iron rod impaled through the prefrontal cortex of his frontal lobe. After the accident, his personality appeared to change, but he eventually learned to cope with the trauma and lived as a coach driver even after such a traumatic event. (credit b: John M. Harlow, MD)*

Secondary Motor Cortices

In generating motor responses, the executive functions of the prefrontal cortex will need to initiate actual movements. One way to define the prefrontal area is any region of the frontal lobe that does not elicit movement when electrically stimulated. These are primarily in the anterior part of the frontal lobe. The regions of the frontal lobe that remain are the regions of the cortex that produce movement. The prefrontal areas project into the secondary motor cortices, which include the **premotor cortex** and the **supplemental motor area**.

Two important regions that assist in planning and coordinating movements are located adjacent to the primary motor cortex. The premotor cortex is more lateral, whereas the supplemental motor area is more medial and superior. The premotor area aids in controlling movements of the core muscles to maintain posture during movement, whereas the supplemental motor area is hypothesized to be responsible for planning and coordinating movement. The supplemental motor area also manages sequential movements that are based on prior experience (that is, learned movements). Neurons in these areas are most active leading up to the initiation of movement. For example, these areas might prepare the body for the movements necessary to drive a car in anticipation of a traffic light changing.

Adjacent to these two regions are two specialized motor planning centers. The **frontal eye fields** are

responsible for moving the eyes in response to visual stimuli. There are direct connections between the frontal eye fields and the superior colliculus. Also, anterior to the premotor cortex and primary motor cortex is **Broca's area**. This area is responsible for controlling movements of the structures of speech production. The area is named after a French surgeon and anatomist who studied patients who could not produce speech. They did not have impairments to understanding speech, only to producing speech sounds, suggesting a damaged or underdeveloped Broca's area.

Primary Motor Cortex

The primary motor cortex is located in the precentral gyrus of the frontal lobe. A neurosurgeon, Walter Penfield, described much of the basic understanding of the primary motor cortex by electrically stimulating the surface of the cerebrum. Penfield would probe the surface of the cortex while the patient was only under local anesthesia so that he could observe responses to the stimulation. This led to the belief that the precentral gyrus directly stimulated muscle movement. We now know that the primary motor cortex receives input from several areas that aid in planning movement, and its principle output stimulates spinal cord neurons to stimulate skeletal muscle contraction.

The primary motor cortex is arranged in a similar fashion to the primary somatosensory cortex, in that it has a topographical map of the body, creating a motor homunculus (see [link]). The neurons responsible for musculature in the feet and lower legs are in the medial wall of the precentral gyrus, with the thighs, trunk, and shoulder at the crest of the longitudinal fissure. The hand and face are in the lateral face of the gyrus. Also, the relative space allotted for the different regions is exaggerated in muscles that have greater enervation. The greatest amount of cortical space is given to muscles that perform fine, agile movements, such as the muscles of the fingers and the lower face. The "power muscles" that perform coarser movements, such as the buttock and back muscles, occupy much less space on the motor cortex.

Descending Pathways

The motor output from the cortex descends into the brain stem and to the spinal cord to control the musculature through motor neurons. Neurons located in the primary motor cortex, named **Betz cells**, are large cortical neurons that synapse with lower motor neurons in the brain stem or in the spinal cord. The two descending pathways travelled by the axons of Betz cells are the **corticobulbar tract** and the **corticospinal tract**, respectively. Both tracts are named for their origin in the cortex and their targets—either the brain stem (the term "bulbar" refers to the brain stem as the bulb, or enlargement, at the top of the spinal cord) or the spinal cord.

These two descending pathways are responsible for the conscious or voluntary movements of skeletal muscles. Any motor command from the primary motor cortex is sent down the axons of the Betz cells to activate upper motor neurons in either the cranial motor nuclei or in the ventral horn of the spinal cord. The axons of the corticobulbar tract are ipsilateral, meaning they project from the cortex to the motor nucleus on the same side of the nervous system. Conversely, the axons of the corticospinal tract are largely contralateral, meaning that they cross the midline of the brain stem or spinal cord and synapse on the opposite side of the body. Therefore, the right motor cortex of the cerebrum controls muscles on the left side of the body, and vice versa.

The corticospinal tract descends from the cortex through the deep white matter of the cerebrum. It then

passes between the caudate nucleus and putamen of the basal nuclei as a bundle called the **internal capsule**. The tract then passes through the midbrain as the **cerebral peduncles**, after which it burrows through the pons. Upon entering the medulla, the tracts make up the large white matter tract referred to as the **pyramids** (Figure 2. Corticospinal Tract). The defining landmark of the medullary-spinal border is the **pyramidal decussation**, which is where most of the fibers in the corticospinal tract cross over to the opposite side of the brain. At this point, the tract separates into two parts, which have control over different domains of the musculature.

Corticospinal Tract

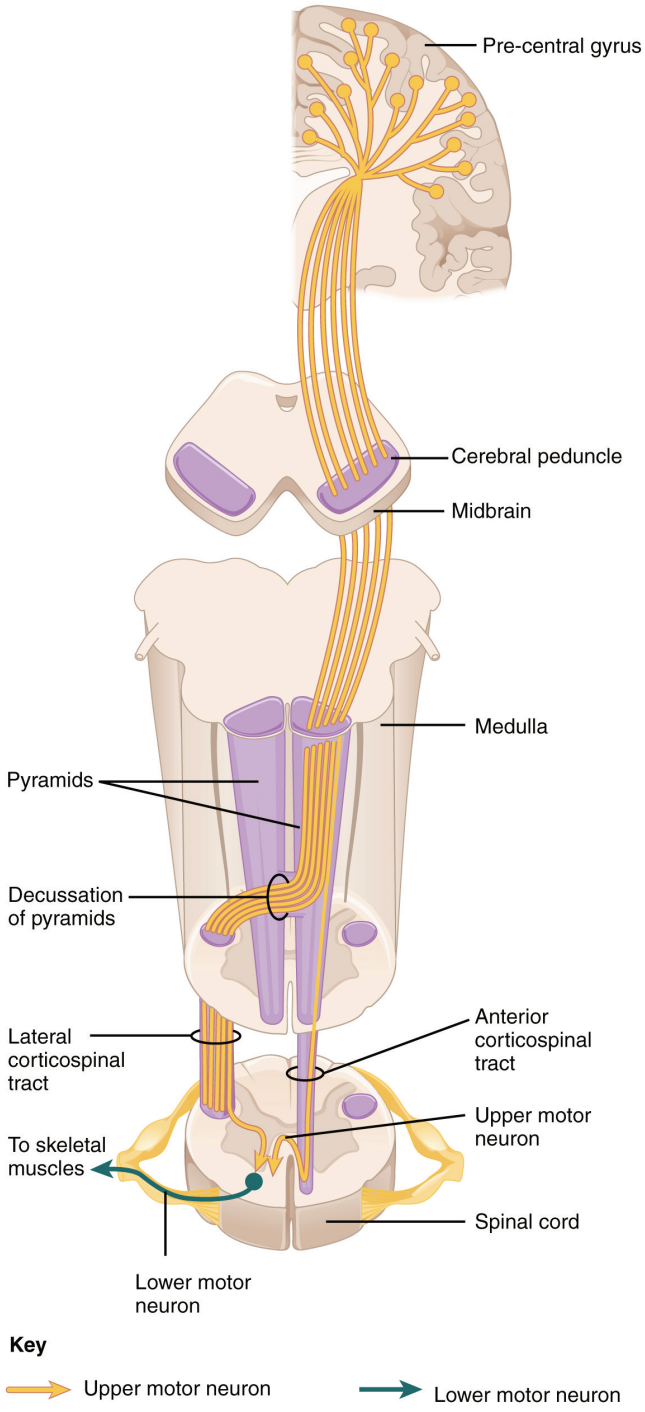


Figure 2. *The major descending tract that controls skeletal muscle movements is the corticospinal tract. It is composed of two neurons, the upper motor neuron and the lower motor neuron. The upper motor neuron has its cell body in the primary motor cortex of the frontal lobe and synapses on the lower motor neuron, which is in the ventral horn of the spinal cord and projects to the skeletal muscle in the periphery.*

Appendicular Control

The **lateral corticospinal tract** is composed of the fibers that cross the midline at the pyramidal decussation (see Figure 2. Corticospinal Tract). The axons cross over from the anterior position of the pyramids in the medulla to the lateral column of the spinal cord. These axons are responsible for controlling appendicular muscles.

This influence over the appendicular muscles means that the lateral corticospinal tract is responsible for moving the muscles of the arms and legs. The ventral horn in both the lower cervical spinal cord and the lumbar spinal cord both have wider ventral horns, representing the greater number of muscles controlled by these motor neurons. The **cervical enlargement** is particularly large because there is greater control over the fine musculature of the upper limbs, particularly of the fingers. The **lumbar enlargement** is not as significant in appearance because there is less fine motor control of the lower limbs.

Axial Control

The **anterior corticospinal tract** is responsible for controlling the muscles of the body trunk (see Figure 2. Corticospinal Tract). These axons do not decussate in the medulla. Instead, they remain in an anterior position as they descend the brain stem and enter the spinal cord. These axons then travel to the spinal cord level at which they synapse with a lower motor neuron. Upon reaching the appropriate level, the axons decussate, entering the ventral horn on the opposite side of the spinal cord from which they entered. In the ventral horn, these axons synapse with their corresponding lower motor neurons. The lower motor neurons are located in the medial regions of the ventral horn, because they control the axial muscles of the trunk.

Because movements of the body trunk involve both sides of the body, the anterior corticospinal tract is not entirely contralateral. Some collateral branches of the tract will project into the ipsilateral ventral horn to control synergistic muscles on that side of the body, or to inhibit antagonistic muscles through interneurons within the ventral horn. Through the influence of both sides of the body, the anterior corticospinal tract can coordinate postural muscles in broad movements of the body. These coordinating axons in the anterior corticospinal tract are often considered bilateral, as they are both ipsilateral and contralateral.

> Watch this video to learn more about the descending motor pathway for the somatic nervous system. The autonomic connections are mentioned, which are covered in another chapter. From this brief video, only some of the descending motor pathway of the somatic nervous system is described. Which division of the pathway is described and which division is left out?

Extrapyramidal Controls

Other descending connections between the brain and the spinal cord are called the **extrapyramidal system**. The name comes from the fact that this system is outside the corticospinal pathway, which includes the pyramids in the medulla. A few pathways originating from the brain stem contribute to this system.

The **tectospinal tract** projects from the midbrain to the spinal cord and is important for postural movements that are driven by the superior colliculus. The name of the tract comes from an alternate name for the superior colliculus, which is the tectum. The **reticulospinal tract** connects the reticular system, a diffuse region of gray matter in the brain stem, with the spinal cord. This tract influences trunk and proximal limb muscles related to posture and locomotion. The reticulospinal tract also contributes to muscle tone and influences autonomic functions. The **vestibulospinal tract** connects the brain stem nuclei of the vestibular system with the spinal cord. This allows posture, movement, and balance to be modulated on the basis of equilibrium information provided by the vestibular system.

The pathways of the extrapyramidal system are influenced by subcortical structures. For example, connections between the secondary motor cortices and the extrapyramidal system modulate spine and cranium movements. The basal nuclei, which are important for regulating movement initiated by the CNS, influence the extrapyramidal system as well as its thalamic feedback to the motor cortex.

The conscious movement of our muscles is more complicated than simply sending a single command from the precentral gyrus down to the proper motor neurons. During the movement of any body part, our muscles relay information back to the brain, and the brain is constantly sending "revised" instructions back to the muscles. The cerebellum is important in contributing to the motor system because it compares cerebral motor commands with proprioceptive feedback. The corticospinal fibers that project to the ventral horn of the spinal cord have branches that also synapse in the pons, which project to the cerebellum. Also, the proprioceptive sensations of the dorsal column system have a collateral projection to the medulla that projects to the cerebellum. These two streams of information are compared in the cerebellar cortex. Conflicts between the motor commands sent by the cerebrum and body position information provided by the proprioceptors cause the cerebellum to stimulate the red nucleus of the midbrain. The **red nucleus** then sends corrective commands to the spinal cord along the **rubrospinal tract**. The name of this tract comes from the word for red that is seen in the English word "ruby."

A good example of how the cerebellum corrects cerebral motor commands can be illustrated by walking in water. An original motor command from the cerebrum to walk will result in a highly coordinated set of learned movements. However, in water, the body cannot actually perform a typical walking movement as instructed. The cerebellum can alter the motor command, stimulating the leg muscles to take larger steps to overcome the water resistance. The cerebellum can make the necessary changes through the rubrospinal tract. Modulating the basic command to walk also relies on spinal reflexes, but the cerebellum is responsible for calculating the appropriate response. When the cerebellum does not work properly, coordination and balance are severely affected. The most dramatic example of this is during the overconsumption of alcohol. Alcohol inhibits the ability of the cerebellum to interpret proprioceptive feedback, making it more difficult to coordinate body movements, such as walking a straight line, or guide the movement of the hand to touch the tip of the nose.

Visit this site to read about an elderly woman who starts to lose the ability to control fine movements, such as speech and the movement of limbs. Many of the usual causes were ruled out. It was not a stroke, Parkinson's disease, diabetes, or thyroid dysfunction. The next most obvious cause

was medication, so her pharmacist had to be consulted. The side effect of a drug meant to help her sleep had resulted in changes in motor control. What regions of the nervous system are likely to be the focus of haloperidol side effects?

Ventral Horn Output

The somatic nervous system provides output strictly to skeletal muscles. The lower motor neurons, which are responsible for the contraction of these muscles, are found in the ventral horn of the spinal cord. These large, multipolar neurons have a corona of dendrites surrounding the cell body and an axon that extends out of the ventral horn. This axon travels through the ventral nerve root to join the emerging spinal nerve. The axon is relatively long because it needs to reach muscles in the periphery of the body. The diameters of cell bodies may be on the order of hundreds of micrometers to support the long axon; some axons are a meter in length, such as the lumbar motor neurons that innervate muscles in the first digits of the feet.

The axons will also branch to innervate multiple muscle fibers. Together, the motor neuron and all the muscle fibers that it controls make up a motor unit. Motor units vary in size. Some may contain up to 1000 muscle fibers, such as in the quadriceps, or they may only have 10 fibers, such as in an extraocular muscle. The number of muscle fibers that are part of a motor unit corresponds to the precision of control of that muscle. Also, muscles that have finer motor control have more motor units connecting to them, and this requires a larger topographical field in the primary motor cortex.

Motor neuron axons connect to muscle fibers at a neuromuscular junction. This is a specialized synaptic structure at which multiple axon terminals synapse with the muscle fiber sarcolemma. The synaptic end bulbs of the motor neurons secrete acetylcholine, which binds to receptors on the sarcolemma. The binding of acetylcholine opens ligand-gated ion channels, increasing the movement of cations across the sarcolemma. This depolarizes the sarcolemma, initiating muscle contraction. Whereas other synapses result in graded potentials that must reach a threshold in the postsynaptic target, activity at the neuromuscular junction reliably leads to muscle fiber contraction with every nerve impulse received from a motor neuron. However, the strength of contraction and the number of fibers that contract can be affected by the frequency of the motor neuron impulses.

Reflexes

This chapter began by introducing reflexes as an example of the basic elements of the somatic nervous system. Simple somatic reflexes do not include the higher centers discussed for conscious or voluntary aspects of movement. Reflexes can be spinal or cranial, depending on the nerves and central components that are involved. The example described at the beginning of the chapter involved heat and pain sensations from a hot stove causing withdrawal of the arm through a connection in the spinal cord that leads to contraction of the biceps brachii. The description of this withdrawal reflex was simplified, for the sake of the introduction, to emphasize the parts of the somatic nervous system. But to consider reflexes fully, more attention needs to be given to this example.

As you withdraw your hand from the stove, you do not want to slow that reflex down. As the biceps brachii contracts, the antagonistic triceps brachii needs to relax. Because the neuromuscular junction is strictly excitatory, the biceps will contract when the motor nerve is active. Skeletal muscles do not actively relax. Instead the motor neuron needs to "quiet down," or be inhibited. In the hot-stove withdrawal reflex, this occurs through an interneuron in the spinal cord. The interneuron's cell body is located in the dorsal horn of the spinal cord. The interneuron receives a synapse from the axon of the sensory neuron that detects that the hand is being burned. In response to this stimulation from the sensory neuron, the interneuron then inhibits the motor neuron that controls the triceps brachii. This is done by releasing a neurotransmitter or other signal that hyperpolarizes the motor neuron connected to the triceps brachii, making it less likely to initiate an action potential. With this motor neuron being inhibited, the triceps brachii relaxes. Without the antagonistic contraction, withdrawal from the hot stove is faster and keeps further tissue damage from occurring.

Another example of a withdrawal reflex occurs when you step on a painful stimulus, like a tack or a sharp rock. The nociceptors that are activated by the painful stimulus activate the motor neurons responsible for contraction of the tibialis anterior muscle. This causes dorsiflexion of the foot. An inhibitory interneuron, activated by a collateral branch of the nociceptor fiber, will inhibit the motor neurons of the gastrocnemius and soleus muscles to cancel plantar flexion. An important difference in this reflex is that plantar flexion is most likely in progress as the foot is pressing down onto the tack. Contraction of the tibialis anterior is not the most important aspect of the reflex, as continuation of plantar flexion will result in further damage from stepping onto the tack.

Another type of reflex is a **stretch reflex**. In this reflex, when a skeletal muscle is stretched, a muscle spindle receptor is activated. The axon from this receptor structure will cause direct contraction of the muscle. A collateral of the muscle spindle fiber will also inhibit the motor neuron of the antagonist muscles. The reflex helps to maintain muscles at a constant length. A common example of this reflex is the knee jerk that is elicited by a rubber hammer struck against the patellar ligament in a physical exam.

A specialized reflex to protect the surface of the eye is the **corneal reflex**, or the eye blink reflex. When the cornea is stimulated by a tactile stimulus, or even by bright light in a related reflex, blinking is initiated. The sensory component travels through the trigeminal nerve, which carries somatosensory information from the face, or through the optic nerve, if the stimulus is bright light. The motor response travels through the facial nerve and innervates the orbicularis oculi on the same side. This reflex is commonly tested during a physical exam using an air puff or a gentle touch of a cotton-tipped applicator.

Watch this video to learn more about the reflex arc of the corneal reflex. When the right cornea senses a tactile stimulus, what happens to the left eye? Explain your answer.

Watch this video to learn more about newborn reflexes. Newborns have a set of reflexes that are expected to have been crucial to survival before the modern age. These reflexes disappear as the baby grows, as some of them may be unnecessary as they age. The video demonstrates a reflex called the Babinski reflex, in which the foot flexes dorsally and the toes splay out when the sole of the foot is lightly scratched. This is normal for newborns, but it is a sign of reduced myelination of the spinal tract in adults. Why would this reflex be a problem for an adult?

Chapter Review

The motor components of the somatic nervous system begin with the frontal lobe of the brain, where the prefrontal cortex is responsible for higher functions such as working memory. The integrative and associate functions of the prefrontal lobe feed into the secondary motor areas, which help plan movements. The premotor cortex and supplemental motor area then feed into the primary motor cortex that initiates movements. Large Betz cells project through the corticobulbar and corticospinal tracts to synapse on lower motor neurons in the brain stem and ventral horn of the spinal cord, respectively. These connections are responsible for generating movements of skeletal muscles.

The extrapyramidal system includes projections from the brain stem and higher centers that influence movement, mostly to maintain balance and posture, as well as to maintain muscle tone. The superior colliculus and red nucleus in the midbrain, the vestibular nuclei in the medulla, and the reticular formation throughout the brain stem each have tracts projecting to the spinal cord in this system. Descending input from the secondary motor cortices, basal nuclei, and cerebellum connect to the origins of these tracts in the brain stem.

All of these motor pathways project to the spinal cord to synapse with motor neurons in the ventral horn of the spinal cord. These lower motor neurons are the cells that connect to skeletal muscle and cause contractions. These neurons project through the spinal nerves to connect to the muscles at neuromuscular junctions. One motor neuron connects to multiple muscle fibers within a target muscle. The number of fibers that are innervated by a single motor neuron varies on the basis of the precision necessary for that muscle and the amount of force necessary for that motor unit. The quadriceps, for example, have many fibers controlled by single motor neurons for powerful contractions that do not need to be precise. The extraocular muscles have only a small number of fibers controlled by each motor neuron because moving the eyes does not require much force, but needs to be very precise.

Reflexes are the simplest circuits within the somatic nervous system. A withdrawal reflex from a painful stimulus only requires the sensory fiber that enters the spinal cord and the motor neuron that projects to a muscle. Antagonist and postural muscles can be coordinated with the withdrawal, making the connections more complex. The simple, single neuronal connection is the basis of somatic reflexes. The corneal reflex is contraction of the orbicularis oculi muscle to blink the eyelid when something touches the surface of the eye. Stretch reflexes maintain a constant length of muscles by causing a contraction of a muscle to compensate for a stretch that can be sensed by a specialized receptor called a muscle spindle.

License

1.5 The Autonomic Nervous System

Introduction

Fight or Flight?

Figure 1. *Though the threats that modern humans face are not large predators, the autonomic nervous system is adapted to this type of stimulus. The modern world presents stimuli that trigger the same response. (credit: Vernon Swanepoel)*

After studying this chapter, you will be able to:

- Describe the components of the autonomic nervous system
- Differentiate between the structures of the sympathetic and parasympathetic divisions in the autonomic nervous system
- Name the components of a visceral reflex specific to the autonomic division to which it belongs
- Predict the response of a target effector to autonomic input on the basis of the released signaling molecule
- Describe how the central nervous system coordinates and contributes to autonomic functions

The autonomic nervous system is often associated with the "fight-or-flight response," which refers to the preparation of the body to either run away from a threat or to stand and fight in the face of that threat. To suggest what this means, consider the (very unlikely) situation of seeing a lioness hunting out on the savannah. Though this is not a common threat that humans deal with in the modern world, it represents the type of environment in which the human species thrived and adapted. The spread of humans around the world to the present state of the modern age occurred much more quickly than any species would adapt to environmental pressures such as predators. However, the reactions modern humans have in the modern world are based on these prehistoric situations. If your boss is walking down the hallway on Friday afternoon looking for "volunteers" to come in on the weekend, your response is the same as the prehistoric human seeing the lioness running across the savannah: fight or flight.

Most likely, your response to your boss—not to mention the lioness—would be flight. Run away! The autonomic system is responsible for the physiological response to make that possible, and hopefully successful. Adrenaline starts to flood your circulatory system. Your heart rate increases. Sweat glands become active. The bronchi of the lungs dilate to allow more air exchange. Pupils dilate to increase visual information. Blood pressure increases in general, and blood vessels dilate in skeletal muscles. Time to run. Similar physiological responses would occur in preparation for fighting off the threat.

This response should sound a bit familiar. The autonomic nervous system is tied into emotional responses as well, and the fight-or-flight response probably sounds like a panic attack. In the modern world, these sorts of reactions are associated with anxiety as much as with response to a threat. It is engrained in the nervous system to respond like this. In fact, the adaptations of the autonomic nervous system probably predate the human species and are likely to be common to all mammals, and perhaps shared by many animals. That lioness might herself be threatened in some other situation.

However, the autonomic nervous system is not just about responding to threats. Besides the fight-or-flight response, there are the responses referred to as "rest and digest." If that lioness is successful in her hunting, then she is going to rest from the exertion. Her heart rate will slow. Breathing will return to normal. The digestive system has a big job to do. Much of the function of the autonomic system is based on the connections within an autonomic, or visceral, reflex.

Divisions of the Autonomic Nervous System

By the end of this section, you will be able to:

- Name the components that generate the sympathetic and parasympathetic responses of the autonomic nervous system
- Explain the differences in output connections within the two divisions of the autonomic nervous system
- Describe the signaling molecules and receptor proteins involved in communication within the two divisions of the autonomic nervous system

The nervous system can be divided into two functional parts: the somatic nervous system and the autonomic nervous system. The major differences between the two systems are evident in the responses that each produces. The somatic nervous system causes contraction of skeletal muscles. The autonomic nervous system controls cardiac and smooth muscle, as well as glandular tissue. The somatic nervous system is associated with voluntary responses (though many can happen without conscious awareness, like breathing), and the autonomic nervous system is associated with involuntary responses, such as those related to homeostasis.

The autonomic nervous system regulates many of the internal organs through a balance of two aspects, or divisions. In addition to the endocrine system, the autonomic nervous system is instrumental in homeostatic mechanisms in the body. The two divisions of the autonomic nervous system are the **sympathetic division** and the **parasympathetic division**. The sympathetic system is associated with the **fight-or-flight response**, and parasympathetic activity is referred to by the epithet of **rest and digest**. Homeostasis is the balance between the two systems. At each target effector, dual innervation determines activity. For example, the heart receives connections from both the sympathetic and parasympathetic divisions. One causes heart rate to increase, whereas the other causes heart rate to decrease.

Watch this video to learn more about adrenaline and the fight-or-flight response. When someone is said to have a rush of adrenaline, the image of bungee jumpers or skydivers usually comes to mind. But adrenaline, also known as epinephrine, is an important chemical in coordinating the body's fight-or-flight response. In this video, you look inside the physiology of the fight-or-flight response, as envisioned for a firefighter. His body's reaction is the result of the sympathetic division of the autonomic nervous system causing system-wide changes as it prepares for extreme responses. What two changes does adrenaline bring about to help the skeletal muscle response?

Sympathetic Division of the Autonomic Nervous System

To respond to a threat—to fight or to run away—the sympathetic system causes divergent effects as many different effector organs are activated together for a common purpose. More oxygen needs to be inhaled and delivered to skeletal muscle. The respiratory, cardiovascular, and musculoskeletal systems are all activated together. Additionally, sweating keeps the excess heat that comes from muscle contraction from causing the body to overheat. The digestive system shuts down so that blood is not absorbing nutrients when it should be delivering oxygen to skeletal muscles. To coordinate all these responses, the connections in the sympathetic system diverge from a limited region of the central nervous system (CNS) to a wide array of ganglia that project to the many effector organs simultaneously. The complex set of structures that compose the output of the sympathetic system make it possible for these disparate effectors to come together in a coordinated, systemic change.

The sympathetic division of the autonomic nervous system influences the various organ systems of the body through connections emerging from the thoracic and upper lumbar spinal cord. It is referred to as the **thoracolumbar system** to reflect this anatomical basis. A **central neuron** in the lateral horn of any of these spinal regions projects to ganglia adjacent to the vertebral column through the ventral spinal roots. The majority of ganglia of the sympathetic system belong to a network of **sympathetic chain ganglia** that runs alongside the vertebral column. The ganglia appear as a series of clusters of neurons linked by axonal bridges. There are

typically 23 ganglia in the chain on either side of the spinal column. Three correspond to the cervical region, 12 are in the thoracic region, four are in the lumbar region, and four correspond to the sacral region. The cervical and sacral levels are not connected to the spinal cord directly through the spinal roots, but through ascending or descending connections through the bridges within the chain.

A diagram that shows the connections of the sympathetic system is somewhat like a circuit diagram that shows the electrical connections between different receptacles and devices. In Figure 1. (Connections of Sympathetic Division of the Autonomic Nervous System), the "circuits" of the sympathetic system are intentionally simplified.

Connections of Sympathetic Division of the Autonomic Nervous System

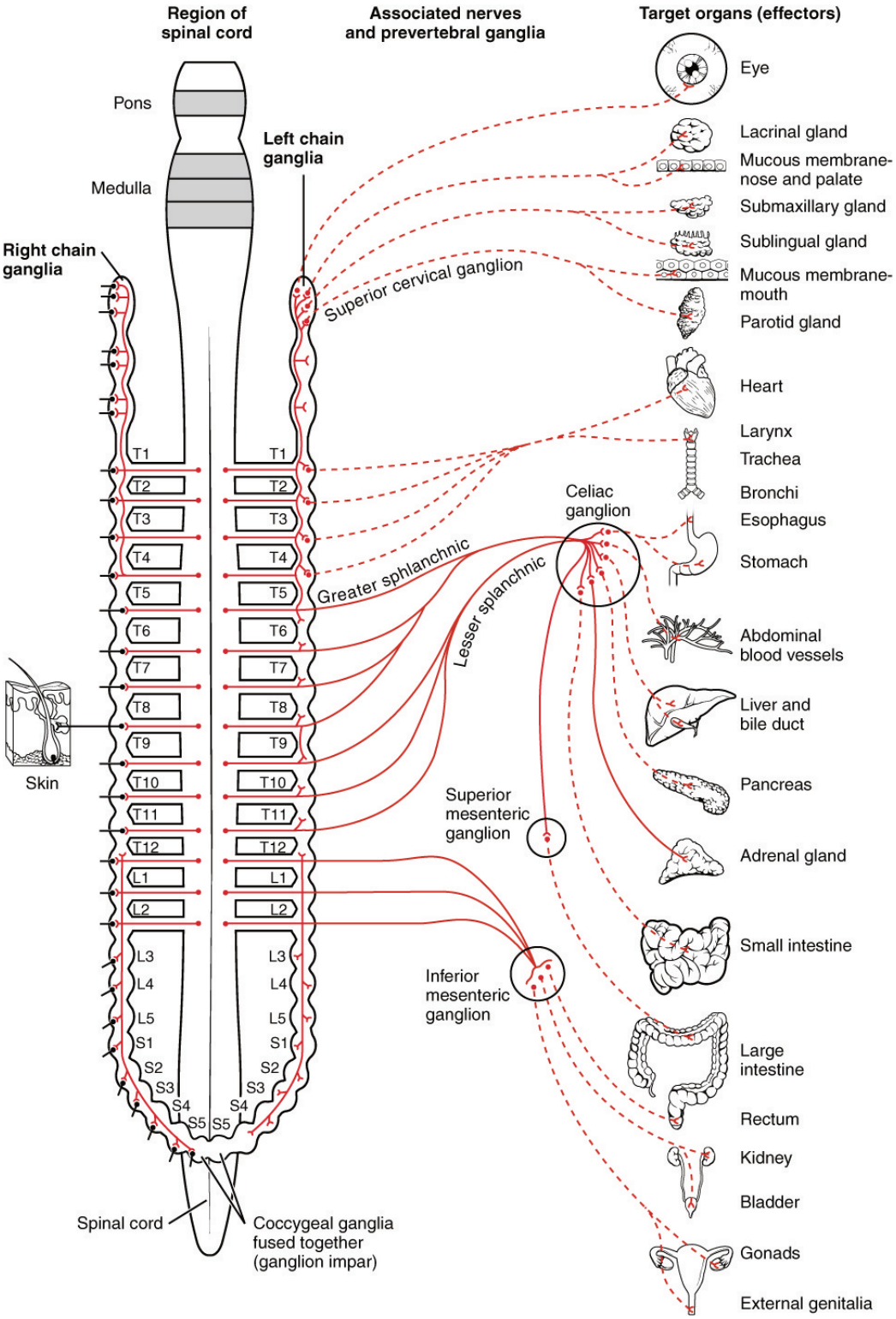


Figure 1. *Neurons from the lateral horn of the spinal cord (preganglionic nerve fibers – solid lines)) project to the chain ganglia on either side of the vertebral column or to collateral (prevertebral) ganglia that are anterior to the vertebral column in the abdominal cavity. Axons from these ganglionic neurons (postganglionic nerve fibers – dotted lines) then project to target effectors throughout the body.*

To continue with the analogy of the circuit diagram, there are three different types of "junctions" that operate within the sympathetic system (Figure 2. Sympathetic Connections and Chain Ganglia). The first type is most direct: the sympathetic nerve projects to the chain ganglion at the same level as the **target effector** (the organ, tissue, or gland to be innervated). An example of this type is spinal nerve T1 that synapses with the T1 chain ganglion to innervate the trachea. The fibers of this branch are called **white rami communicantes** (singular = ramus communicans); they are myelinated and therefore referred to as white (see Figure 2 a. Sympathetic Connections and Chain Ganglia). The axon from the central neuron (the preganglionic fiber shown as a solid line) synapses with the **ganglionic neuron** (with the postganglionic fiber shown as a dashed line). This neuron then projects to a target effector—in this case, the trachea—via **gray rami communicantes**, which are unmyelinated axons.

In some cases, the target effectors are located superior or inferior to the spinal segment at which the preganglionic fiber emerges. With respect to the "wiring" involved, the synapse with the ganglionic neuron occurs at chain ganglia superior or inferior to the location of the central neuron. An example of this is spinal nerve T1 that innervates the eye. The spinal nerve tracks up through the chain until it reaches the **superior cervical ganglion**, where it synapses with the postganglionic neuron (see Figure 2 b. Sympathetic Connections and Chain Ganglia). The cervical ganglia are referred to as **paravertebral ganglia**, given their location adjacent to prevertebral ganglia in the sympathetic chain.

Not all axons from the central neurons terminate in the chain ganglia. Additional branches from the ventral nerve root continue through the chain and on to one of the collateral ganglia as the **greater splanchnic nerve** or **lesser splanchnic nerve**. For example, the greater splanchnic nerve at the level of T5 synapses with a collateral ganglion outside the chain before making the connection to the postganglionic nerves that innervate the stomach (see Figure 2 c. Sympathetic Connections and Chain Ganglia).

Collateral ganglia, also called **prevertebral ganglia**, are situated anterior to the vertebral column and receive inputs from splanchnic nerves as well as central sympathetic neurons. They are associated with controlling organs in the abdominal cavity, and are also considered part of the enteric nervous system. The three collateral ganglia are the **celiac ganglion**, the **superior mesenteric ganglion**, and the **inferior mesenteric ganglion** (see Figure 1.). The word celiac is derived from the Latin word "coelom," which refers to a body cavity (in this case, the abdominal cavity), and the word mesenteric refers to the digestive system.

Sympathetic Connections and Chain Ganglia

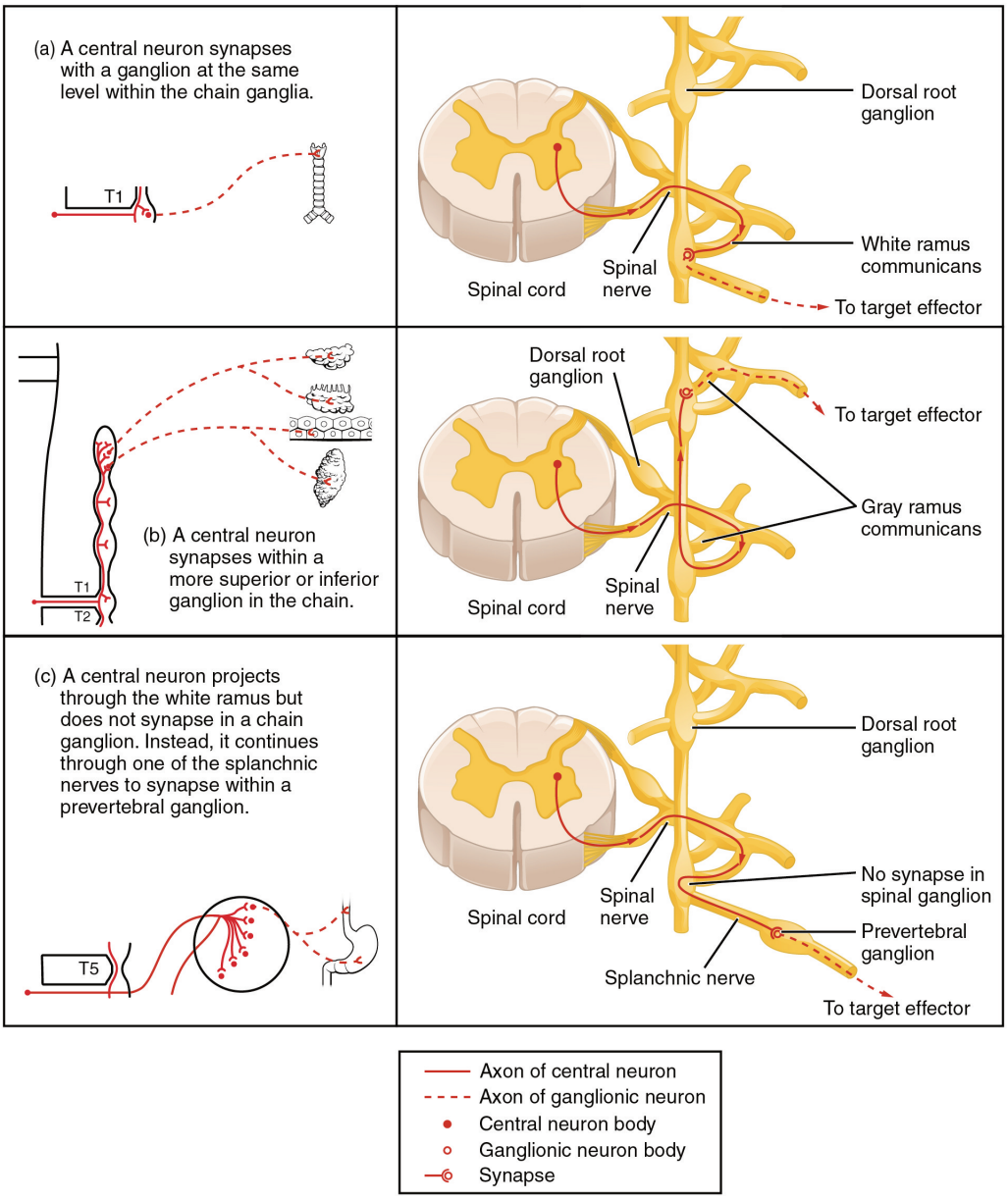


Figure 2. *The axon from a central sympathetic neuron in the spinal cord can project to the periphery in a number of different ways. (a) The fiber can project out to the ganglion at the same level and synapse on a ganglionic neuron. (b) A branch can project to more superior or inferior ganglion in the chain. (c) A branch can project through the white ramus communicans, but not terminate on a ganglionic neuron in the chain. Instead, it projects through one of the splanchnic nerves to a collateral ganglion or the adrenal medulla (not pictured).*

An axon from the central neuron that projects to a sympathetic ganglion is referred to as a **preganglionic fiber** or neuron, and represents the output from the CNS to the ganglion. Because the sympathetic ganglia are adjacent to the vertebral column, preganglionic sympathetic fibers are relatively short, and they are myelinated. A **postganglionic fiber**–the axon from a ganglionic neuron that projects to the target effector–represents the output of a ganglion that directly influences the organ. Compared with the preganglionic fibers, postganglionic sympathetic fibers are long because of the relatively greater distance from the ganglion to the target effector. These fibers are unmyelinated. (Note that the term "postganglionic neuron" may be used to describe the

projection from a ganglion to the target. The problem with that usage is that the cell body is in the ganglion, and only the fiber is postganglionic. Typically, the term neuron applies to the entire cell.)

One type of preganglionic sympathetic fiber does not terminate in a ganglion. These are the axons from central sympathetic neurons that project to the **adrenal medulla**, the interior portion of the adrenal gland. These axons are still referred to as preganglionic fibers, but the target is not a ganglion. The adrenal medulla releases signaling molecules into the bloodstream, rather than using axons to communicate with target structures. The cells in the adrenal medulla that are contacted by the preganglionic fibers are called **chromaffin cells**. These cells are neurosecretory cells that develop from the neural crest along with the sympathetic ganglia, reinforcing the idea that the gland is, functionally, a sympathetic ganglion.

The projections of the sympathetic division of the autonomic nervous system diverge widely, resulting in a broad influence of the system throughout the body. As a response to a threat, the sympathetic system would increase heart rate and breathing rate and cause blood flow to the skeletal muscle to increase and blood flow to the digestive system to decrease. Sweat gland secretion should also increase as part of an integrated response. All of those physiological changes are going to be required to occur together to run away from the hunting lioness, or the modern equivalent. This divergence is seen in the branching patterns of preganglionic sympathetic neurons—a single preganglionic sympathetic neuron may have 10–20 targets. An axon that leaves a central neuron of the lateral horn in the thoracolumbar spinal cord will pass through the white ramus communicans and enter the sympathetic chain, where it will branch toward a variety of targets. At the level of the spinal cord at which the preganglionic sympathetic fiber exits the spinal cord, a branch will synapse on a neuron in the adjacent chain ganglion. Some branches will extend up or down to a different level of the chain ganglia. Other branches will pass through the chain ganglia and project through one of the splanchnic nerves to a collateral ganglion. Finally, some branches may project through the splanchnic nerves to the adrenal medulla. All of these branches mean that one preganglionic neuron can influence different regions of the sympathetic system very broadly, by acting on widely distributed organs.

Parasympathetic Division of the Autonomic Nervous System

The parasympathetic division of the autonomic nervous system is named because its central neurons are located on either side of the thoracolumbar region of the spinal cord (para- = "beside" or "near"). The parasympathetic system can also be referred to as the **craniosacral system** (or outflow) because the preganglionic neurons are located in nuclei of the brain stem and the lateral horn of the sacral spinal cord.

The connections, or "circuits," of the parasympathetic division are similar to the general layout of the sympathetic division with a few specific differences (Figure 3. Connections of Parasympathetic Division of the Autonomic Nervous System). The preganglionic fibers from the cranial region travel in cranial nerves, whereas preganglionic fibers from the sacral region travel in spinal nerves. The targets of these fibers are **terminal ganglia**, which are located near—or even within—the target effector. These ganglia are often referred to as **intramural ganglia** when they are found within the walls of the target organ. The postganglionic fiber projects from the terminal ganglia a short distance to the target effector, or to the specific target tissue within the organ. Comparing the relative lengths of axons in the parasympathetic system, the preganglionic fibers are long and the postganglionic fibers are short because the ganglia are close to—and sometimes within—the target effectors.

The cranial component of the parasympathetic system is based in particular nuclei of the brain stem. In the midbrain, the **Edinger–Westphal nucleus** is part of the oculomotor complex, and axons from those neurons travel with the fibers in the oculomotor nerve (cranial nerve III) that innervate the extraocular muscles. The preganglionic parasympathetic fibers within cranial nerve III terminate in the **ciliary ganglion**, which is located

in the posterior orbit. The postganglionic parasympathetic fibers then project to the smooth muscle of the iris to control pupillary size. In the upper medulla, the salivatory nuclei contain neurons with axons that project through the facial and glossopharyngeal nerves to ganglia that control salivary glands. Tear production is influenced by parasympathetic fibers in the facial nerve, which activate a ganglion, and ultimately the lacrimal (tear) gland. Neurons in the **dorsal nucleus of the vagus nerve** and the **nucleus ambiguus** project through the vagus nerve (cranial nerve X) to the terminal ganglia of the thoracic and abdominal cavities. Parasympathetic preganglionic fibers primarily influence the heart, bronchi, and esophagus in the thoracic cavity and the stomach, liver, pancreas, gall bladder, and small intestine of the abdominal cavity. The postganglionic fibers from the ganglia activated by the vagus nerve are often incorporated into the structure of the organ, such as the **mesenteric plexus** of the digestive tract organs and the intramural ganglia.

Connections of Parasympathetic Division of the Autonomic Nervous System

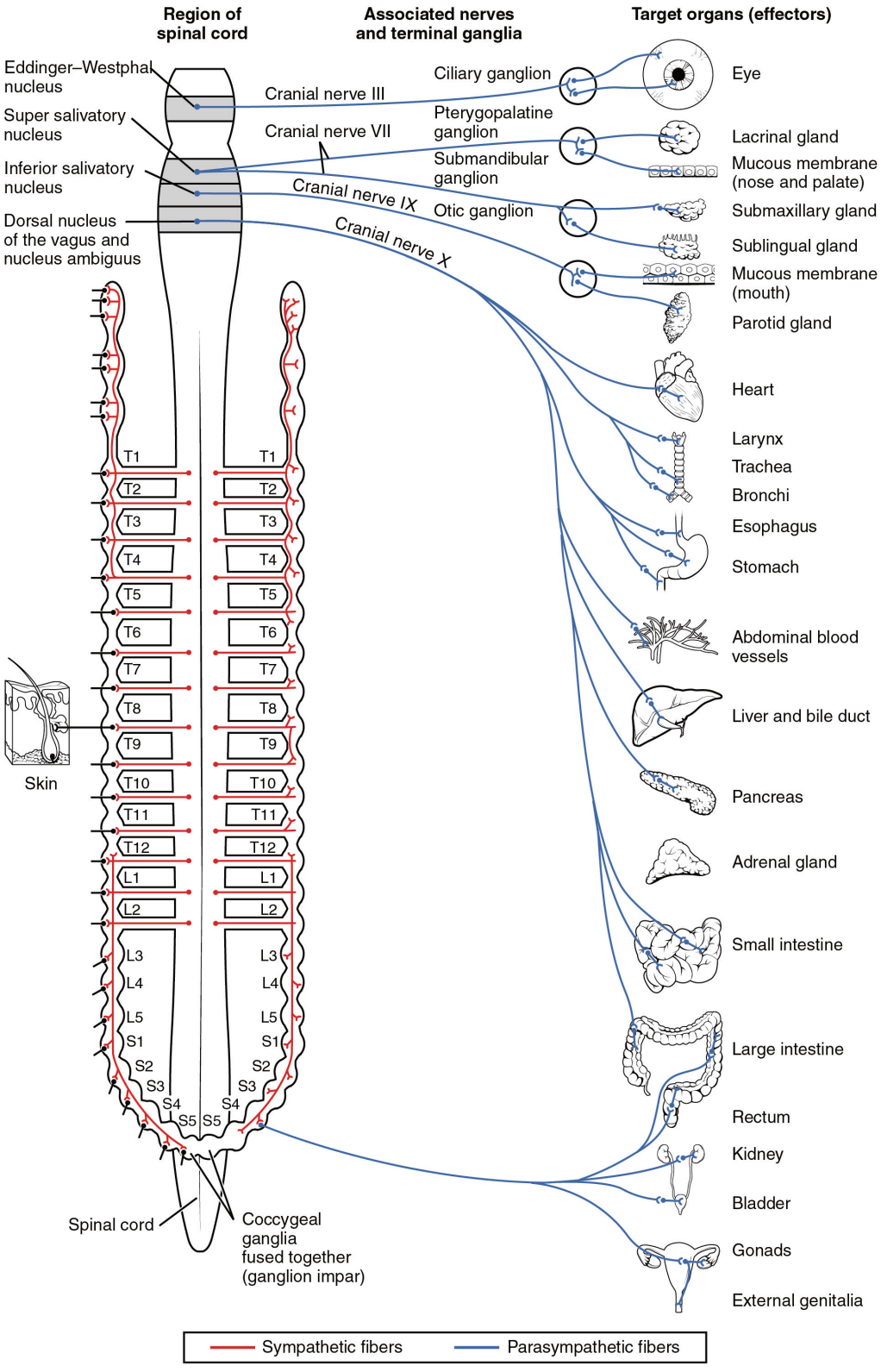


Figure 3. *Neurons from brain-stem nuclei, or from the lateral horn of the sacral spinal cord, project to terminal ganglia near or within the various organs of the body. Axons from these ganglionic neurons then project the short distance to those target effectors.*

Chemical Signaling in the Autonomic Nervous System

Where an autonomic neuron connects with a target, there is a synapse. The electrical signal of the action potential causes the release of a signaling molecule, which will bind to receptor proteins on the target cell. Synapses of the autonomic system are classified as either **cholinergic**, meaning that **acetylcholine (ACh)** is released, or **adrenergic**, meaning that **norepinephrine** is released. The terms cholinergic and adrenergic refer not only to the signaling molecule that is released but also to the class of receptors that each binds.

The cholinergic system includes two classes of receptor: the **nicotinic receptor** and the **muscarinic receptor**. Both receptor types bind to ACh and cause changes in the target cell. The nicotinic receptor is a **ligand-gated cation channel** and the muscarinic receptor is a **G protein–coupled receptor**. The receptors are named for, and differentiated by, other molecules that bind to them. Whereas nicotine will bind to the nicotinic receptor, and muscarine will bind to the muscarinic receptor, there is no cross-reactivity between the receptors. The situation is similar to locks and keys. Imagine two locks—one for a classroom and the other for an office—that are opened by two separate keys. The classroom key will not open the office door and the office key will not open the classroom door. This is similar to the specificity of nicotine and muscarine for their receptors. However, a master key can open multiple locks, such as a master key for the Biology Department that opens both the classroom and the office doors. This is similar to ACh that binds to both types of receptors. The molecules that define these receptors are not crucial—they are simply tools for researchers to use in the laboratory. These molecules are **exogenous**, meaning that they are made outside of the human body, so a researcher can use them without any confounding **endogenous** results (results caused by the molecules produced in the body).

The adrenergic system also has two types of receptors, named the **alpha (α)-adrenergic receptor** and **beta (β)-adrenergic receptor**. Unlike cholinergic receptors, these receptor types are not classified by which drugs can bind to them. All of them are G protein–coupled receptors. There are three types of α-adrenergic receptors, termed α_1, α_2, and α_3, and there are two types of β-adrenergic receptors, termed β_1 and β_2. An additional aspect of the adrenergic system is that there is a second signaling molecule called **epinephrine**. The chemical difference between norepinephrine and epinephrine is the addition of a methyl group (CH_3) in epinephrine. The prefix "nor-" actually refers to this chemical difference, in which a methyl group is missing.

The term adrenergic should remind you of the word adrenaline, which is associated with the fight-or-flight response described at the beginning of the chapter. Adrenaline and epinephrine are two names for the same molecule. The adrenal gland (in Latin, ad- = "on top of"; renal = "kidney") secretes adrenaline. The ending "-ine" refers to the chemical being derived, or extracted, from the adrenal gland. A similar construction from Greek instead of Latin results in the word epinephrine (epi- = "above"; nephr- = "kidney"). In scientific usage, epinephrine is preferred in the United States, whereas adrenaline is preferred in Great Britain, because "adrenalin" was once a registered, proprietary drug name in the United States. Though the drug is no longer sold, the convention of referring to this molecule by the two different names persists. Similarly, norepinephrine and noradrenaline are two names for the same molecule.

Having understood the cholinergic and adrenergic systems, their role in the autonomic system is relatively simple to understand. All preganglionic fibers, both sympathetic and parasympathetic, release ACh. All ganglionic neurons—the targets of these preganglionic fibers—have nicotinic receptors in their cell membranes. The nicotinic receptor is a ligand-gated cation channel that results in depolarization of the postsynaptic membrane. The postganglionic parasympathetic fibers also release ACh, but the receptors on their targets are muscarinic receptors, which are G protein–coupled receptors and do not exclusively cause depolarization of the postsynaptic membrane. Postganglionic sympathetic fibers release norepinephrine, except for fibers that project to sweat glands and to blood vessels associated with skeletal muscles, which release ACh (Table (Autonomic System Signaling Molecules)).

Autonomic System Signaling Molecules		
	Sympathetic	**Parasympathetic**
Preganglionic	Acetylcholine → nicotinic receptor	Acetylcholine → nicotinic receptor
Postganglionic	Norepinephrine → α- or β-adrenergic receptors Acetylcholine → muscarinic receptor (associated with sweat glands and the blood vessels associated with skeletal muscles only	Acetylcholine → muscarinic receptor

Signaling molecules can belong to two broad groups. Neurotransmitters are released at synapses, whereas hormones are released into the bloodstream. These are simplistic definitions, but they can help to clarify this point. Acetylcholine can be considered a neurotransmitter because it is released by axons at synapses. The adrenergic system, however, presents a challenge. Postganglionic sympathetic fibers release norepinephrine, which can be considered a neurotransmitter. But the adrenal medulla releases epinephrine and norepinephrine into circulation, so they should be considered hormones.

What are referred to here as synapses may not fit the strictest definition of synapse. Some sources will refer to the connection between a postganglionic fiber and a target effector as neuroeffector junctions; neurotransmitters, as defined above, would be called neuromodulators. The structure of postganglionic connections are not the typical synaptic end bulb that is found at the neuromuscular junction, but rather are chains of swellings along the length of a postganglionic fiber called a **varicosity** (Figure 4. Autonomic Varicosities).

Autonomic Varicosities

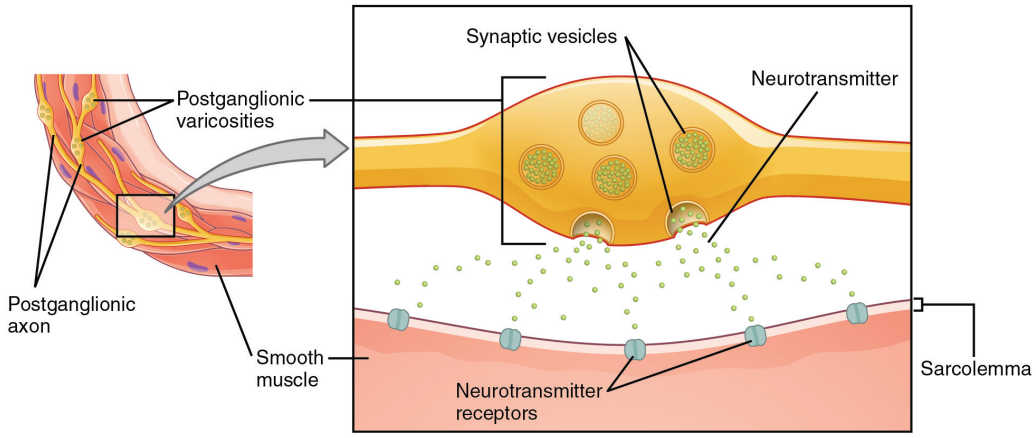


Figure 4. *The connection between autonomic fibers and target effectors is not the same as the typical synapse, such as the neuromuscular junction. Instead of a synaptic end bulb, a neurotransmitter is released from swellings along the length of a fiber that makes an extended network of connections in the target effector.*

EVERYDAY CONNECTIONS

Fight or Flight? What About Fright and Freeze?The original usage of the epithet "fight or flight" comes from a scientist named Walter Cannon who worked at Harvard in 1915. The concept of homeostasis and the functioning of the sympathetic system had been introduced in France in the previous century. Cannon expanded the idea, and introduced the idea that an animal responds to a

threat by preparing to stand and fight or run away. The nature of this response was thoroughly explained in a book on the physiology of pain, hunger, fear, and rage.

When students learn about the sympathetic system and the fight-or-flight response, they often stop and wonder about other responses. If you were faced with a lioness running toward you as pictured at the beginning of this chapter, would you run or would you stand your ground? Some people would say that they would freeze and not know what to do. So isn't there really more to what the autonomic system does than fight, flight, rest, or digest. What about fear and paralysis in the face of a threat?

The common epithet of "fight or flight" is being enlarged to be "fight, flight, or fright" or even "fight, flight, fright, or freeze." Cannon's original contribution was a catchy phrase to express some of what the nervous system does in response to a threat, but it is incomplete. The sympathetic system is responsible for the physiological responses to emotional states. The name "sympathetic" can be said to mean that (sym- = "together"; -pathos = "pain," "suffering," or "emotion").

Watch this video to learn more about the nervous system. As described in this video, the nervous system has a way to deal with threats and stress that is separate from the conscious control of the somatic nervous system. The system comes from a time when threats were about survival, but in the modern age, these responses become part of stress and anxiety. This video describes how the autonomic system is only part of the response to threats, or stressors. What other organ system gets involved, and what part of the brain coordinates the two systems for the entire response, including epinephrine (adrenaline) and cortisol?

Chapter Review

The primary responsibilities of the autonomic nervous system are to regulate homeostatic mechanisms in the body, which is also part of what the endocrine system does. The key to understanding the autonomic system is to explore the response pathways—the output of the nervous system. The way we respond to the world around us, to manage the internal environment on the basis of the external environment, is divided between two parts of the autonomic nervous system. The sympathetic division responds to threats and produces a readiness to confront the threat or to run away: the fight-or-flight response. The parasympathetic division plays the opposite role. When the external environment does not present any immediate danger, a restful mode descends on the body, and the digestive system is more active.

The sympathetic output of the nervous system originates out of the lateral horn of the thoracolumbar spinal cord. An axon from one of these central neurons projects by way of the ventral spinal nerve root and spinal nerve to a sympathetic ganglion, either in the sympathetic chain ganglia or one of the collateral locations, where it synapses on a ganglionic neuron. These preganglionic fibers release ACh, which excites the ganglionic neuron through the nicotinic receptor. The axon from the ganglionic neuron—the postganglionic fiber—then

projects to a target effector where it will release norepinephrine to bind to an adrenergic receptor, causing a change in the physiology of that organ in keeping with the broad, divergent sympathetic response. The postganglionic connections to sweat glands in the skin and blood vessels supplying skeletal muscle are, however, exceptions; those fibers release ACh onto muscarinic receptors. The sympathetic system has a specialized preganglionic connection to the adrenal medulla that causes epinephrine and norepinephrine to be released into the bloodstream rather than exciting a neuron that contacts an organ directly. This hormonal component means that the sympathetic chemical signal can spread throughout the body very quickly and affect many organ systems at once.

The parasympathetic output is based in the brain stem and sacral spinal cord. Neurons from particular nuclei in the brain stem or from the lateral horn of the sacral spinal cord (preganglionic neurons) project to terminal (intramural) ganglia located close to or within the wall of target effectors. These preganglionic fibers also release ACh onto nicotinic receptors to excite the ganglionic neurons. The postganglionic fibers then contact the target tissues within the organ to release ACh, which binds to muscarinic receptors to induce rest-and-digest responses.

Signaling molecules utilized by the autonomic nervous system are released from axons and can be considered as either neurotransmitters (when they directly interact with the effector) or as hormones (when they are released into the bloodstream). The same molecule, such as norepinephrine, could be considered either a neurotransmitter or a hormone on the basis of whether it is released from a postganglionic sympathetic axon or from the adrenal gland. The synapses in the autonomic system are not always the typical type of connection first described in the neuromuscular junction. Instead of having synaptic end bulbs at the very end of an axonal fiber, they may have swellings—called varicosities—along the length of a fiber so that it makes a network of connections within the target tissue.

Autonomic Reflexes and Homeostasis

By the end of this section, you will be able to:

- Compare the structure of somatic and autonomic reflex arcs
- Explain the differences in sympathetic and parasympathetic reflexes
- Differentiate between short and long reflexes
- Determine the effect of the autonomic nervous system on the regulation of the various organ systems on the basis of the signaling molecules involved
- Describe the effects of drugs that affect autonomic function

The autonomic nervous system regulates organ systems through circuits that resemble the reflexes described in the somatic nervous system. The main difference between the somatic and autonomic systems is in what target tissues are effectors. Somatic responses are solely based on skeletal muscle contraction. The autonomic system, however, targets cardiac and smooth muscle, as well as glandular tissue. Whereas the basic circuit is a **reflex arc**, there are differences in the structure of those reflexes for the somatic and autonomic systems.

The Structure of Reflexes

One difference between a **somatic reflex**, such as the withdrawal reflex, and a **visceral reflex**, which is an autonomic reflex, is in the **efferent branch**. The output of a somatic reflex is the lower motor neuron in the ventral horn of the spinal cord that projects directly to a skeletal muscle to cause its contraction. The output of a visceral reflex is a two-step pathway starting with the preganglionic fiber emerging from a lateral horn neuron in the spinal cord, or a cranial nucleus neuron in the brain stem, to a ganglion—followed by the postganglionic fiber projecting to a target effector. The other part of a reflex, the **afferent branch**, is often the same between the two systems. Sensory neurons receiving input from the periphery—with cell bodies in the sensory ganglia, either of a cranial nerve or a dorsal root ganglion adjacent to the spinal cord—project into the CNS to initiate the reflex (Figure). The Latin root "effere" means "to carry." Adding the prefix "ef-" suggests the meaning "to carry away," whereas adding the prefix "af-" suggests "to carry toward or inward."

Comparison of Somatic and Visceral Reflexes

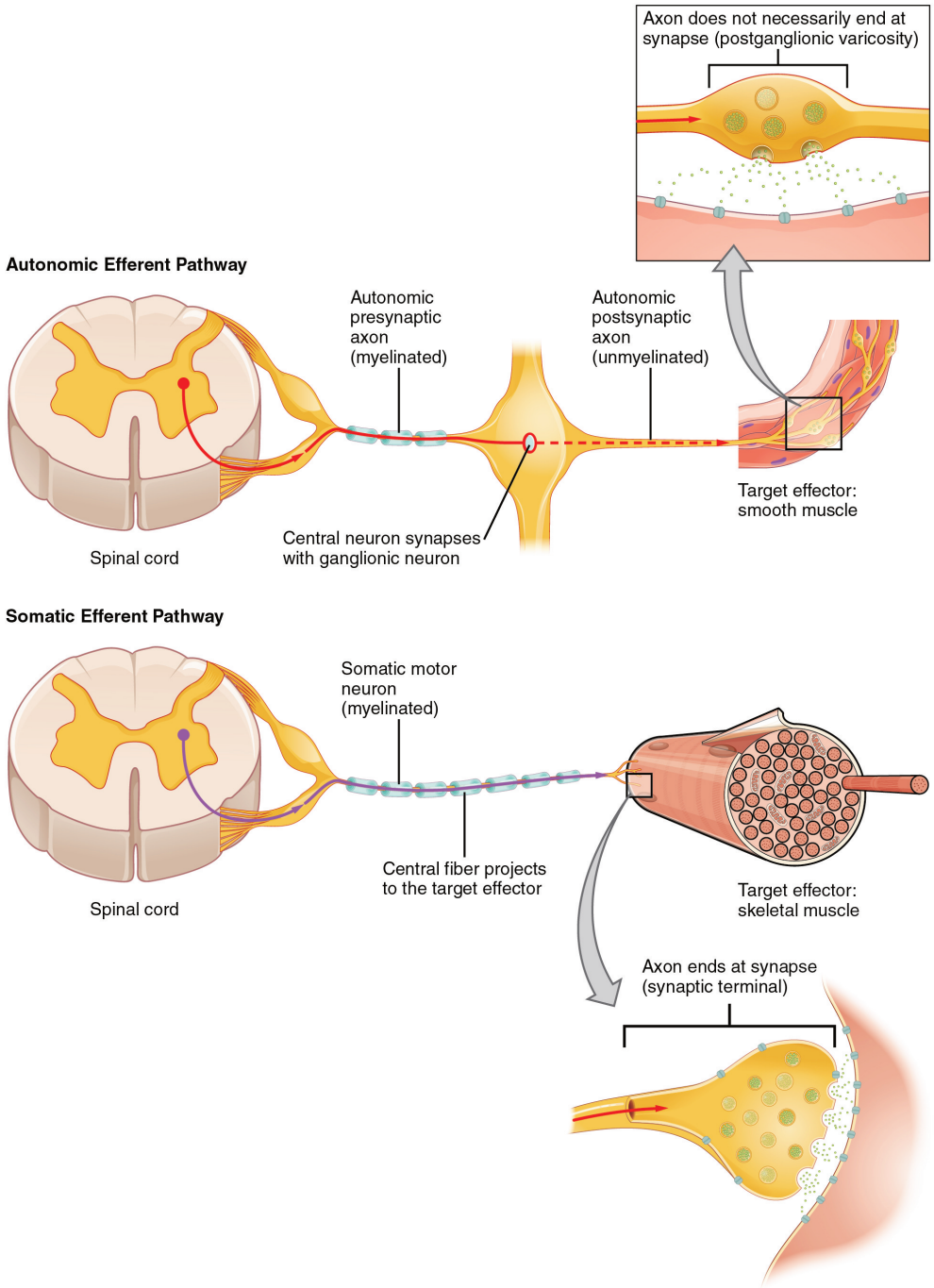


Figure 1. *The afferent inputs to somatic and visceral reflexes are essentially the same, whereas the efferent branches are different. Somatic reflexes, for instance, involve a direct connection from the ventral horn of the spinal cord to the skeletal muscle. Visceral reflexes involve a projection from the central neuron to a ganglion, followed by a second projection from the ganglion to the target effector.*

Afferent Branch

The afferent branch of a reflex arc does differ between somatic and visceral reflexes in some instances. Many of the inputs to visceral reflexes are from special or somatic senses, but particular senses are associated with the viscera that are not part of the conscious perception of the environment through the somatic nervous system. For example, there is a specific type of mechanoreceptor, called a **baroreceptor**, in the walls of the aorta and carotid sinuses that senses the stretch of those organs when blood volume or pressure increases. You do not have a conscious perception of having high blood pressure, but that is an important afferent branch of the cardiovascular and, particularly, vasomotor reflexes. The sensory neuron is essentially the same as any other general sensory neuron. The baroreceptor apparatus is part of the ending of a unipolar neuron that has a cell body in a sensory ganglion. The baroreceptors from the carotid arteries have axons in the glossopharyngeal nerve, and those from the aorta have axons in the vagus nerve.

Though visceral senses are not primarily a part of conscious perception, those sensations sometimes make it to conscious awareness. If a visceral sense is strong enough, it will be perceived. The sensory homunculus—the representation of the body in the primary somatosensory cortex—only has a small region allotted for the perception of internal stimuli. If you swallow a large bolus of food, for instance, you will probably feel the lump of that food as it pushes through your esophagus, or even if your stomach is distended after a large meal. If you inhale especially cold air, you can feel it as it enters your larynx and trachea. These sensations are not the same as feeling high blood pressure or blood sugar levels.

When particularly strong visceral sensations rise to the level of conscious perception, the sensations are often felt in unexpected places. For example, strong visceral sensations of the heart will be felt as pain in the left shoulder and left arm. This irregular pattern of projection of conscious perception of visceral sensations is called **referred pain**. Depending on the organ system affected, the referred pain will project to different areas of the body (Figure 2. Referred Pain Chart). The location of referred pain is not random, but a definitive explanation of the mechanism has not been established. The most broadly accepted theory for this phenomenon is that the visceral sensory fibers enter into the same level of the spinal cord as the somatosensory fibers of the referred pain location. By this explanation, the visceral sensory fibers from the mediastinal region, where the heart is located, would enter the spinal cord at the same level as the spinal nerves from the shoulder and arm, so the brain misinterprets the sensations from the mediastinal region as being from the axillary and brachial regions. Projections from the medial and inferior divisions of the cervical ganglia do enter the spinal cord at the middle to lower cervical levels, which is where the somatosensory fibers enter.

Referred Pain Chart

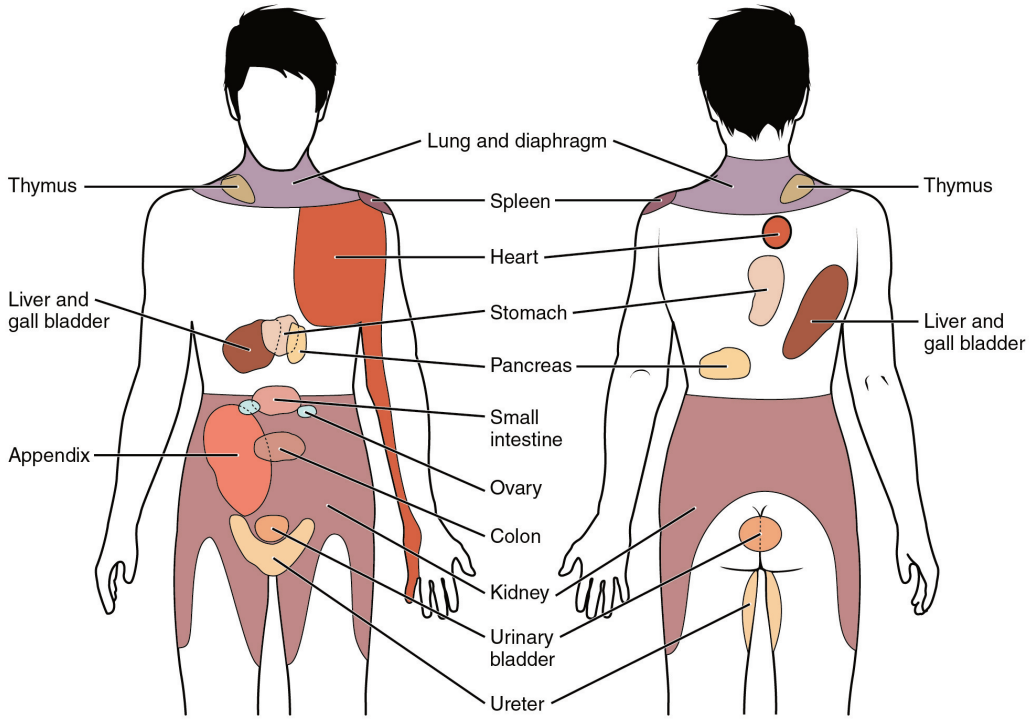


Figure 2. *Conscious perception of visceral sensations map to specific regions of the body, as shown in this chart. Some sensations are felt locally, whereas others are perceived as affecting areas that are quite distant from the involved organ.*

DISORDERS OF THE...

Nervous System: Kehr's Sign

Kehr's sign is the presentation of pain in the left shoulder, chest, and neck regions following rupture of the spleen. The spleen is in the upper-left abdominopelvic quadrant, but the pain is more in the shoulder and neck. How can this be? The sympathetic fibers connected to the spleen are from the celiac ganglion, which would be from the mid-thoracic to lower thoracic region whereas parasympathetic fibers are found in the vagus nerve, which connects in the medulla of the brain stem. However, the neck and shoulder would connect to the spinal cord at the mid-cervical level of the spinal cord. These connections do not fit with the expected correspondence of visceral and somatosensory fibers entering at the same level of the spinal cord.

The incorrect assumption would be that the visceral sensations are coming from the spleen directly. In fact, the visceral fibers are coming from the diaphragm. The nerve connecting to the diaphragm takes a special route. The phrenic nerve is connected to the spinal cord at cervical levels 3 to 5. The motor fibers that make up this nerve are responsible for the muscle contractions that drive ventilation. These fibers have left the spinal cord to enter the phrenic nerve, meaning that spinal

cord damage below the mid-cervical level is not fatal by making ventilation impossible. Therefore, the visceral fibers from the diaphragm enter the spinal cord at the same level as the somatosensory fibers from the neck and shoulder.

The diaphragm plays a role in Kehr's sign because the spleen is just inferior to the diaphragm in the upper-left quadrant of the abdominopelvic cavity. When the spleen ruptures, blood spills into this region. The accumulating hemorrhage then puts pressure on the diaphragm. The visceral sensation is actually in the diaphragm, so the referred pain is in a region of the body that corresponds to the diaphragm, not the spleen.

Efferent Branch

The efferent branch of the visceral reflex arc begins with the projection from the central neuron along the preganglionic fiber. This fiber then makes a synapse on the ganglionic neuron that projects to the target effector.

The effector organs that are the targets of the autonomic system range from the iris and ciliary body of the eye to the urinary bladder and reproductive organs. The thoracolumbar output, through the various sympathetic ganglia, reaches all of these organs. The cranial component of the parasympathetic system projects from the eye to part of the intestines. The sacral component picks up with the majority of the large intestine and the pelvic organs of the urinary and reproductive systems.

Short and Long Reflexes

Somatic reflexes involve sensory neurons that connect sensory receptors to the CNS and motor neurons that project back out to the skeletal muscles. Visceral reflexes that involve the thoracolumbar or craniosacral systems share similar connections. However, there are reflexes that do not need to involve any CNS components. A **long reflex** has afferent branches that enter the spinal cord or brain and involve the efferent branches, as previously explained. A **short reflex** is completely peripheral and only involves the local integration of sensory input with motor output (Figure 3. Short and Long Reflexes).

Short and Long Reflexes

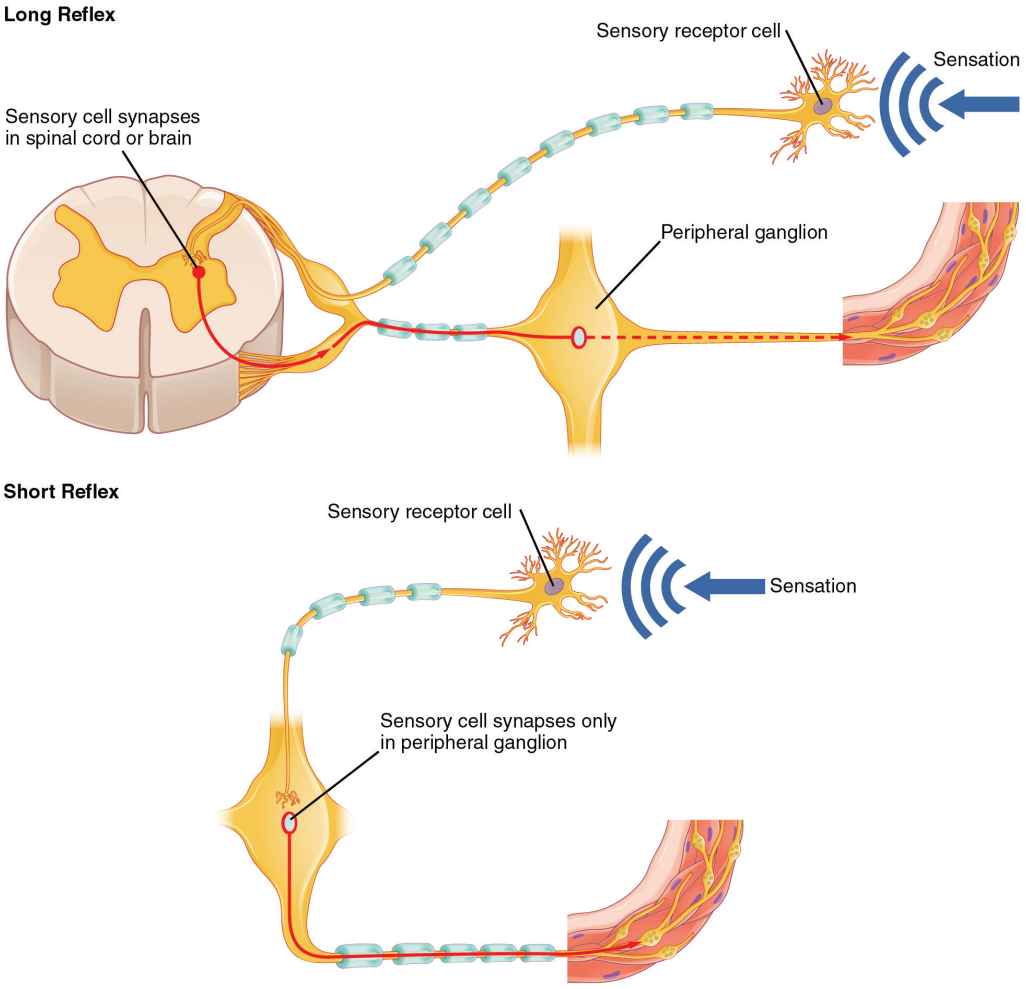


Figure 3. *Sensory input can stimulate either a short or a long reflex. A sensory neuron can project to the CNS or to an autonomic ganglion. The short reflex involves the direct stimulation of a postganglionic fiber by the sensory neuron, whereas the long reflex involves integration in the spinal cord or brain.*

The difference between short and long reflexes is in the involvement of the CNS. Somatic reflexes always involve the CNS, even in a monosynaptic reflex in which the sensory neuron directly activates the motor neuron. That synapse is in the spinal cord or brain stem, so it has to involve the CNS. However, in the autonomic system there is the possibility that the CNS is not involved. Because the efferent branch of a visceral reflex involves two neurons—the central neuron and the ganglionic neuron—a "short circuit" can be possible. If a sensory neuron projects directly to the ganglionic neuron and causes it to activate the effector target, then the CNS is not involved.

A division of the nervous system that is related to the autonomic nervous system is the enteric nervous system. The word enteric refers to the digestive organs, so this represents the nervous tissue that is part of the digestive system. There are a few myenteric plexuses in which the nervous tissue in the wall of the digestive tract organs can directly influence digestive function. If stretch receptors in the stomach are activated by the filling and distension of the stomach, a short reflex will directly activate the smooth muscle fibers of the stomach wall to increase motility to digest the excessive food in the stomach. No CNS involvement is needed because the stretch receptor is directly activating a neuron in the wall of the stomach that causes the smooth muscle to

contract. That neuron, connected to the smooth muscle, is a postganglionic parasympathetic neuron that can be controlled by a fiber found in the vagus nerve.

Read this article to learn about a teenager who experiences a series of spells that suggest a stroke. He undergoes endless tests and seeks input from multiple doctors. In the end, one expert, one question, and a simple blood pressure cuff answers the question. Why would the heart have to beat faster when the teenager changes his body position from lying down to sitting, and then to standing?

Balance in Competing Autonomic Reflex Arcs

The autonomic nervous system is important for homeostasis because its two divisions compete at the target effector. The balance of homeostasis is attributable to the competing inputs from the sympathetic and parasympathetic divisions (dual innervation). At the level of the target effector, the signal of which system is sending the message is strictly chemical. A signaling molecule binds to a receptor that causes changes in the target cell, which in turn causes the tissue or organ to respond to the changing conditions of the body.

Competing Neurotransmitters

The postganglionic fibers of the sympathetic and parasympathetic divisions both release neurotransmitters that bind to receptors on their targets. Postganglionic sympathetic fibers release norepinephrine, with a minor exception, whereas postganglionic parasympathetic fibers release ACh. For any given target, the difference in which division of the autonomic nervous system is exerting control is just in what chemical binds to its receptors. The target cells will have adrenergic and muscarinic receptors. If norepinephrine is released, it will bind to the adrenergic receptors present on the target cell, and if ACh is released, it will bind to the muscarinic receptors on the target cell.

In the sympathetic system, there are exceptions to this pattern of dual innervation. The postganglionic sympathetic fibers that contact the blood vessels within skeletal muscle and that contact sweat glands do not release norepinephrine, they release ACh. This does not create any problem because there is no parasympathetic input to the sweat glands. Sweat glands have muscarinic receptors and produce and secrete sweat in response to the presence of ACh.

At most of the other targets of the autonomic system, the effector response is based on which neurotransmitter is released and what receptor is present. For example, regions of the heart that establish heart rate are contacted by postganglionic fibers from both systems. If norepinephrine is released onto those cells, it binds to an adrenergic receptor that causes the cells to depolarize faster, and the heart rate increases. If ACh is released onto those cells, it binds to a muscarinic receptor that causes the cells to hyperpolarize so that they cannot reach threshold as easily, and the heart rate slows. Without this parasympathetic input, the heart would work at a rate of approximately 100 beats per minute (bpm). The sympathetic system speeds that up, as it would during exercise, to 120–140 bpm, for example. The parasympathetic system slows it down to the resting heart rate of 60–80 bpm.

Another example is in the control of pupillary size (Figure 4. Autonomic Control of Pupillary Size). The afferent branch responds to light hitting the retina. Photoreceptors are activated, and the signal is transferred to the retinal ganglion cells that send an action potential along the optic nerve into the diencephalon. If light levels are low, the sympathetic system sends a signal out through the upper thoracic spinal cord to the superior cervical ganglion of the sympathetic chain. The postganglionic fiber then projects to the iris, where it releases norepinephrine onto the radial fibers of the iris (a smooth muscle). When those fibers contract, the pupil dilates–increasing the amount of light hitting the retina. If light levels are too high, the parasympathetic system sends a signal out from the Eddinger–Westphal nucleus through the oculomotor nerve. This fiber synapses in the ciliary ganglion in the posterior orbit. The postganglionic fiber then projects to the iris, where it releases ACh onto the circular fibers of the iris–another smooth muscle. When those fibers contract, the pupil constricts to limit the amount of light hitting the retina.

Autonomic Control of Pupillary Size

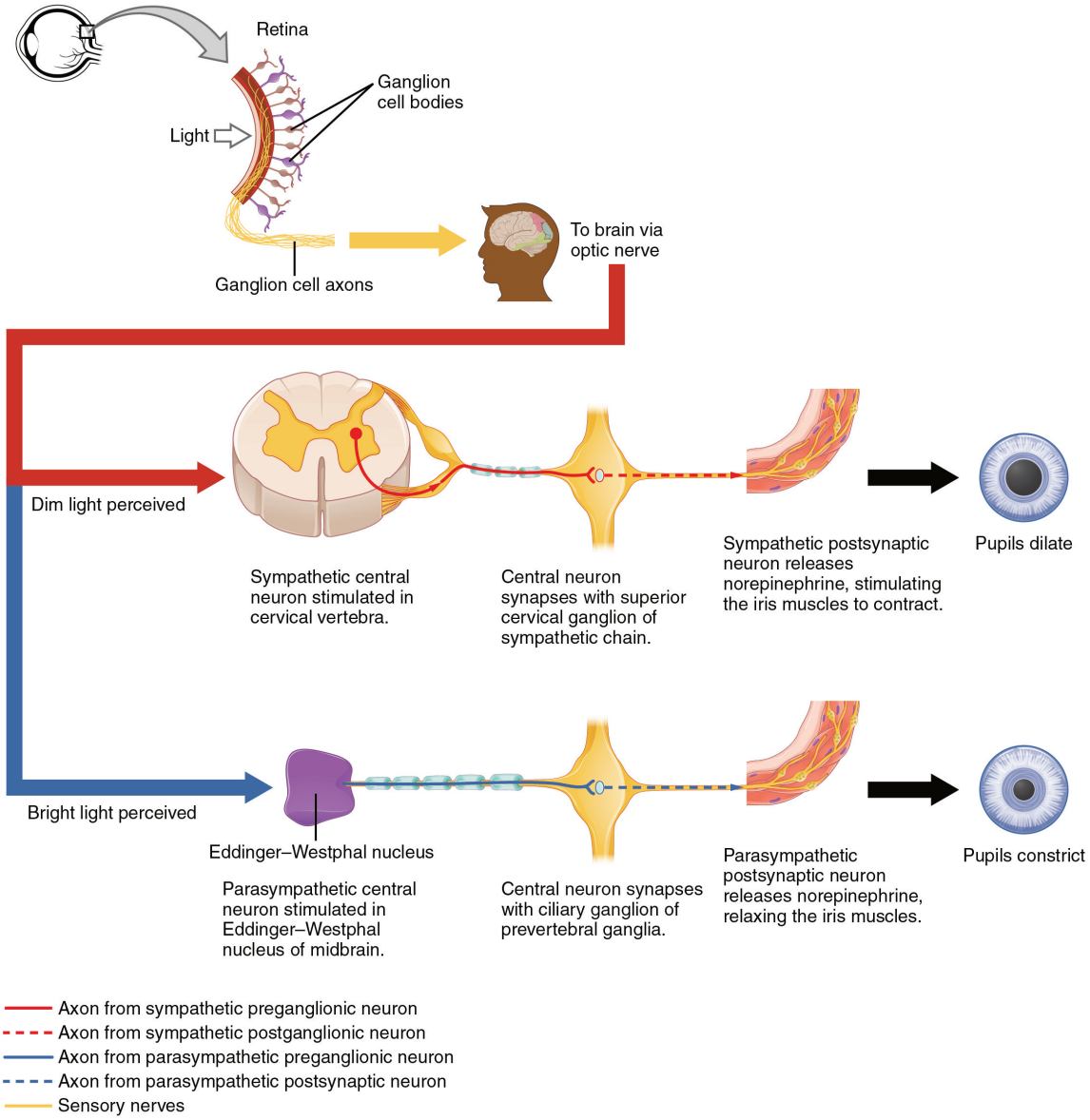


Figure 4. *Activation of the pupillary reflex comes from the amount of light activating the retinal ganglion cells, as sent along the optic nerve. The output of the sympathetic system projects through the superior cervical ganglion,*

whereas the parasympathetic system originates out of the midbrain and projects through the oculomotor nerve to the ciliary ganglion, which then projects to the iris. The postganglionic fibers of either division release neurotransmitters onto the smooth muscles of the iris to cause changes in the pupillary size. Norepinephrine results in dilation and ACh results in constriction.

In this example, the autonomic system is controlling how much light hits the retina. It is a homeostatic reflex mechanism that keeps the activation of photoreceptors within certain limits. In the context of avoiding a threat like the lioness on the savannah, the sympathetic response for fight or flight will increase pupillary diameter so that more light hits the retina and more visual information is available for running away. Likewise, the parasympathetic response of rest reduces the amount of light reaching the retina, allowing the photoreceptors to cycle through bleaching and be regenerated for further visual perception; this is what the homeostatic process is attempting to maintain.

> Watch this video to learn about the pupillary reflexes. The pupillary light reflex involves sensory input through the optic nerve and motor response through the oculomotor nerve to the ciliary ganglion, which projects to the circular fibers of the iris. As shown in this short animation, pupils will constrict to limit the amount of light falling on the retina under bright lighting conditions. What constitutes the afferent and efferent branches of the competing reflex (dilation)?

Autonomic Tone

Organ systems are balanced between the input from the sympathetic and parasympathetic divisions. When something upsets that balance, the homeostatic mechanisms strive to return it to its regular state. For each organ system, there may be more of a sympathetic or parasympathetic tendency to the resting state, which is known as the **autonomic tone** of the system. For example, the heart rate was described above. Because the resting heart rate is the result of the parasympathetic system slowing the heart down from its intrinsic rate of 100 bpm, the heart can be said to be in parasympathetic tone.

In a similar fashion, another aspect of the cardiovascular system is primarily under sympathetic control. Blood pressure is partially determined by the contraction of smooth muscle in the walls of blood vessels. These tissues have adrenergic receptors that respond to the release of norepinephrine from postganglionic sympathetic fibers by constricting and increasing blood pressure. The hormones released from the adrenal medulla—epinephrine and norepinephrine—will also bind to these receptors. Those hormones travel through the bloodstream where they can easily interact with the receptors in the vessel walls. The parasympathetic system has no significant input to the systemic blood vessels, so the sympathetic system determines their tone.

There are a limited number of blood vessels that respond to sympathetic input in a different fashion. Blood vessels in skeletal muscle, particularly those in the lower limbs, are more likely to dilate. It does not have an overall effect on blood pressure to alter the tone of the vessels, but rather allows for blood flow to increase for those skeletal muscles that will be active in the fight-or-flight response. The blood vessels that have a parasympathetic projection are limited to those in the erectile tissue of the reproductive organs. Acetylcholine released by these postganglionic parasympathetic fibers cause the vessels to dilate, leading to the engorgement of the erectile tissue.

HOMEOSTATIC IMBALANCES

Orthostatic Hypotension

Have you ever stood up quickly and felt dizzy for a moment? This is because, for one reason or another, blood is not getting to your brain so it is briefly deprived of oxygen. When you change position from sitting or lying down to standing, your cardiovascular system has to adjust for a new challenge, keeping blood pumping up into the head while gravity is pulling more and more blood down into the legs.

The reason for this is a sympathetic reflex that maintains the output of the heart in response to postural change. When a person stands up, proprioceptors indicate that the body is changing position. A signal goes to the CNS, which then sends a signal to the upper thoracic spinal cord neurons of the sympathetic division. The sympathetic system then causes the heart to beat faster and the blood vessels to constrict. Both changes will make it possible for the cardiovascular system to maintain the rate of blood delivery to the brain. Blood is being pumped superiorly through the internal branch of the carotid arteries into the brain, against the force of gravity. Gravity is not increasing while standing, but blood is more likely to flow down into the legs as they are extended for standing. This sympathetic reflex keeps the brain well oxygenated so that cognitive and other neural processes are not interrupted.

Sometimes this does not work properly. If the sympathetic system cannot increase cardiac output, then blood pressure into the brain will decrease, and a brief neurological loss can be felt. This can be brief, as a slight "wooziness" when standing up too quickly, or a loss of balance and neurological impairment for a period of time. The name for this is orthostatic hypotension, which means that blood pressure goes below the homeostatic set point when standing. It can be the result of standing up faster than the reflex can occur, which may be referred to as a benign "head rush," or it may be the result of an underlying cause.

There are two basic reasons that orthostatic hypotension can occur. First, blood volume is too low and the sympathetic reflex is not effective. This hypovolemia may be the result of dehydration or medications that affect fluid balance, such as diuretics or vasodilators. Both of these medications are meant to lower blood pressure, which may be necessary in the case of systemic hypertension, and regulation of the medications may alleviate the problem. Sometimes increasing fluid intake or water retention through salt intake can improve the situation.

The second underlying cause of orthostatic hypotension is autonomic failure. There are several disorders that result in compromised sympathetic functions. The disorders range from diabetes to multiple system atrophy (a loss of control over many systems in the body), and addressing the underlying condition can improve the hypotension. For example, with diabetes, peripheral nerve damage can occur, which would affect the postganglionic sympathetic fibers. Getting blood glucose levels under control can improve neurological deficits associated with diabetes.

Chapter Review

Autonomic nervous system function is based on the visceral reflex. This reflex is similar to the somatic reflex, but the efferent branch is composed of two neurons. The central neuron projects from the spinal cord or brain stem to synapse on the ganglionic neuron that projects to the effector. The afferent branch of the somatic and visceral reflexes is very similar, as many somatic and special senses activate autonomic responses. However, there are visceral senses that do not form part of conscious perception. If a visceral sensation, such as cardiac pain, is strong enough, it will rise to the level of consciousness. However, the sensory homunculus does not provide a representation of the internal structures to the same degree as the surface of the body, so visceral sensations are often experienced as referred pain, such as feelings of pain in the left shoulder and arm in connection with a heart attack.

The role of visceral reflexes is to maintain a balance of function in the organ systems of the body. The two divisions of the autonomic system each play a role in effecting change, usually in competing directions. The sympathetic system increases heart rate, whereas the parasympathetic system decreases heart rate. The sympathetic system dilates the pupil of the eye, whereas the parasympathetic system constricts the pupil. The competing inputs can contribute to the resting tone of the organ system. Heart rate is normally under parasympathetic tone, whereas blood pressure is normally under sympathetic tone. The heart rate is slowed by the autonomic system at rest, whereas blood vessels retain a slight constriction at rest.

In a few systems of the body, the competing input from the two divisions is not the norm. The sympathetic tone of blood vessels is caused by the lack of parasympathetic input to the systemic circulatory system. Only certain regions receive parasympathetic input that relaxes the smooth muscle wall of the blood vessels. Sweat glands are another example, which only receive input from the sympathetic system.

Central Control

By the end of this section, you will be able to:

- Describe the role of higher centers of the brain in autonomic regulation
- Explain the connection of the hypothalamus to homeostasis
- Describe the regions of the CNS that link the autonomic system with emotion
- Describe the pathways important to descending control of the autonomic system

The pupillary light reflex (Figure 1. Pupillary Reflex Pathways) begins when light hits the retina and causes a signal to travel along the optic nerve. This is visual sensation, because the afferent branch of this reflex is simply sharing the special sense pathway. Bright light hitting the retina leads to the parasympathetic response, through the oculomotor nerve, followed by the postganglionic fiber from the ciliary ganglion, which stimulates the circular fibers of the iris to contract and constrict the pupil. When light hits the retina in one eye, both pupils contract. When that light is removed, both pupils dilate again back to the resting position. When the stimulus is unilateral

(presented to only one eye), the response is bilateral (both eyes). The same is not true for somatic reflexes. If you touch a hot radiator, you only pull that arm back, not both. Central control of autonomic reflexes is different than for somatic reflexes. The hypothalamus, along with other CNS locations, controls the autonomic system.

Pupillary Reflex Pathways

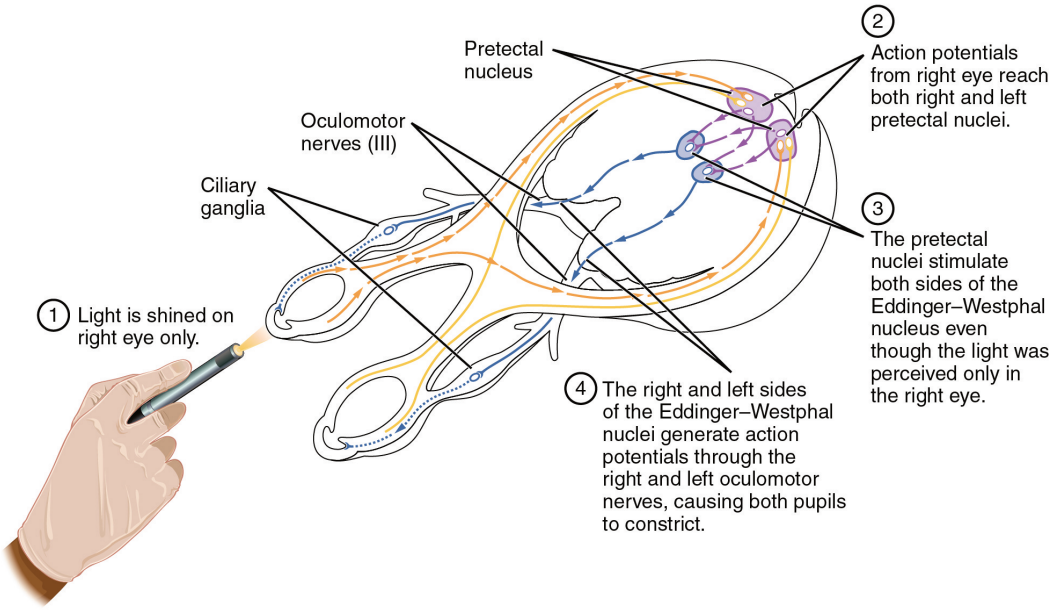


Figure 1. *The pupil is under competing autonomic control in response to light levels hitting the retina. The sympathetic system will dilate the pupil when the retina is not receiving enough light, and the parasympathetic system will constrict the pupil when too much light hits the retina.*

Forebrain Structures

Autonomic control is based on the visceral reflexes, composed of the afferent and efferent branches. These homeostatic mechanisms are based on the balance between the two divisions of the autonomic system, which results in tone for various organs that is based on the predominant input from the sympathetic or parasympathetic systems. Coordinating that balance requires integration that begins with forebrain structures like the hypothalamus and continues into the brain stem and spinal cord.

The Hypothalamus

The hypothalamus is the control center for many homeostatic mechanisms. It regulates both autonomic function and endocrine function. The roles it plays in the pupillary reflexes demonstrates the importance of this control center. The optic nerve projects primarily to the thalamus, which is the necessary relay to the occipital cortex for conscious visual perception. Another projection of the optic nerve, however, goes to the hypothalamus.

The hypothalamus then uses this visual system input to drive the pupillary reflexes. If the retina is activated by high levels of light, the hypothalamus stimulates the parasympathetic response. If the optic nerve message shows that low levels of light are falling on the retina, the hypothalamus activates the sympathetic response. Output

from the hypothalamus follows two main tracts, the **dorsal longitudinal fasciculus** and the **medial forebrain bundle** (Figure 2. Fiber Tracts of the Central Autonomic System). Along these two tracts, the hypothalamus can influence the Eddinger–Westphal nucleus of the oculomotor complex or the lateral horns of the thoracic spinal cord.

Fiber Tracts of the Central Autonomic System

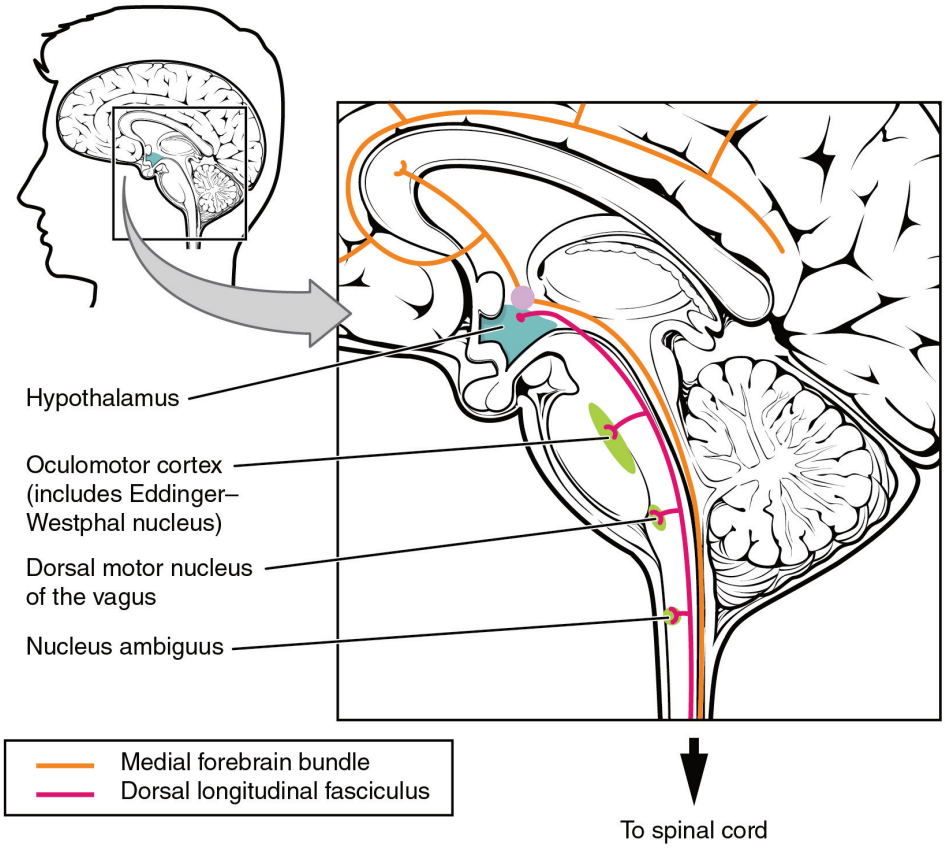


Figure 2. *The hypothalamus is the source of most of the central control of autonomic function. It receives input from cerebral structures and projects to brain stem and spinal cord structures to regulate the balance of sympathetic and parasympathetic input to the organ systems of the body. The main pathways for this are the medial forebrain bundle and the dorsal longitudinal fasciculus.*

These two tracts connect the hypothalamus with the major parasympathetic nuclei in the brain stem and the preganglionic (central) neurons of the thoracolumbar spinal cord. The hypothalamus also receives input from other areas of the forebrain through the medial forebrain bundle. The olfactory cortex, the septal nuclei of the basal forebrain, and the amygdala project into the hypothalamus through the medial forebrain bundle. These forebrain structures inform the hypothalamus about the state of the nervous system and can influence the regulatory processes of homeostasis. A good example of this is found in the amygdala, which is found beneath the cerebral cortex of the temporal lobe and plays a role in our ability to remember and feel emotions.

The Amygdala

The amygdala is a group of nuclei in the medial region of the temporal lobe that is part of the **limbic lobe** (Figure

3. The Limbic Lobe). The limbic lobe includes structures that are involved in emotional responses, as well as structures that contribute to memory function. The limbic lobe has strong connections with the hypothalamus and influences the state of its activity on the basis of emotional state. For example, when you are anxious or scared, the amygdala will send signals to the hypothalamus along the medial forebrain bundle that will stimulate the sympathetic fight-or-flight response. The hypothalamus will also stimulate the release of stress hormones through its control of the endocrine system in response to amygdala input.

The Limbic Lobe

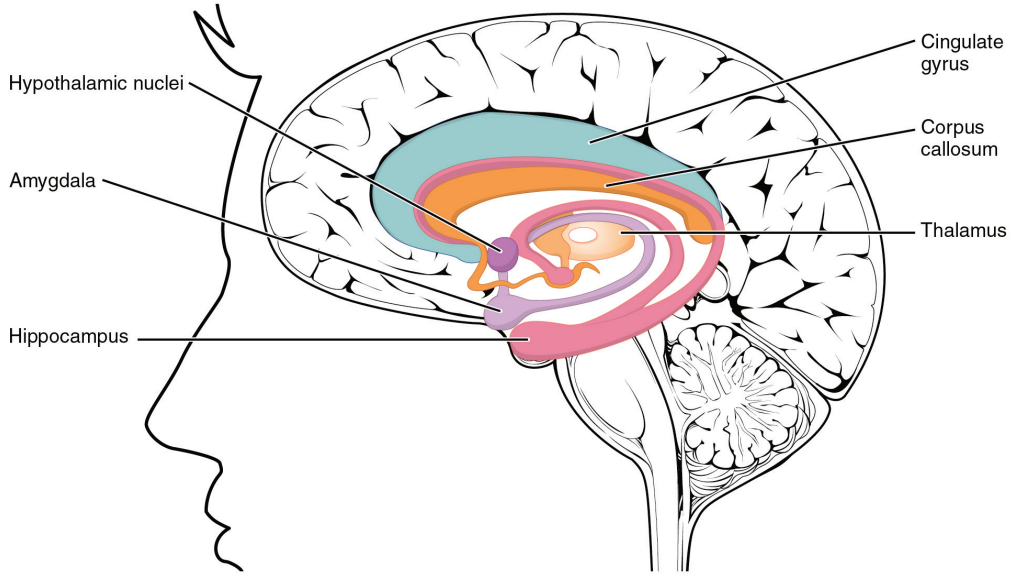


Figure 3. *Structures arranged around the edge of the cerebrum constitute the limbic lobe, which includes the amygdala, hippocampus, and cingulate gyrus, and connects to the hypothalamus.*

The Medulla

The medulla contains nuclei referred to as the **cardiovascular center**, which controls the smooth and cardiac muscle of the cardiovascular system through autonomic connections. When the homeostasis of the cardiovascular system shifts, such as when blood pressure changes, the coordination of the autonomic system can be accomplished within this region. Furthermore, when descending inputs from the hypothalamus stimulate this area, the sympathetic system can increase activity in the cardiovascular system, such as in response to anxiety or stress. The preganglionic sympathetic fibers that are responsible for increasing heart rate are referred to as the **cardiac accelerator nerves**, whereas the preganglionic sympathetic fibers responsible for constricting blood vessels compose the **vasomotor nerves**.

Several brain stem nuclei are important for the visceral control of major organ systems. One brain stem nucleus involved in cardiovascular function is the solitary nucleus. It receives sensory input about blood pressure and cardiac function from the glossopharyngeal and vagus nerves, and its output will activate sympathetic stimulation of the heart or blood vessels through the upper thoracic lateral horn. Another brain stem nucleus important for visceral control is the dorsal motor nucleus of the vagus nerve, which is the motor nucleus for the parasympathetic functions ascribed to the vagus nerve, including decreasing the heart rate, relaxing bronchial tubes in the lungs, and activating digestive function through the enteric nervous system. The nucleus ambiguus, which is named for its ambiguous histology, also contributes to the parasympathetic output of the

vagus nerve and targets muscles in the pharynx and larynx for swallowing and speech, as well as contributing to the parasympathetic tone of the heart along with the dorsal motor nucleus of the vagus.

EVERYDAY CONNECTIONS

Exercise and the Autonomic System

In addition to its association with the fight-or-flight response and rest-and-digest functions, the autonomic system is responsible for certain everyday functions. For example, it comes into play when homeostatic mechanisms dynamically change, such as the physiological changes that accompany exercise. Getting on the treadmill and putting in a good workout will cause the heart rate to increase, breathing to be stronger and deeper, sweat glands to activate, and the digestive system to suspend activity. These are the same physiological changes associated with the fight-or-flight response, but there is nothing chasing you on that treadmill.

This is not a simple homeostatic mechanism at work because "maintaining the internal environment" would mean getting all those changes back to their set points. Instead, the sympathetic system has become active during exercise so that your body can cope with what is happening. A homeostatic mechanism is dealing with the conscious decision to push the body away from a resting state. The heart, actually, is moving away from its homeostatic set point. Without any input from the autonomic system, the heart would beat at approximately 100 bpm, and the parasympathetic system slows that down to the resting rate of approximately 70 bpm. But in the middle of a good workout, you should see your heart rate at 120–140 bpm. You could say that the body is stressed because of what you are doing to it. Homeostatic mechanisms are trying to keep blood pH in the normal range, or to keep body temperature under control, but those are in response to the choice to exercise.

Watch this video to learn about physical responses to emotion. The autonomic system, which is important for regulating the homeostasis of the organ systems, is also responsible for our physiological responses to emotions such as fear. The video summarizes the extent of the body's reactions and describes several effects of the autonomic system in response to fear. On the basis of what you have already studied about autonomic function, which effect would you expect to be associated with parasympathetic, rather than sympathetic, activity?

Chapter Review

The autonomic system integrates sensory information and higher cognitive processes to generate output, which balances homeostatic mechanisms. The central autonomic structure is the hypothalamus, which coordinates sympathetic and parasympathetic efferent pathways to regulate activities of the organ systems of the body. The majority of hypothalamic output travels through the medial forebrain bundle and the dorsal longitudinal fasciculus to influence brain stem and spinal components of the autonomic nervous system. The medial

forebrain bundle also connects the hypothalamus with higher centers of the limbic system where emotion can influence visceral responses. The amygdala is a structure within the limbic system that influences the hypothalamus in the regulation of the autonomic system, as well as the endocrine system.

These higher centers have descending control of the autonomic system through brain stem centers, primarily in the medulla, such as the cardiovascular center. This collection of medullary nuclei regulates cardiac function, as well as blood pressure. Sensory input from the heart, aorta, and carotid sinuses project to these regions of the medulla. The solitary nucleus increases sympathetic tone of the cardiovascular system through the cardiac accelerator and vasomotor nerves. The nucleus ambiguus and the dorsal motor nucleus both contribute fibers to the vagus nerve, which exerts parasympathetic control of the heart by decreasing heart rate.

Drugs that Affect the Autonomic System

By the end of this section, you will be able to:

- List the classes of pharmaceuticals that interact with the autonomic nervous system
- Differentiate between cholinergic and adrenergic compounds
- Differentiate between sympathomimetic and sympatholytic drugs
- Relate the consequences of nicotine abuse with respect to autonomic control of the cardiovascular system

An important way to understand the effects of native neurochemicals in the autonomic system is in considering the effects of pharmaceutical drugs. This can be considered in terms of how drugs change autonomic function. These effects will primarily be based on how drugs act at the receptors of the autonomic system neurochemistry. The signaling molecules of the nervous system interact with proteins in the cell membranes of various target cells. In fact, no effect can be attributed to just the signaling molecules themselves without considering the receptors. A chemical that the body produces to interact with those receptors is called an **endogenous chemical**, whereas a chemical introduced to the system from outside is an **exogenous chemical**. Exogenous chemicals may be of a natural origin, such as a plant extract, or they may be synthetically produced in a pharmaceutical laboratory.

Broad Autonomic Effects

One important drug that affects the autonomic system broadly is not a pharmaceutical therapeutic agent associated with the system. This drug is nicotine. The effects of nicotine on the autonomic nervous system are important in considering the role smoking can play in health.

All ganglionic neurons of the autonomic system, in both sympathetic and parasympathetic ganglia, are activated by ACh released from preganglionic fibers. The ACh receptors on these neurons are of the nicotinic

type, meaning that they are ligand-gated ion channels. When the neurotransmitter released from the preganglionic fiber binds to the receptor protein, a channel opens to allow positive ions to cross the cell membrane. The result is depolarization of the ganglia. Nicotine acts as an ACh analog at these synapses, so when someone takes in the drug, it binds to these ACh receptors and activates the ganglionic neurons, causing them to depolarize.

Ganglia of both divisions are activated equally by the drug. For many target organs in the body, this results in no net change. The competing inputs to the system cancel each other out and nothing significant happens. For example, the sympathetic system will cause sphincters in the digestive tract to contract, limiting digestive propulsion, but the parasympathetic system will cause the contraction of other muscles in the digestive tract, which will try to push the contents of the digestive system along. The end result is that the food does not really move along and the digestive system has not appreciably changed.

The system in which this can be problematic is in the cardiovascular system, which is why smoking is a risk factor for cardiovascular disease. First, there is no significant parasympathetic regulation of blood pressure. Only a limited number of blood vessels are affected by parasympathetic input, so nicotine will preferentially cause the vascular tone to become more sympathetic, which means blood pressure will be increased. Second, the autonomic control of the heart is special. Unlike skeletal or smooth muscles, cardiac muscle is intrinsically active, meaning that it generates its own action potentials. The autonomic system does not cause the heart to beat, it just speeds it up (sympathetic) or slows it down (parasympathetic). The mechanisms for this are not mutually exclusive, so the heart receives conflicting signals, and the rhythm of the heart can be affected (Figure 1. Autonomic Connections to Heart and Blood Vessels).

Autonomic Connections to Heart and Blood Vessels

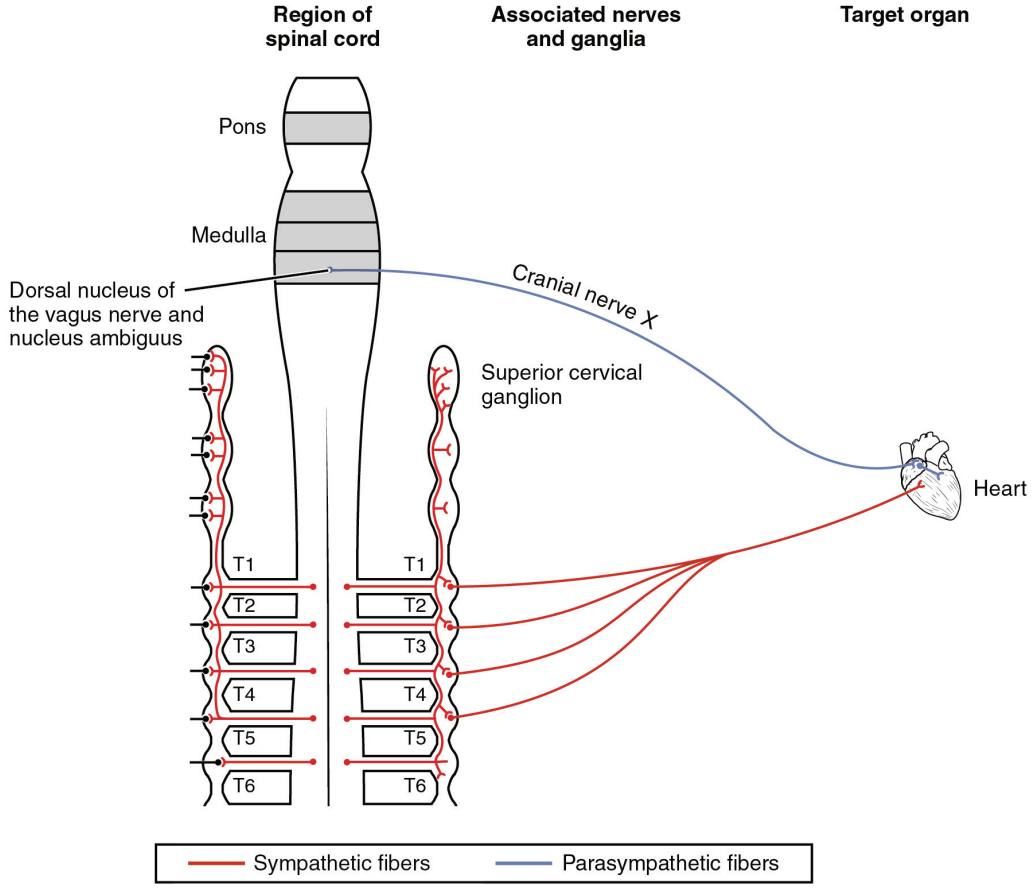


Figure 1. *The nicotinic receptor is found on all autonomic ganglia, but the cardiovascular connections are particular, and do not conform to the usual competitive projections that would just cancel each other out when stimulated by nicotine. The opposing signals to the heart would both depolarize and hyperpolarize the heart cells that establish the rhythm of the heartbeat, likely causing arrhythmia. Only the sympathetic system governs systemic blood pressure so nicotine would cause an increase.*

Sympathetic Effect

The neurochemistry of the sympathetic system is based on the adrenergic system. Norepinephrine and epinephrine influence target effectors by binding to the α-adrenergic or β-adrenergic receptors. Drugs that affect the sympathetic system affect these chemical systems. The drugs can be classified by whether they enhance the functions of the sympathetic system or interrupt those functions. A drug that enhances adrenergic function is known as a **sympathomimetic drug**, whereas a drug that interrupts adrenergic function is a **sympatholytic drug**.

Sympathomimetic Drugs

When the sympathetic system is not functioning correctly or the body is in a state of homeostatic imbalance, these drugs act at postganglionic terminals and synapses in the sympathetic efferent pathway. These drugs either bind to particular adrenergic receptors and mimic norepinephrine at the synapses between sympathetic postganglionic fibers and their targets, or they increase the production and release of norepinephrine from postganglionic fibers. Also, to increase the effectiveness of adrenergic chemicals released from the fibers, some of these drugs may block the removal or reuptake of the neurotransmitter from the synapse.

A common sympathomimetic drug is phenylephrine, which is a common component of decongestants. It can also be used to dilate the pupil and to raise blood pressure. Phenylephrine is known as an α_1-adrenergic agonist, meaning that it binds to a specific adrenergic receptor, stimulating a response. In this role, phenylephrine will bind to the adrenergic receptors in bronchioles of the lungs and cause them to dilate. By opening these structures, accumulated mucus can be cleared out of the lower respiratory tract. Phenylephrine is often paired with other pharmaceuticals, such as analgesics, as in the "sinus" version of many over-the-counter drugs, such as Tylenol Sinus® or Excedrin Sinus®, or in expectorants for chest congestion such as in Robitussin CF®.

A related molecule, called pseudoephedrine, was much more commonly used in these applications than was phenylephrine, until the molecule became useful in the illicit production of amphetamines. Phenylephrine is not as effective as a drug because it can be partially broken down in the digestive tract before it is ever absorbed. Like the adrenergic agents, phenylephrine is effective in dilating the pupil, known as **mydriasis** (Figure 2. Mydriasis). Phenylephrine is used during an eye exam in an ophthalmologist's or optometrist's office for this purpose. It can also be used to increase blood pressure in situations in which cardiac function is compromised, such as under anesthesia or during septic shock.

Mydriasis

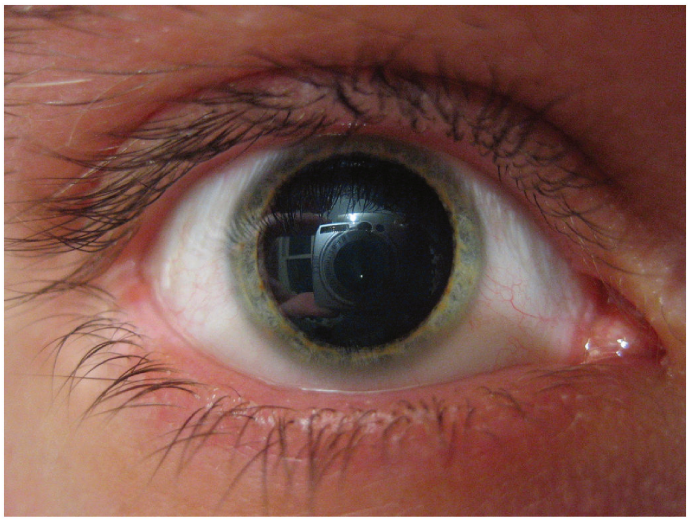


Figure 2. *The sympathetic system causes pupillary dilation when norepinephrine binds to an adrenergic receptor in the radial fibers of the iris smooth muscle. Phenylephrine mimics this action by binding to the same receptor when drops are applied onto the surface of the eye in a doctor's office. (credit: Corey Theiss)*

Other drugs that enhance adrenergic function are not associated with therapeutic uses, but affect the functions of the sympathetic system in a similar fashion. Cocaine primarily interferes with the uptake of dopamine at the synapse and can also increase adrenergic function. Caffeine is an antagonist to a different neurotransmitter receptor, called the adenosine receptor. Adenosine will suppress adrenergic activity, specifically the release of norepinephrine at synapses, so caffeine indirectly increases adrenergic activity. There is some evidence that caffeine can aid in the therapeutic use of drugs, perhaps by potentiating (increasing) sympathetic function, as is suggested by the inclusion of caffeine in over-the-counter analgesics such as Excedrin®.

Sympatholytic Drugs

Drugs that interfere with sympathetic function are referred to as sympatholytic, or sympathoplegic, drugs. They primarily work as an **antagonist** to the adrenergic receptors. They block the ability of norepinephrine or epinephrine to bind to the receptors so that the effect is "cut" or "takes a blow," to refer to the endings "-lytic" and "-plegic," respectively. The various drugs of this class will be specific to α-adrenergic or β-adrenergic receptors, or to their receptor subtypes.

Possibly the most familiar type of sympatholytic drug are the β-blockers. These drugs are often used to treat cardiovascular disease because they block the β-receptors associated with vasoconstriction and cardioacceleration. By allowing blood vessels to dilate, or keeping heart rate from increasing, these drugs can improve cardiac function in a compromised system, such as for a person with congestive heart failure or who has previously suffered a heart attack. A couple of common versions of β-blockers are metoprolol, which specifically blocks the β_1-receptor, and propanolol, which nonspecifically blocks β-receptors. There are other drugs that are α-blockers and can affect the sympathetic system in a similar way.

Other uses for sympatholytic drugs are as anti-anxiety medications. A common example of this is clonidine, which is an α-agonist. The sympathetic system is tied to anxiety to the point that the sympathetic response can be referred to as "fight, flight, or fright." Clonidine is used for other treatments aside from hypertension and anxiety, including pain conditions and attention deficit hyperactivity disorder.

Parasympathetic Effects

Drugs affecting parasympathetic functions can be classified into those that increase or decrease activity at postganglionic terminals. Parasympathetic postganglionic fibers release ACh, and the receptors on the targets are muscarinic receptors. There are several types of muscarinic receptors, M1–M5, but the drugs are not usually specific to the specific types. Parasympathetic drugs can be either muscarinic agonists or antagonists, or have indirect effects on the cholinergic system. Drugs that enhance cholinergic effects are called **parasympathomimetic drugs**, whereas those that inhibit cholinergic effects are referred to as **anticholinergic drugs**.

Pilocarpine is a nonspecific muscarinic agonist commonly used to treat disorders of the eye. It reverses mydriasis, such as is caused by phenylephrine, and can be administered after an eye exam. Along with constricting the pupil through the smooth muscle of the iris, pilocarpine will also cause the ciliary muscle to contract. This will open perforations at the base of the cornea, allowing for the drainage of aqueous humor from the anterior compartment of the eye and, therefore, reducing intraocular pressure related to glaucoma.

Atropine and scopolamine are part of a class of muscarinic antagonists that come from the *Atropa* genus of plants that include belladonna or deadly nightshade (Figure 3. Belladonna Plant). The name of one of these plants, belladonna, refers to the fact that extracts from this plant were used cosmetically for dilating the pupil. The active chemicals from this plant block the muscarinic receptors in the iris and allow the pupil to dilate, which is considered attractive because it makes the eyes appear larger. Humans are instinctively attracted to anything with larger eyes, which comes from the fact that the ratio of eye-to-head size is different in infants (or baby animals) and can elicit an emotional response. The cosmetic use of belladonna extract was essentially acting on this response. Atropine is no longer used in this cosmetic capacity for reasons related to the other name for the plant, which is deadly nightshade. Suppression of parasympathetic function, especially when it becomes systemic, can be fatal. Autonomic regulation is disrupted and anticholinergic symptoms develop. The berries of this plant are highly toxic, but can be mistaken for other berries. The antidote for atropine or scopolamine poisoning is pilocarpine.

Belladonna Plant

Figure 3. *The plant from the genus* Atropa, *which is known as belladonna or deadly nightshade, was used cosmetically to dilate pupils, but can be fatal when ingested. The berries on the plant may seem attractive as a fruit, but they contain the same anticholinergic compounds as the rest of the plant.*

Sympathetic and Parasympathetic Effects of Different Drug Types

Drug type	Example(s)	Sympathetic effect	Parasympathetic effect	Overall result
Nicotinic agonists	Nicotine	Mimic ACh at preganglionic synapses, causing activation of postganglionic fibers and the release of norepinephrine onto the target organ	Mimic ACh at preganglionic synapses, causing activation of postganglionic fibers and the release of ACh onto the target organ	Most conflicting signals cancel each other out, but cardiovascular system is susceptible to hypertension and arrhythmias
Sympathomimetic drugs	Phenylephrine	Bind to adrenergic receptors or mimics sympathetic action in some other way	No effect	Increase sympathetic tone
Sympatholytic drugs	β-blockers such as propanolol or metoprolol; α-agonists such as clonidine	Block binding to adrenergic drug or decrease adrenergic signals	No effect	Increase parasympathetic tone
Parasymphatho-mimetics/ muscarinic agonists	Pilocarpine	No effect, except on sweat glands	Bind to muscarinic receptor, similar to ACh	Increase parasympathetic tone
Anticholinergics/ muscarinic antagonists	Atropine, scopolamine, dimenhydrinate	No effect	Block muscarinic receptors and parasympathetic function	Increase sympathetic tone

DISORDERS OF THE...

Autonomic Nervous System

Approximately 33 percent of people experience a mild problem with motion sickness, whereas up to 66 percent experience motion sickness under extreme conditions, such as being on a tossing boat with no view of the horizon. Connections between regions in the brain stem and the autonomic system result in the symptoms of nausea, cold sweats, and vomiting.

The part of the brain responsible for vomiting, or emesis, is known as the area postrema. It is located next to the fourth ventricle and is not restricted by the blood–brain barrier, which allows it to respond to chemicals in the bloodstream—namely, toxins that will stimulate emesis. There are significant connections between this area, the solitary nucleus, and the dorsal motor nucleus of the vagus nerve. These autonomic system and nuclei connections are associated with the symptoms of motion sickness.

Motion sickness is the result of conflicting information from the visual and vestibular systems. If motion is perceived by the visual system without the complementary vestibular stimuli, or through vestibular stimuli without visual confirmation, the brain stimulates emesis and the associated symptoms. The area postrema, by itself, appears to be able to stimulate emesis in response to toxins in the blood, but it is also connected to the autonomic system and can trigger a similar response to motion.

Autonomic drugs are used to combat motion sickness. Though it is often described as a dangerous

and deadly drug, scopolamine is used to treat motion sickness. A popular treatment for motion sickness is the transdermal scopolamine patch. Scopolamine is one of the substances derived from the *Atropa* genus along with atropine. At higher doses, those substances are thought to be poisonous and can lead to an extreme sympathetic syndrome. However, the transdermal patch regulates the release of the drug, and the concentration is kept very low so that the dangers are avoided. For those who are concerned about using "The Most Dangerous Drug," as some websites will call it, antihistamines such as dimenhydrinate (Dramamine®) can be used.

Watch this video to learn about the side effects of 3-D movies. As discussed in this video, movies that are shot in 3-D can cause motion sickness, which elicits the autonomic symptoms of nausea and sweating. The disconnection between the perceived motion on the screen and the lack of any change in equilibrium stimulates these symptoms. Why do you think sitting close to the screen or right in the middle of the theater makes motion sickness during a 3-D movie worse?

Chapter Review

The autonomic system is affected by a number of exogenous agents, including some that are therapeutic and some that are illicit. These drugs affect the autonomic system by mimicking or interfering with the endogenous agents or their receptors. A survey of how different drugs affect autonomic function illustrates the role that the neurotransmitters and hormones play in autonomic function. Drugs can be thought of as chemical tools to effect changes in the system with some precision, based on where those drugs are effective.

Nicotine is not a drug that is used therapeutically, except for smoking cessation. When it is introduced into the body via products, it has broad effects on the autonomic system. Nicotine carries a risk for cardiovascular disease because of these broad effects. The drug stimulates both sympathetic and parasympathetic ganglia at the preganglionic fiber synapse. For most organ systems in the body, the competing input from the two postganglionic fibers will essentially cancel each other out. However, for the cardiovascular system, the results are different. Because there is essentially no parasympathetic influence on blood pressure for the entire body, the sympathetic input is increased by nicotine, causing an increase in blood pressure. Also, the influence that the autonomic system has on the heart is not the same as for other systems. Other organs have smooth muscle or glandular tissue that is activated or inhibited by the autonomic system. Cardiac muscle is intrinsically active and is modulated by the autonomic system. The contradictory signals do not just cancel each other out, they alter the regularity of the heart rate and can cause arrhythmias. Both hypertension and arrhythmias are risk factors for heart disease.

Other drugs affect one division of the autonomic system or the other. The sympathetic system is affected by drugs that mimic the actions of adrenergic molecules (norepinephrine and epinephrine) and are called sympathomimetic drugs. Drugs such as phenylephrine bind to the adrenergic receptors and stimulate target organs just as sympathetic activity would. Other drugs are sympatholytic because they block adrenergic activity

and cancel the sympathetic influence on the target organ. Drugs that act on the parasympathetic system also work by either enhancing the postganglionic signal or blocking it. A muscarinic agonist (or parasympathomimetic drug) acts just like ACh released by the parasympathetic postganglionic fiber. Anticholinergic drugs block muscarinic receptors, suppressing parasympathetic interaction with the organ.

License

1.6 The Neurological Exam

Introduction

Neurological Exam

Figure 1. *Health care professionals, such as this air force nurse, can rapidly assess the neurological functions of a patient using the neurological exam. One part of the exam is the inspection of the oral cavity and pharynx, which enables the doctor to not only inspect the tissues for signs of infection, but also provides a means to test the functions of the cranial nerves associated with the oral cavity. (credit: U.S. Department of Defense)*

After studying this chapter, you will be able to:

- Describe the major sections of the neurological exam
- Outline the benefits of rapidly assessing neurological function
- Relate anatomical structures of the nervous system to specific functions

- Diagram the connections of the nervous system to the musculature and integument involved in primary sensorimotor responses
- Compare and contrast the somatic and visceral reflexes with respect to how they are assessed through the neurological exam

A man arrives at the hospital after feeling faint and complaining of a "pins-and-needles" feeling all along one side of his body. The most likely explanation is that he has suffered a stroke, which has caused a loss of oxygen to a particular part of the central nervous system (CNS). The problem is finding where in the entire nervous system the stroke has occurred. By checking reflexes, sensory responses, and motor control, a health care provider can focus on what abilities the patient may have lost as a result of the stroke and can use this information to determine where the injury occurred. In the emergency department of the hospital, this kind of rapid assessment of neurological function is key to treating trauma to the nervous system. In the classroom, the neurological exam is a valuable tool for learning the anatomy and physiology of the nervous system because it allows you to relate the functions of the system to particular locations in the nervous system.

As a student of anatomy and physiology, you may be planning to go into an allied health field, perhaps nursing or physical therapy. You could be in the emergency department treating a patient such as the one just described. An important part of this course is to understand the nervous system. This can be especially challenging because you need to learn about the nervous system using your own nervous system. The first chapter in this unit about the nervous system began with a quote: "If the human brain were simple enough for us to understand, we would be too simple to understand it." However, you are being asked to understand aspects of it. A healthcare provider can pinpoint problems with the nervous system in minutes by running through the series of tasks to test neurological function that are described in this chapter. You can use the same approach, though not as quickly, to learn about neurological function and its relationship to the structures of the nervous system.

Nervous tissue is different from other tissues in that it is not classified into separate tissue types. It does contain two types of cells, neurons and glia, but it is all just nervous tissue. White matter and gray matter are not types of nervous tissue, but indications of different specializations within the nervous tissue. However, not all nervous tissue performs the same function. Furthermore, specific functions are not wholly localized to individual brain structures in the way that other bodily functions occur strictly within specific organs. In the CNS, we must consider the connections between cells over broad areas, not just the function of cells in one particular nucleus or region. In a broad sense, the nervous system is responsible for the majority of electrochemical signaling in the body, but the use of those signals is different in various regions.

The nervous system is made up of the brain and spinal cord as the central organs, and the ganglia and nerves as organs in the periphery. The brain and spinal cord can be thought of as a collection of smaller organs, most of which would be the nuclei (such as the oculomotor nuclei), but white matter structures play an important role (such as the corpus callosum). Studying the nervous system requires an understanding of the varied physiology of the nervous system. For example, the hypothalamus plays a very different role than the visual cortex. The neurological exam provides a way to elicit behavior that represents those varied functions.

Overview of the Neurological Exam

By the end of this section, you will be able to:

- List the major sections of the neurological exam
- Explain the connection between location and function in the nervous system
- Explain the benefit of a rapid assessment for neurological function in a clinical setting
- List the causes of neurological deficits
- Describe the different ischemic events in the nervous system

The **neurological exam** is a clinical assessment tool used to determine what specific parts of the CNS are affected by damage or disease. It can be performed in a short time—sometimes as quickly as 5 minutes—to establish neurological function. In the emergency department, this rapid assessment can make the difference with respect to proper treatment and the extent of recovery that is possible.

The exam is a series of subtests separated into five major sections. The first of these is the **mental status exam**, which assesses the higher cognitive functions such as memory, orientation, and language. Then there is the **cranial nerve exam**, which tests the function of the 12 cranial nerves and, therefore, the central and peripheral structures associated with them. The cranial nerve exam tests the sensory and motor functions of each of the nerves, as applicable. Two major sections, the **sensory exam** and the **motor exam**, test the sensory and motor functions associated with spinal nerves. Finally, the **coordination exam** tests the ability to perform complex and coordinated movements. The **gait exam**, which is often considered a sixth major exam, specifically assesses the motor function of walking and can be considered part of the coordination exam because walking is a coordinated movement.

Neuroanatomy and the Neurological Exam

Localization of function is the concept that circumscribed locations are responsible for specific functions. The neurological exam highlights this relationship. For example, the cognitive functions that are assessed in the mental status exam are based on functions in the cerebrum, mostly in the cerebral cortex. Several of the subtests examine language function. Deficits in neurological function uncovered by these examinations usually point to damage to the left cerebral cortex. In the majority of individuals, language function is localized to the left hemisphere between the superior temporal lobe and the posterior frontal lobe, including the intervening connections through the inferior parietal lobe.

The five major sections of the neurological exam are related to the major regions of the CNS (Figure 1. Anatomical Underpinnings of the Neurological Exam). The mental status exam assesses functions related to the cerebrum. The cranial nerve exam is for the nerves that connect to the diencephalon and brain stem (as well as the olfactory connections to the forebrain). The coordination exam and the related gait exam primarily assess the functions of the cerebellum. The motor and sensory exams are associated with the spinal cord and its connections through the spinal nerves.

Anatomical Underpinnings of the Neurological Exam

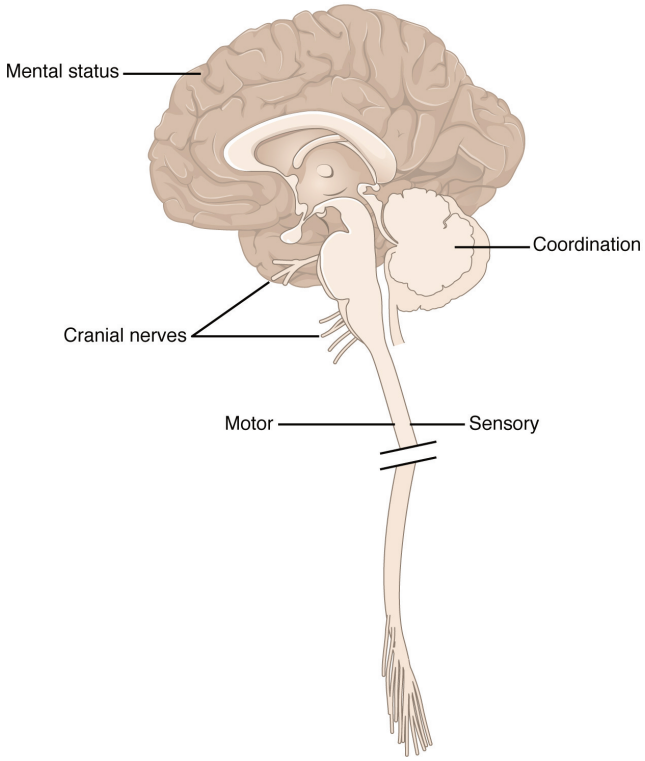


Figure 1. *The different regions of the CNS relate to the major sections of the neurological exam: the mental status exam, cranial nerve exam, sensory exam, motor exam, and coordination exam (including the gait exam).*

Part of the power of the neurological exam is this link between structure and function. Testing the various functions represented in the exam allows an accurate estimation of where the nervous system may be damaged. Consider the patient described in the chapter introduction. In the emergency department, he is given a quick exam to find where the deficit may be localized. Knowledge of where the damage occurred will lead to the most effective therapy.

In rapid succession, he is asked to smile, raise his eyebrows, stick out his tongue, and shrug his shoulders. The doctor tests muscular strength by providing resistance against his arms and legs while he tries to lift them. With his eyes closed, he has to indicate when he feels the tip of a pen touch his legs, arms, fingers, and face. He follows the tip of a pen as the doctor moves it through the visual field and finally toward his face. A formal mental status exam is not needed at this point; the patient will demonstrate any possible deficits in that area during normal interactions with the interviewer. If cognitive or language deficits are apparent, the interviewer can pursue mental status in more depth. All of this takes place in less than 5 minutes. The patient reports that he feels pins and needles in his left arm and leg, and has trouble feeling the tip of the pen when he is touched on those limbs. This suggests a problem with the sensory systems between the spinal cord and the brain. The emergency department has a lead to follow before a CT scan is performed. He is put on aspirin therapy to limit the possibility of blood clots forming, in case the cause is an embolus—an obstruction such as a blood clot that blocks the flow of blood in an artery or vein.

Watch this video to see a demonstration of the neurological exam—a series of tests that can be performed rapidly when a patient is initially brought into an emergency department. The exam can be repeated on a regular basis to keep a record of how and if neurological function changes over time. In what order were the sections of the neurological exam tested in this video, and which section seemed to be left out?

Causes of Neurological Deficits

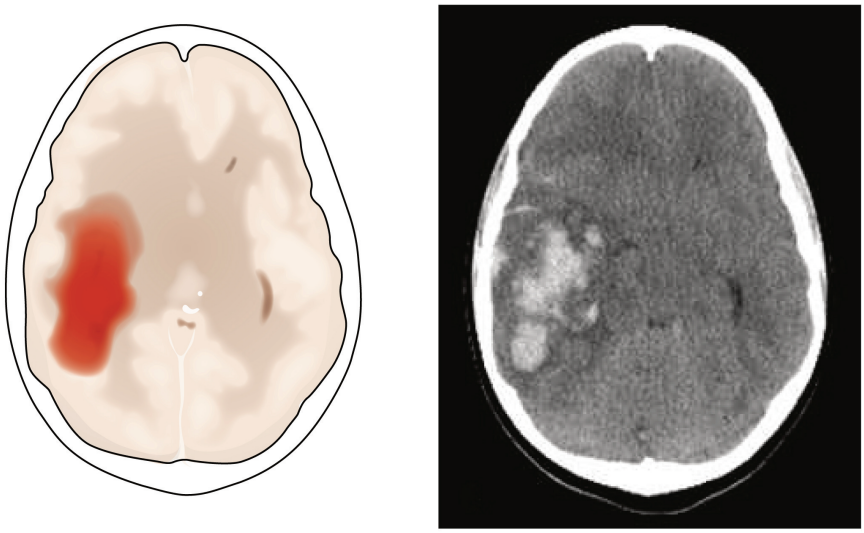
Damage to the nervous system can be limited to individual structures or can be distributed across broad areas of the brain and spinal cord. Localized, limited injury to the nervous system is most often the result of circulatory problems. Neurons are very sensitive to oxygen deprivation and will start to deteriorate within 1 or 2 minutes, and permanent damage (cell death) could result within a few hours. The loss of blood flow to part of the brain is known as a **stroke**, or a cerebrovascular accident (CVA).

There are two main types of stroke, depending on how the blood supply is compromised: ischemic and hemorrhagic. An **ischemic stroke** is the loss of blood flow to an area because vessels are blocked or narrowed. This is often caused by an embolus, which may be a blood clot or fat deposit. Ischemia may also be the result of thickening of the blood vessel wall, or a drop in blood volume in the brain known as **hypovolemia**.

A related type of CVA is known as a **transient ischemic attack (TIA)**, which is similar to a stroke although it does not last as long. The diagnostic definition of a stroke includes effects that last at least 24 hours. Any stroke symptoms that are resolved within a 24-hour period because of restoration of adequate blood flow are classified as a TIA.

A **hemorrhagic stroke** is bleeding into the brain because of a damaged blood vessel. Accumulated blood fills a region of the cranial vault and presses against the tissue in the brain (Figure 2. Hemorrhagic Stroke). Physical pressure on the brain can cause the loss of function, as well as the squeezing of local arteries resulting in compromised blood flow beyond the site of the hemorrhage. As blood pools in the nervous tissue and the vasculature is damaged, the blood-brain barrier can break down and allow additional fluid to accumulate in the region, which is known as **edema**.

Hemorrhagic Stroke



(a) (b)

Figure 2. *(a) A hemorrhage into the tissue of the cerebrum results in a large accumulation of blood with an additional edema in the adjacent tissue. The hemorrhagic area causes the entire brain to be disfigured as suggested here by the lateral ventricles being squeezed into the opposite hemisphere. (b) A CT scan shows an intraparenchymal hemorrhage within the parietal lobe. (credit b: James Heilman)*

Whereas hemorrhagic stroke may involve bleeding into a large region of the CNS, such as into the deep white matter of a cerebral hemisphere, other events can cause widespread damage and loss of neurological functions. Infectious diseases can lead to loss of function throughout the CNS as components of nervous tissue, specifically astrocytes and microglia, react to the disease. Blunt force trauma, such as from a motor vehicle accident, can physically damage the CNS.

A class of disorders that affect the nervous system are the neurodegenerative diseases: Alzheimer's disease, Parkinson's disease, Huntington's disease, amyotrophic lateral sclerosis (ALS), Creutzfeld–Jacob disease, multiple sclerosis (MS), and other disorders that are the result of nervous tissue degeneration. In diseases like Alzheimer's, Parkinson's, or ALS, neurons die; in diseases like MS, myelin is affected. Some of these disorders affect motor function, and others present with dementia. How patients with these disorders perform in the neurological exam varies, but is often broad in its effects, such as memory deficits that compromise many aspects of the mental status exam, or movement deficits that compromise aspects of the cranial nerve exam, the motor exam, or the coordination exam. The causes of these disorders are also varied. Some are the result of genetics, such as Huntington's disease, or the result of autoimmunity, such as MS; others are not entirely understood, such as Alzheimer's and Parkinson's diseases. Current research suggests that many of these diseases are related in how the degeneration takes place and may be treated by common therapies.

Finally, a common cause of neurological changes is observed in developmental disorders. Whether the result of genetic factors or the environment during development, there are certain situations that result in neurological functions being different from the expected norms. Developmental disorders are difficult to define because they are caused by defects that existed in the past and disrupted the normal development of the CNS. These defects probably involve multiple environmental and genetic factors—most of the time, we don't know what the cause is other than that it is more complex than just one factor. Furthermore, each defect on its own may not be a problem, but when several are added together, they can disrupt growth processes that are not well understand in the first place. For instance, it is possible for a stroke to damage a specific region of the brain and lead to the loss of the ability to recognize faces (prosopagnosia). The link between cell death in the fusiform gyrus and the symptom is relatively easy to understand. In contrast, similar deficits can be seen in children with the

developmental disorder, autism spectrum disorder (ASD). However, these children do not lack a fusiform gyrus, nor is there any damage or defect visible to this brain region. We conclude, rather poorly, that this brain region is not connected properly to other brain regions.

Infection, trauma, and congenital disorders can all lead to significant signs, as identified through the neurological exam. It is important to differentiate between an acute event, such as stroke, and a chronic or global condition such as blunt force trauma. Responses seen in the neurological exam can help. A loss of language function observed in all its aspects is more likely a global event as opposed to a discrete loss of one function, such as not being able to say certain types of words. A concern, however, is that a specific function—such as controlling the muscles of speech—may mask other language functions. The various subtests within the mental status exam can address these finer points and help clarify the underlying cause of the neurological loss.

Watch this video for an introduction to the neurological exam. Studying the neurological exam can give insight into how structure and function in the nervous system are interdependent. This is a tool both in the clinic and in the classroom, but for different reasons. In the clinic, this is a powerful but simple tool to assess a patient's neurological function. In the classroom, it is a different way to think about the nervous system. Though medical technology provides noninvasive imaging and real-time functional data, the presenter says these cannot replace the history at the core of the medical examination. What does history mean in the context of medical practice?

Chapter Review

The neurological exam is a clinical assessment tool to determine the extent of function from the nervous system. It is divided into five major sections that each deal with a specific region of the CNS. The mental status exam is concerned with the cerebrum and assesses higher functions such as memory, language, and emotion. The cranial nerve exam tests the functions of all of the cranial nerves and, therefore, their connections to the CNS through the forebrain and brain stem. The sensory and motor exams assess those functions as they relate to the spinal cord, as well as the combination of the functions in spinal reflexes. The coordination exam targets cerebellar function in coordinated movements, including those functions associated with gait.

Damage to and disease of the nervous system lead to loss of function. The location of the injury will correspond to the functional loss, as suggested by the principle of localization of function. The neurological exam provides the opportunity for a clinician to determine where damage has occurred on the basis of the function that is lost. Damage from acute injuries such as strokes may result in specific functions being lost, whereas broader effects in infection or developmental disorders may result in general losses across an entire section of the neurological exam.

The Mental Status Exam

By the end of this section, you will be able to:

- Describe the relationship of mental status exam results to cerebral functions
- Explain the categorization of regions of the cortex based on anatomy and physiology
- Differentiate between primary, association, and integration areas of the cerebral cortex
- Provide examples of localization of function related to the cerebral cortex

In the clinical setting, the set of subtests known as the mental status exam helps us understand the relationship of the brain to the body. Ultimately, this is accomplished by assessing behavior. Tremors related to intentional movements, incoordination, or the neglect of one side of the body can be indicative of failures of the connections of the cerebrum either within the hemispheres, or from the cerebrum to other portions of the nervous system. There is no strict test for what the cerebrum does alone, but rather in what it does through its control of the rest of the CNS, the peripheral nervous system (PNS), and the musculature.

Sometimes eliciting a behavior is as simple as asking a question. Asking a patient to state his or her name is not only to verify that the file folder in a health care provider's hands is the correct one, but also to be sure that the patient is aware, oriented, and capable of interacting with another person. If the answer to "What is your name?" is "Santa Claus," the person may have a problem understanding reality. If the person just stares at the examiner with a confused look on their face, the person may have a problem understanding or producing speech.

Functions of the Cerebral Cortex

The cerebrum is the seat of many of the higher mental functions, such as memory and learning, language, and conscious perception, which are the subjects of subtests of the mental status exam. The cerebral cortex is the thin layer of gray matter on the outside of the cerebrum. It is approximately a millimeter thick in most regions and highly folded to fit within the limited space of the cranial vault. These higher functions are distributed across various regions of the cortex, and specific locations can be said to be responsible for particular functions. There is a limited set of regions, for example, that are involved in language function, and they can be subdivided on the basis of the particular part of language function that each governs.

The basis for parceling out areas of the cortex and attributing them to various functions has its root in pure anatomical underpinnings. The German neurologist and histologist Korbinian Brodmann, who made a careful study of the **cytoarchitecture** of the cerebrum around the turn of the nineteenth century, described approximately 50 regions of the cortex that differed enough from each other to be considered separate areas (Figure 1. Brodmann's Areas of the Cerebral Cortex). Brodmann made preparations of many different regions of the cerebral cortex to view with a microscope. He compared the size, shape, and number of neurons to find anatomical differences in the various parts of the cerebral cortex. Continued investigation into these anatomical areas over the subsequent 100 or more years has demonstrated a strong correlation between the structures and the functions attributed to those structures. For example, the first three areas in Brodmann's list—which

are in the postcentral gyrus—compose the primary somatosensory cortex. Within this area, finer separation can be made on the basis of the concept of the sensory homunculus, as well as the different submodalities of somatosensation such as touch, vibration, pain, temperature, or proprioception. Today, we more frequently refer to these regions by their function (i.e., primary sensory cortex) than by the number Brodmann assigned to them, but in some situations the use of Brodmann numbers persists.

Brodmann's Areas of the Cerebral Cortex

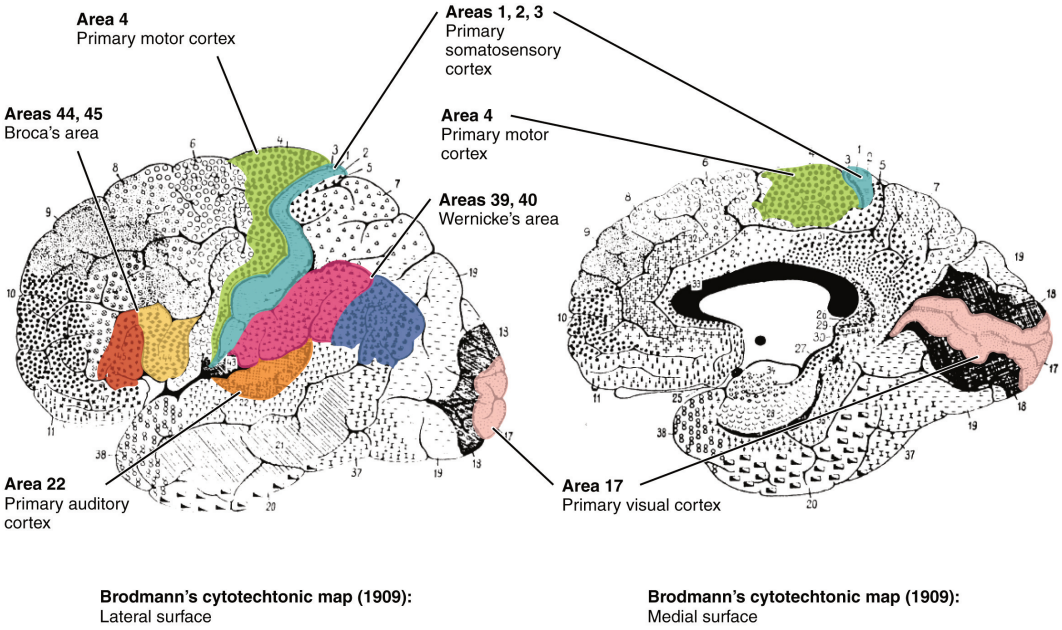


Figure 1. *On the basis of cytoarchitecture, the anatomist Korbinian Brodmann described the extensive array of cortical regions, as illustrated in his figure. Subsequent investigations found that these areas corresponded very well to functional differences in the cerebral cortex. (credit: modification of work by "Looie496"/Wikimedia Commons, based on original work by Korvinian Brodmann)*

Area 17, as Brodmann described it, is also known as the primary visual cortex. Adjacent to that are areas 18 and 19, which constitute subsequent regions of visual processing. Area 22 is the primary auditory cortex, and it is followed by area 23, which further processes auditory information. Area 4 is the primary motor cortex in the precentral gyrus, whereas area 6 is the premotor cortex. These areas suggest some specialization within the cortex for functional processing, both in sensory and motor regions. The fact that Brodmann's areas correlate so closely to functional localization in the cerebral cortex demonstrates the strong link between structure and function in these regions.

Areas 1, 2, 3, 4, 17, and 22 are each described as primary cortical areas. The adjoining regions are each referred to as association areas. Primary areas are where sensory information is initially received from the thalamus for conscious perception, or—in the case of the primary motor cortex—where descending commands are sent down to the brain stem or spinal cord to execute movements (Figure 2. Types of Cortical Areas).

Types of Cortical Areas

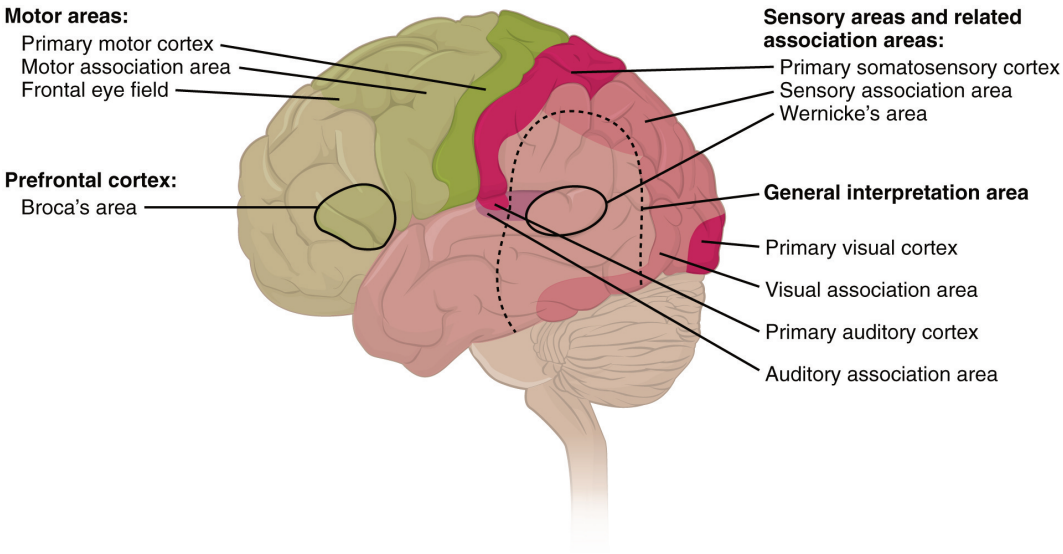


Figure 2. *The cerebral cortex can be described as containing three types of processing regions: primary, association, and integration areas. The primary cortical areas are where sensory information is initially processed, or where motor commands emerge to go to the brain stem or spinal cord. Association areas are adjacent to primary areas and further process the modality-specific input. Multimodal integration areas are found where the modality-specific regions meet; they can process multiple modalities together or different modalities on the basis of similar functions, such as spatial processing in vision or somatosensation.*

A number of other regions, which extend beyond these primary or association areas of the cortex, are referred to as integrative areas. These areas are found in the spaces between the domains for particular sensory or motor functions, and they integrate multisensory information, or process sensory or motor information in more complex ways. Consider, for example, the posterior parietal cortex that lies between the somatosensory cortex and visual cortex regions. This has been ascribed to the coordination of visual and motor functions, such as reaching to pick up a glass. The somatosensory function that would be part of this is the proprioceptive feedback from moving the arm and hand. The weight of the glass, based on what it contains, will influence how those movements are executed.

Cognitive Abilities

Assessment of cerebral functions is directed at cognitive abilities. The abilities assessed through the mental status exam can be separated into four groups: orientation and memory, language and speech, sensorium, and judgment and abstract reasoning.

Orientation and Memory

Orientation is the patient's awareness of his or her immediate circumstances. It is awareness of time, not in terms of the clock, but of the date and what is occurring around the patient. It is awareness of place, such that a patient should know where he or she is and why. It is also awareness of who the patient is—recognizing personal identity

and being able to relate that to the examiner. The initial tests of orientation are based on the questions, "Do you know what the date is?" or "Do you know where you are?" or "What is your name?" Further understanding of a patient's awareness of orientation can come from questions that address remote memory, such as "Who is the President of the United States?", or asking what happened on a specific date.

There are also specific tasks to address memory. One is the three-word recall test. The patient is given three words to recall, such as book, clock, and shovel. After a short interval, during which other parts of the interview continue, the patient is asked to recall the three words. Other tasks that assess memory—aside from those related to orientation—have the patient recite the months of the year in reverse order to avoid the overlearned sequence and focus on the memory of the months in an order, or to spell common words backwards, or to recite a list of numbers back.

Memory is largely a function of the temporal lobe, along with structures beneath the cerebral cortex such as the hippocampus and the amygdala. The storage of memory requires these structures of the medial temporal lobe. A famous case of a man who had both medial temporal lobes removed to treat intractable epilepsy provided insight into the relationship between the structures of the brain and the function of memory.

Henry Molaison, who was referred to as patient HM when he was alive, had epilepsy localized to both of his medial temporal lobes. In 1953, a bilateral lobectomy was performed that alleviated the epilepsy but resulted in the inability for HM to form new memories—a condition called **anterograde amnesia**. HM was able to recall most events from before his surgery, although there was a partial loss of earlier memories, which is referred to as **retrograde amnesia**. HM became the subject of extensive studies into how memory works. What he was unable to do was form new memories of what happened to him, what are now called **episodic memory**. Episodic memory is autobiographical in nature, such as remembering riding a bicycle as a child around the neighborhood, as opposed to the **procedural memory** of how to ride a bike. HM also retained his **short-term memory**, such as what is tested by the three-word task described above. After a brief period, those memories would dissipate or decay and not be stored in the long-term because the medial temporal lobe structures were removed.

The difference in short-term, procedural, and episodic memory, as evidenced by patient HM, suggests that there are different parts of the brain responsible for those functions. The long-term storage of episodic memory requires the hippocampus and related medial temporal structures, and the location of those memories is in the multimodal integration areas of the cerebral cortex. However, short-term memory—also called working or active memory—is localized to the prefrontal lobe. Because patient HM had only lost his medial temporal lobe—and lost very little of his previous memories, and did not lose the ability to form new short-term memories—it was concluded that the function of the hippocampus, and adjacent structures in the medial temporal lobe, is to move (or consolidate) short-term memories (in the pre-frontal lobe) to long-term memory (in the temporal lobe).

The prefrontal cortex can also be tested for the ability to organize information. In one subtest of the mental status exam called set generation, the patient is asked to generate a list of words that all start with the same letter, but not to include proper nouns or names. The expectation is that a person can generate such a list of at least 10 words within 1 minute. Many people can likely do this much more quickly, but the standard separates the accepted normal from those with compromised prefrontal cortices.

Read this article to learn about a young man who texts his fiancée in a panic as he finds that he is having trouble remembering things. At the hospital, a neurologist administers the mental status exam, which is mostly normal except for the three-word recall test. The young man could not recall them even 30 seconds after hearing them and repeating them back to the doctor. An undiscovered mass in the mediastinum region was found to be Hodgkin's lymphoma, a type of cancer that affects

the immune system and likely caused antibodies to attack the nervous system. The patient eventually regained his ability to remember, though the events in the hospital were always elusive. Considering that the effects on memory were temporary, but resulted in the loss of the specific events of the hospital stay, what regions of the brain were likely to have been affected by the antibodies and what type of memory does that represent?

Language and Speech

Language is, arguably, a very human aspect of neurological function. There are certainly strides being made in understanding communication in other species, but much of what makes the human experience seemingly unique is its basis in language. Any understanding of our species is necessarily reflective, as suggested by the question "What am I?" And the fundamental answer to this question is suggested by the famous quote by René Descartes: "Cogito Ergo Sum" (translated from Latin as "I think, therefore I am"). Formulating an understanding of yourself is largely describing who you are to yourself. It is a confusing topic to delve into, but language is certainly at the core of what it means to be self-aware.

The neurological exam has two specific subtests that address language. One measures the ability of the patient to understand language by asking them to follow a set of instructions to perform an action, such as "touch your right finger to your left elbow and then to your right knee." Another subtest assesses the fluency and coherency of language by having the patient generate descriptions of objects or scenes depicted in drawings, and by reciting sentences or explaining a written passage. Language, however, is important in so many ways in the neurological exam. The patient needs to know what to do, whether it is as simple as explaining how the knee-jerk reflex is going to be performed, or asking a question such as "What is your name?" Often, language deficits can be determined without specific subtests; if a person cannot reply to a question properly, there may be a problem with the reception of language.

An important example of multimodal integrative areas is associated with language function (Figure 3. Broca's and Wernicke's Areas). Adjacent to the auditory association cortex, at the end of the lateral sulcus just anterior to the viral cortex, is **Wernicke's area**. In the lateral aspect of the frontal lobe, just anterior to the region of the motor cortex associated with the head and neck, is Broca's area. Both regions were originally described on the basis of losses of speech and language, which is called **aphasia**. The aphasia associated with Broca's area is known as an **expressive aphasia**, which means that speech production is compromised. This type of aphasia is often described as non-fluency because the ability to say some words leads to broken or halting speech. Grammar can also appear to be lost. The aphasia associated with Wernicke's area is known as a receptive aphasia, which is not a loss of speech production, but a loss of understanding of content. Patients, after recovering from acute forms of this aphasia, report not being able to understand what is said to them or what they are saying themselves, but they often cannot keep from talking.

The two regions are connected by white matter tracts that run between the posterior temporal lobe and the lateral aspect of the frontal lobe. **Conduction aphasia** associated with damage to this connection refers to the problem of connecting the understanding of language to the production of speech. This is a very rare condition, but is likely to present as an inability to faithfully repeat spoken language.

Broca's and Wernicke's Areas

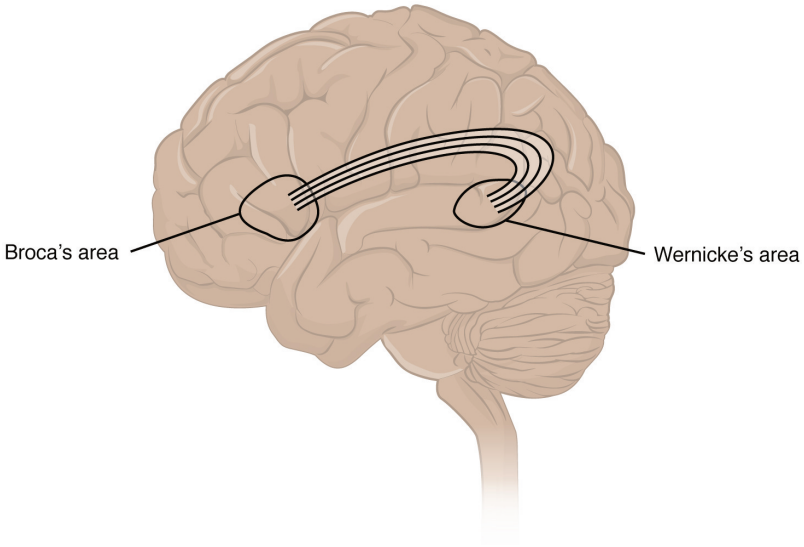


Figure 3. *Two important integration areas of the cerebral cortex associated with language function are Broca's and Wernicke's areas. The two areas are connected through the deep white matter running from the posterior temporal lobe to the frontal lobe.*

Sensorium

Those parts of the brain involved in the reception and interpretation of sensory stimuli are referred to collectively as the sensorium. The cerebral cortex has several regions that are necessary for sensory perception. From the primary cortical areas of the somatosensory, visual, auditory, and gustatory senses to the association areas that process information in these modalities, the cerebral cortex is the seat of conscious sensory perception. In contrast, sensory information can also be processed by deeper brain regions, which we may vaguely describe as subconscious—for instance, we are not constantly aware of the proprioceptive information that the cerebellum uses to maintain balance. Several of the subtests can reveal activity associated with these sensory modalities, such as being able to hear a question or see a picture. Two subtests assess specific functions of these cortical areas.

The first is **praxis**, a practical exercise in which the patient performs a task completely on the basis of verbal description without any demonstration from the examiner. For example, the patient can be told to take their left hand and place it palm down on their left thigh, then flip it over so the palm is facing up, and then repeat this four times. The examiner describes the activity without any movements on their part to suggest how the movements are to be performed. The patient needs to understand the instructions, transform them into movements, and use sensory feedback, both visual and proprioceptive, to perform the movements correctly.

The second subtest for sensory perception is **gnosis**, which involves two tasks. The first task, known as **stereognosis**, involves the naming of objects strictly on the basis of the somatosensory information that comes from manipulating them. The patient keeps their eyes closed and is given a common object, such as a coin, that they have to identify. The patient should be able to indicate the particular type of coin, such as a dime versus a penny, or a nickel versus a quarter, on the basis of the sensory cues involved. For example, the size, thickness, or weight of the coin may be an indication, or to differentiate the pairs of coins suggested here, the smooth or corrugated edge of the coin will correspond to the particular denomination. The second task, **graphesthesia**, is to recognize numbers or letters written on the palm of the hand with a dull pointer, such as a pen cap.

Praxis and gnosis are related to the conscious perception and cortical processing of sensory information. Being able to transform verbal commands into a sequence of motor responses, or to manipulate and recognize a common object and associate it with a name for that object. Both subtests have language components because language function is integral to these functions. The relationship between the words that describe actions, or the nouns that represent objects, and the cerebral location of these concepts is suggested to be localized to particular cortical areas. Certain aphasias can be characterized by a deficit of verbs or nouns, known as V impairment or N impairment, or may be classified as V–N dissociation. Patients have difficulty using one type of word over the other. To describe what is happening in a photograph as part of the expressive language subtest, a patient will use active- or image-based language. The lack of one or the other of these components of language can relate to the ability to use verbs or nouns. Damage to the region at which the frontal and temporal lobes meet, including the region known as the insula, is associated with V impairment; damage to the middle and inferior temporal lobe is associated with N impairment.

Judgment and Abstract Reasoning

Planning and producing responses requires an ability to make sense of the world around us. Making judgments and reasoning in the abstract are necessary to produce movements as part of larger responses. For example, when your alarm goes off, do you hit the snooze button or jump out of bed? Is 10 extra minutes in bed worth the extra rush to get ready for your day? Will hitting the snooze button multiple times lead to feeling more rested or result in a panic as you run late? How you mentally process these questions can affect your whole day.

The prefrontal cortex is responsible for the functions responsible for planning and making decisions. In the mental status exam, the subtest that assesses judgment and reasoning is directed at three aspects of frontal lobe function. First, the examiner asks questions about problem solving, such as “If you see a house on fire, what would you do?” The patient is also asked to interpret common proverbs, such as “Don’t look a gift horse in the mouth.” Additionally, pairs of words are compared for similarities, such as apple and orange, or lamp and cabinet.

The prefrontal cortex is composed of the regions of the frontal lobe that are not directly related to specific motor functions. The most posterior region of the frontal lobe, the precentral gyrus, is the primary motor cortex. Anterior to that are the premotor cortex, Broca’s area, and the frontal eye fields, which are all related to planning certain types of movements. Anterior to what could be described as motor association areas are the regions of the prefrontal cortex. They are the regions in which judgment, abstract reasoning, and working memory are localized. The antecedents to planning certain movements are judging whether those movements should be made, as in the example of deciding whether to hit the snooze button.

To an extent, the prefrontal cortex may be related to personality. The neurological exam does not necessarily assess personality, but it can be within the realm of neurology or psychiatry. A clinical situation that suggests this link between the prefrontal cortex and personality comes from the story of Phineas Gage, the railroad worker from the mid-1800s who had a metal spike impale his prefrontal cortex. There are suggestions that the steel rod led to changes in his personality. A man who was a quiet, dependable railroad worker became a raucous, irritable drunkard. Later anecdotal evidence from his life suggests that he was able to support himself, although he had to relocate and take on a different career as a stagecoach driver.

A psychiatric practice to deal with various disorders was the prefrontal lobotomy. This procedure was common in the 1940s and early 1950s, until antipsychotic drugs became available. The connections between the prefrontal cortex and other regions of the brain were severed. The disorders associated with this procedure included some aspects of what are now referred to as personality disorders, but also included mood disorders and psychoses.

Depictions of lobotomies in popular media suggest a link between cutting the white matter of the prefrontal cortex and changes in a patient's mood and personality, though this correlation is not well understood.

EVERYDAY CONNECTIONS

Left Brain, Right Brain

Popular media often refer to right-brained and left-brained people, as if the brain were two independent halves that work differently for different people. This is a popular misinterpretation of an important neurological phenomenon. As an extreme measure to deal with a debilitating condition, the corpus callosum may be sectioned to overcome intractable epilepsy. When the connections between the two cerebral hemispheres are cut, interesting effects can be observed.

If a person with an intact corpus callosum is asked to put their hands in their pockets and describe what is there on the basis of what their hands feel, they might say that they have keys in their right pocket and loose change in the left. They may even be able to count the coins in their pocket and say if they can afford to buy a candy bar from the vending machine. If a person with a sectioned corpus callosum is given the same instructions, they will do something quite peculiar. They will only put their right hand in their pocket and say they have keys there. They will not even move their left hand, much less report that there is loose change in the left pocket.

The reason for this is that the language functions of the cerebral cortex are localized to the left hemisphere in 95 percent of the population. Additionally, the left hemisphere is connected to the right side of the body through the corticospinal tract and the ascending tracts of the spinal cord. Motor commands from the precentral gyrus control the opposite side of the body, whereas sensory information processed by the postcentral gyrus is received from the opposite side of the body. For a verbal command to initiate movement of the right arm and hand, the left side of the brain needs to be connected by the corpus callosum. Language is processed in the left side of the brain and directly influences the left brain and right arm motor functions, but is sent to influence the right brain and left arm motor functions through the corpus callosum. Likewise, the left-handed sensory perception of what is in the left pocket travels across the corpus callosum from the right brain, so no verbal report on those contents would be possible if the hand happened to be in the pocket.

Watch the video titled "The Man With Two Brains" to see the neuroscientist Michael Gazzaniga introduce a patient he has worked with for years who has had his corpus callosum cut, separating his two cerebral hemispheres. A few tests are run to demonstrate how this manifests in tests of cerebral function. Unlike normal people, this patient can perform two independent tasks at the same time because the lines of communication between the right and left sides of his brain have been removed. Whereas a person with an intact corpus callosum cannot overcome the dominance of one hemisphere over the other, this patient can. If the left cerebral hemisphere is dominant in the majority of people, why would right-handedness be most common?

The Mental Status Exam

The cerebrum, particularly the cerebral cortex, is the location of important cognitive functions that are the focus of the mental status exam. The regionalization of the cortex, initially described on the basis of anatomical evidence of cytoarchitecture, reveals the distribution of functionally distinct areas. Cortical regions can be described as primary sensory or motor areas, association areas, or multimodal integration areas. The functions attributed to these regions include attention, memory, language, speech, sensation, judgment, and abstract reasoning.

The mental status exam addresses these cognitive abilities through a series of subtests designed to elicit particular behaviors ascribed to these functions. The loss of neurological function can illustrate the location of damage to the cerebrum. Memory functions are attributed to the temporal lobe, particularly the medial temporal lobe structures known as the hippocampus and amygdala, along with the adjacent cortex. Evidence of the importance of these structures comes from the side effects of a bilateral temporal lobectomy that were studied in detail in patient HM.

Losses of language and speech functions, known as aphasias, are associated with damage to the important integration areas in the left hemisphere known as Broca's or Wernicke's areas, as well as the connections in the white matter between them. Different types of aphasia are named for the particular structures that are damaged. Assessment of the functions of the sensorium includes praxis and gnosis. The subtests related to these functions depend on multimodal integration, as well as language-dependent processing.

The prefrontal cortex contains structures important for planning, judgment, reasoning, and working memory. Damage to these areas can result in changes to personality, mood, and behavior. The famous case of Phineas Gage suggests a role for this cortex in personality, as does the outdated practice of prefrontal lobectomy.

The Cranial Nerve Exam

By the end of this section, you will be able to:

- Describe the functional grouping of cranial nerves
- Match the regions of the forebrain and brain stem that are connected to each cranial nerve
- Suggest diagnoses that would explain certain losses of function in the cranial nerves
- Relate cranial nerve deficits to damage of adjacent, unrelated structures

The twelve cranial nerves are typically covered in introductory anatomy courses, and memorizing their names is facilitated by numerous mnemonics developed by students over the years of this practice. But knowing the names of the nerves in order often leaves much to be desired in understanding what the nerves do. The nerves can be categorized by functions, and subtests of the cranial nerve exam can clarify these functional groupings.

Three of the nerves are strictly responsible for special senses whereas four others contain fibers for special and general senses. Three nerves are connected to the extraocular muscles resulting in the control of gaze.

Four nerves connect to muscles of the face, oral cavity, and pharynx, controlling facial expressions, mastication, swallowing, and speech. Four nerves make up the cranial component of the parasympathetic nervous system responsible for pupillary constriction, salivation, and the regulation of the organs of the thoracic and upper abdominal cavities. Finally, one nerve controls the muscles of the neck, assisting with spinal control of the movement of the head and neck.

The cranial nerve exam allows directed tests of forebrain and brain stem structures. The twelve cranial nerves serve the head and neck. The vagus nerve (cranial nerve X) has autonomic functions in the thoracic and superior abdominal cavities. The special senses are served through the cranial nerves, as well as the general senses of the head and neck. The movement of the eyes, face, tongue, throat, and neck are all under the control of cranial nerves. Preganglionic parasympathetic nerve fibers that control pupillary size, salivary glands, and the thoracic and upper abdominal viscera are found in four of the nerves. Tests of these functions can provide insight into damage to specific regions of the brain stem and may uncover deficits in adjacent regions.

Sensory Nerves

The olfactory, optic, and vestibulocochlear nerves (cranial nerves I, II, and VIII) are dedicated to four of the special senses: smell, vision, equilibrium, and hearing, respectively. Taste sensation is relayed to the brain stem through fibers of the facial and glossopharyngeal nerves. The trigeminal nerve is a mixed nerve that carries the general somatic senses from the head, similar to those coming through spinal nerves from the rest of the body.

Testing smell is straightforward, as common smells are presented to one nostril at a time. The patient should be able to recognize the smell of coffee or mint, indicating the proper functioning of the olfactory system. Loss of the sense of smell is called anosmia and can be lost following blunt trauma to the head or through aging. The short axons of the first cranial nerve regenerate on a regular basis. The neurons in the olfactory epithelium have a limited life span, and new cells grow to replace the ones that die off. The axons from these neurons grow back into the CNS by following the existing axons—representing one of the few examples of such growth in the mature nervous system. If all of the fibers are sheared when the brain moves within the cranium, such as in a motor vehicle accident, then no axons can find their way back to the olfactory bulb to re-establish connections. If the nerve is not completely severed, the anosmia may be temporary as new neurons can eventually reconnect.

Olfaction is not the pre-eminent sense, but its loss can be quite detrimental. The enjoyment of food is largely based on our sense of smell. Anosmia means that food will not seem to have the same taste, though the gustatory sense is intact, and food will often be described as being bland. However, the taste of food can be improved by adding ingredients (e.g., salt) that stimulate the gustatory sense.

Testing vision relies on the tests that are common in an optometry office. The **Snellen chart** (Figure 1. The Snellen Chart) demonstrates visual acuity by presenting standard Roman letters in a variety of sizes. The result of this test is a rough generalization of the acuity of a person based on the normal accepted acuity, such that a letter that subtends a visual angle of 5 minutes of an arc at 20 feet can be seen. To have 20/60 vision, for example, means that the smallest letters that a person can see at a 20-foot distance could be seen by a person with normal acuity from 60 feet away. Testing the extent of the visual field means that the examiner can establish the boundaries of peripheral vision as simply as holding their hands out to either side and asking the patient when the fingers are no longer visible without moving the eyes to track them. If it is necessary, further tests can establish the perceptions in the visual fields. Physical inspection of the optic disk, or where the optic nerve emerges from the eye, can be accomplished by looking through the pupil with an ophthalmoscope.

The Snellen Chart

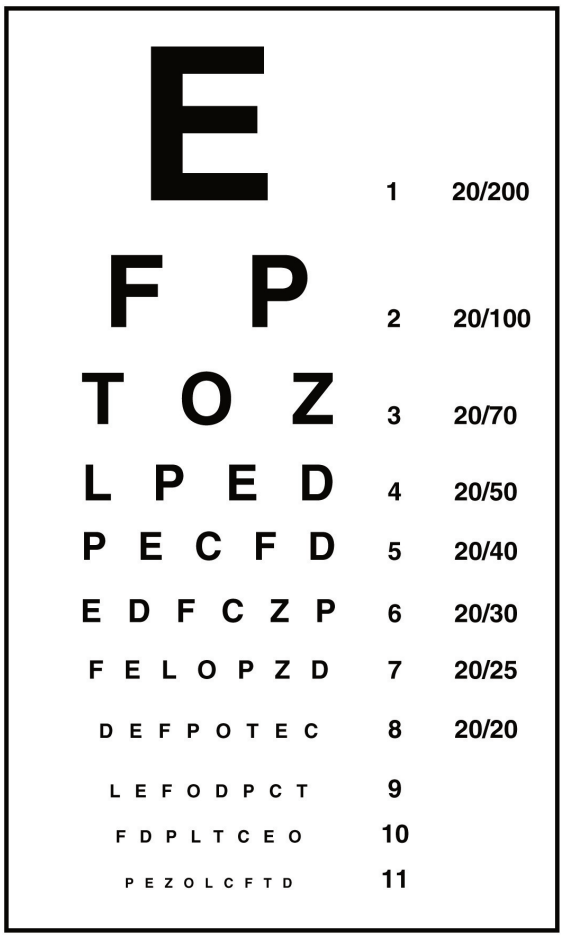


Figure 1. *The Snellen chart for visual acuity presents a limited number of Roman letters in lines of decreasing size. The line with letters that subtend 5 minutes of an arc from 20 feet represents the smallest letters that a person with normal acuity should be able to read at that distance. The different sizes of letters in the other lines represent rough approximations of what a person of normal acuity can read at different distances. For example, the line that represents 20/200 vision would have larger letters so that they are legible to the person with normal acuity at 200 feet.*

The optic nerves from both sides enter the cranium through the respective optic canals and meet at the optic chiasm at which fibers sort such that the two halves of the visual field are processed by the opposite sides of the brain. Deficits in visual field perception often suggest damage along the length of the optic pathway between the orbit and the diencephalon. For example, loss of peripheral vision may be the result of a pituitary tumor pressing on the optic chiasm (Figure 2. Pituitary Tumor). The pituitary, seated in the sella turcica of the sphenoid bone, is directly inferior to the optic chiasm. The axons that decussate in the chiasm are from the medial retinae of either eye, and therefore carry information from the peripheral visual field.

Pituitary Tumor

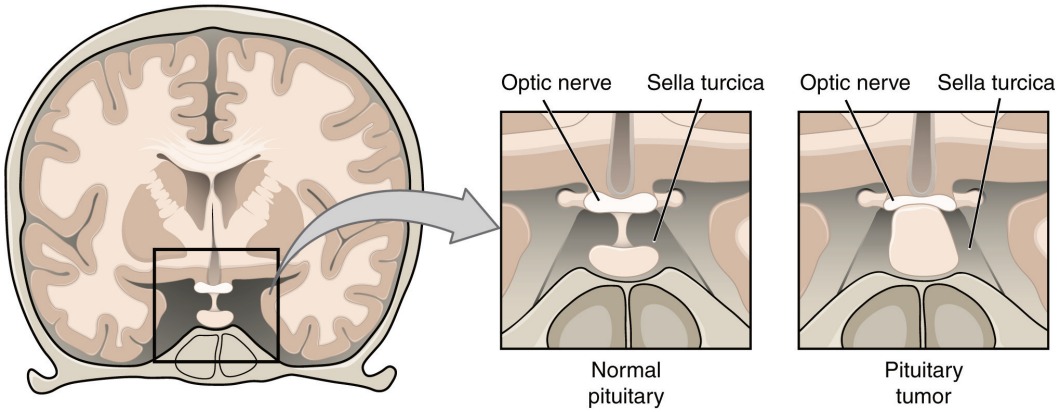


Figure 2. *The pituitary gland is located in the sella turcica of the sphenoid bone within the cranial floor, placing it immediately inferior to the optic chiasm. If the pituitary gland develops a tumor, it can press against the fibers crossing in the chiasm. Those fibers are conveying peripheral visual information to the opposite side of the brain, so the patient will experience "tunnel vision"—meaning that only the central visual field will be perceived.*

The vestibulocochlear nerve (CN VIII) carries both equilibrium and auditory sensations from the inner ear to the medulla. Though the two senses are not directly related, anatomy is mirrored in the two systems. Problems with balance, such as vertigo, and deficits in hearing may both point to problems with the inner ear. Within the petrous region of the temporal bone is the bony labyrinth of the inner ear. The vestibule is the portion for equilibrium, composed of the utricle, saccule, and the three semicircular canals. The cochlea is responsible for transducing sound waves into a neural signal. The sensory nerves from these two structures travel side-by-side as the vestibulocochlear nerve, though they are really separate divisions. They both emerge from the inner ear, pass through the internal auditory meatus, and synapse in nuclei of the superior medulla. Though they are part of distinct sensory systems, the vestibular nuclei and the cochlear nuclei are close neighbors with adjacent inputs. Deficits in one or both systems could occur from damage that encompasses structures close to both. Damage to structures near the two nuclei can result in deficits to one or both systems.

Balance or hearing deficits may be the result of damage to the middle or inner ear structures. Ménière's disease is a disorder that can affect both equilibrium and audition in a variety of ways. The patient can suffer from vertigo, a low-frequency ringing in the ears, or a loss of hearing. From patient to patient, the exact presentation of the disease can be different. Additionally, within a single patient, the symptoms and signs may change as the disease progresses. Use of the neurological exam subtests for the vestibulocochlear nerve illuminates the changes a patient may go through. The disease appears to be the result of accumulation, or over-production, of fluid in the inner ear, in either the vestibule or cochlea.

Tests of equilibrium are important for coordination and gait and are related to other aspects of the neurological exam. The vestibulo-ocular reflex involves the cranial nerves for gaze control. Balance and equilibrium, as tested by the Romberg test, are part of spinal and cerebellar processes and involved in those components of the neurological exam, as discussed later.

Hearing is tested by using a tuning fork in a couple of different ways. The **Rinne test** involves using a tuning fork to distinguish between **conductive hearing** and **sensorineural hearing**. Conductive hearing relies on vibrations being conducted through the ossicles of the middle ear. Sensorineural hearing is the transmission of sound stimuli through the neural components of the inner ear and cranial nerve. A vibrating tuning fork is placed on the mastoid process and the patient indicates when the sound produced from this is no longer present. Then the fork is immediately moved to just next to the ear canal so the sound travels through the air. If the sound is not heard through the ear, meaning the sound is conducted better through the temporal bone than through the ossicles, a conductive hearing deficit is present. The **Weber test** also uses a tuning fork to differentiate between

conductive versus sensorineural hearing loss. In this test, the tuning fork is placed at the top of the skull, and the sound of the tuning fork reaches both inner ears by travelling through bone. In a healthy patient, the sound would appear equally loud in both ears. With unilateral conductive hearing loss, however, the tuning fork sounds louder in the ear with hearing loss. This is because the sound of the tuning fork has to compete with background noise coming from the outer ear, but in conductive hearing loss, the background noise is blocked in the damaged ear, allowing the tuning fork to sound relatively louder in that ear. With unilateral sensorineural hearing loss, however, damage to the cochlea or associated nervous tissue means that the tuning fork sounds quieter in that ear.

The trigeminal system of the head and neck is the equivalent of the ascending spinal cord systems of the dorsal column and the spinothalamic pathways. Somatosensation of the face is conveyed along the nerve to enter the brain stem at the level of the pons. Synapses of those axons, however, are distributed across nuclei found throughout the brain stem. The mesencephalic nucleus processes proprioceptive information of the face, which is the movement and position of facial muscles. It is the sensory component of the **jaw-jerk reflex**, a stretch reflex of the masseter muscle. The chief nucleus, located in the pons, receives information about light touch as well as proprioceptive information about the mandible, which are both relayed to the thalamus and, ultimately, to the postcentral gyrus of the parietal lobe. The spinal trigeminal nucleus, located in the medulla, receives information about crude touch, pain, and temperature to be relayed to the thalamus and cortex. Essentially, the projection through the chief nucleus is analogous to the dorsal column pathway for the body, and the projection through the spinal trigeminal nucleus is analogous to the spinothalamic pathway.

Subtests for the sensory component of the trigeminal system are the same as those for the sensory exam targeting the spinal nerves. The primary sensory subtest for the trigeminal system is sensory discrimination. A cotton-tipped applicator, which is cotton attached to the end of a thin wooden stick, can be used easily for this. The wood of the applicator can be snapped so that a pointed end is opposite the soft cotton-tipped end. The cotton end provides a touch stimulus, while the pointed end provides a painful, or sharp, stimulus. While the patient's eyes are closed, the examiner touches the two ends of the applicator to the patient's face, alternating randomly between them. The patient must identify whether the stimulus is sharp or dull. These stimuli are processed by the trigeminal system separately. Contact with the cotton tip of the applicator is a light touch, relayed by the chief nucleus, but contact with the pointed end of the applicator is a painful stimulus relayed by the spinal trigeminal nucleus. Failure to discriminate these stimuli can localize problems within the brain stem. If a patient cannot recognize a painful stimulus, that might indicate damage to the spinal trigeminal nucleus in the medulla. The medulla also contains important regions that regulate the cardiovascular, respiratory, and digestive systems, as well as being the pathway for ascending and descending tracts between the brain and spinal cord. Damage, such as a stroke, that results in changes in sensory discrimination may indicate these unrelated regions are affected as well.

Gaze Control

The three nerves that control the extraocular muscles are the oculomotor, trochlear, and abducens nerves, which are the third, fourth, and sixth cranial nerves. As the name suggests, the abducens nerve is responsible for abducting the eye, which it controls through contraction of the lateral rectus muscle. The trochlear nerve controls the superior oblique muscle to rotate the eye along its axis in the orbit medially, which is called **intorsion**, and is a component of focusing the eyes on an object close to the face. The oculomotor nerve controls all the other extraocular muscles, as well as a muscle of the upper eyelid. Movements of the two eyes need to be coordinated to locate and track visual stimuli accurately. When moving the eyes to locate an object

in the horizontal plane, or to track movement horizontally in the visual field, the lateral rectus muscle of one eye and medial rectus muscle of the other eye are both active. The lateral rectus is controlled by neurons of the abducens nucleus in the superior medulla, whereas the medial rectus is controlled by neurons in the oculomotor nucleus of the midbrain.

Coordinated movement of both eyes through different nuclei requires integrated processing through the brain stem. In the midbrain, the superior colliculus integrates visual stimuli with motor responses to initiate eye movements. The **paramedian pontine reticular formation (PPRF)** will initiate a rapid eye movement, or **saccade**, to bring the eyes to bear on a visual stimulus quickly. These areas are connected to the oculomotor, trochlear, and abducens nuclei by the **medial longitudinal fasciculus (MLF)** that runs through the majority of the brain stem. The MLF allows for **conjugate gaze**, or the movement of the eyes in the same direction, during horizontal movements that require the lateral and medial rectus muscles. Control of conjugate gaze strictly in the vertical direction is contained within the oculomotor complex. To elevate the eyes, the oculomotor nerve on either side stimulates the contraction of both superior rectus muscles; to depress the eyes, the oculomotor nerve on either side stimulates the contraction of both inferior rectus muscles.

Purely vertical movements of the eyes are not very common. Movements are often at an angle, so some horizontal components are necessary, adding the medial and lateral rectus muscles to the movement. The rapid movement of the eyes used to locate and direct the fovea onto visual stimuli is called a saccade. Notice that the paths that are traced in Figure 3. (Saccadic Eye Movements) are not strictly vertical. The movements between the nose and the mouth are closest, but still have a slant to them. Also, the superior and inferior rectus muscles are not perfectly oriented with the line of sight. The origin for both muscles is medial to their insertions, so elevation and depression may require the lateral rectus muscles to compensate for the slight adduction inherent in the contraction of those muscles, requiring MLF activity as well.

Saccadic Eye Movements

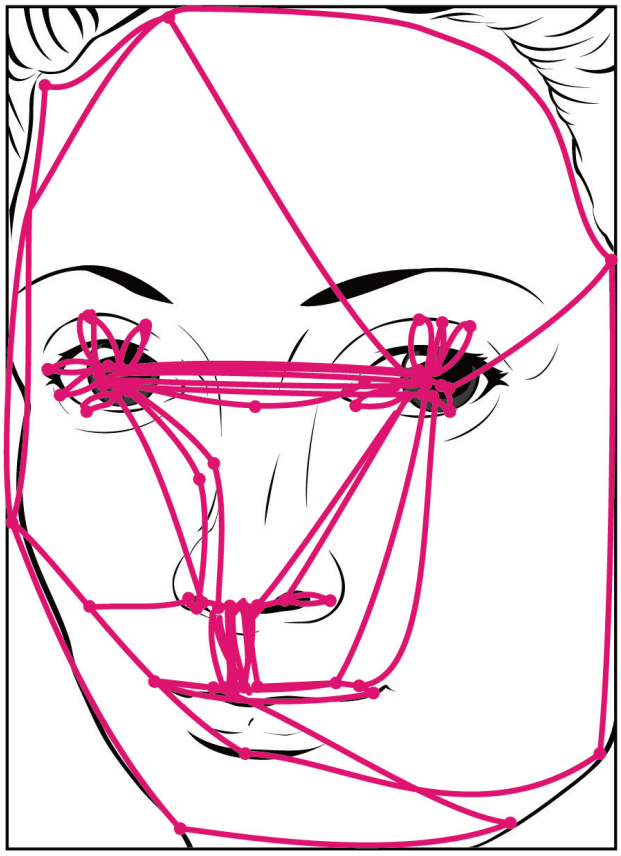


Figure 3. *Saccades are rapid, conjugate movements of the eyes to survey a complicated visual stimulus, or to follow a moving visual stimulus. This image represents the shifts in gaze typical of a person studying a face. Notice the concentration of gaze on the major features of the face and the large number of paths traced between the eyes or around the mouth.*

Testing eye movement is simply a matter of having the patient track the tip of a pen as it is passed through the visual field. This may appear similar to testing visual field deficits related to the optic nerve, but the difference is that the patient is asked to not move the eyes while the examiner moves a stimulus into the peripheral visual field. Here, the extent of movement is the point of the test. The examiner is watching for conjugate movements representing proper function of the related nuclei and the MLF. Failure of one eye to abduct while the other adducts in a horizontal movement is referred to as **internuclear ophthalmoplegia**. When this occurs, the patient will experience **diplopia**, or double vision, as the two eyes are temporarily pointed at different stimuli. Diplopia is not restricted to failure of the lateral rectus, because any of the extraocular muscles may fail to move one eye in perfect conjugation with the other.

The final aspect of testing eye movements is to move the tip of the pen in toward the patient's face. As visual stimuli move closer to the face, the two medial recti muscles cause the eyes to move in the one nonconjugate movement that is part of gaze control. When the two eyes move to look at something closer to the face, they both adduct, which is referred to as **convergence**. To keep the stimulus in focus, the eye also needs to change the shape of the lens, which is controlled through the parasympathetic fibers of the oculomotor nerve. The change in focal power of the eye is referred to as **accommodation**. Accommodation ability changes with age; focusing on nearer objects, such as the written text of a book or on a computer screen, may require corrective lenses later in

life. Coordination of the skeletal muscles for convergence and coordination of the smooth muscles of the ciliary body for accommodation are referred to as the **accommodation–convergence reflex**.

A crucial function of the cranial nerves is to keep visual stimuli centered on the fovea of the retina. The **vestibulo-ocular reflex (VOR)** coordinates all of the components (Figure 4. Vestibulo-ocular Reflex), both sensory and motor, that make this possible. If the head rotates in one direction–for example, to the right–the horizontal pair of semicircular canals in the inner ear indicate the movement by increased activity on the right and decreased activity on the left. The information is sent to the abducens nuclei and oculomotor nuclei on either side to coordinate the lateral and medial rectus muscles. The left lateral rectus and right medial rectus muscles will contract, rotating the eyes in the opposite direction of the head, while nuclei controlling the right lateral rectus and left medial rectus muscles will be inhibited to reduce antagonism of the contracting muscles. These actions stabilize the visual field by compensating for the head rotation with opposite rotation of the eyes in the orbits. Deficits in the VOR may be related to vestibular damage, such as in Ménière's disease, or from dorsal brain stem damage that would affect the eye movement nuclei or their connections through the MLF.

Vestibulo-ocular Reflex

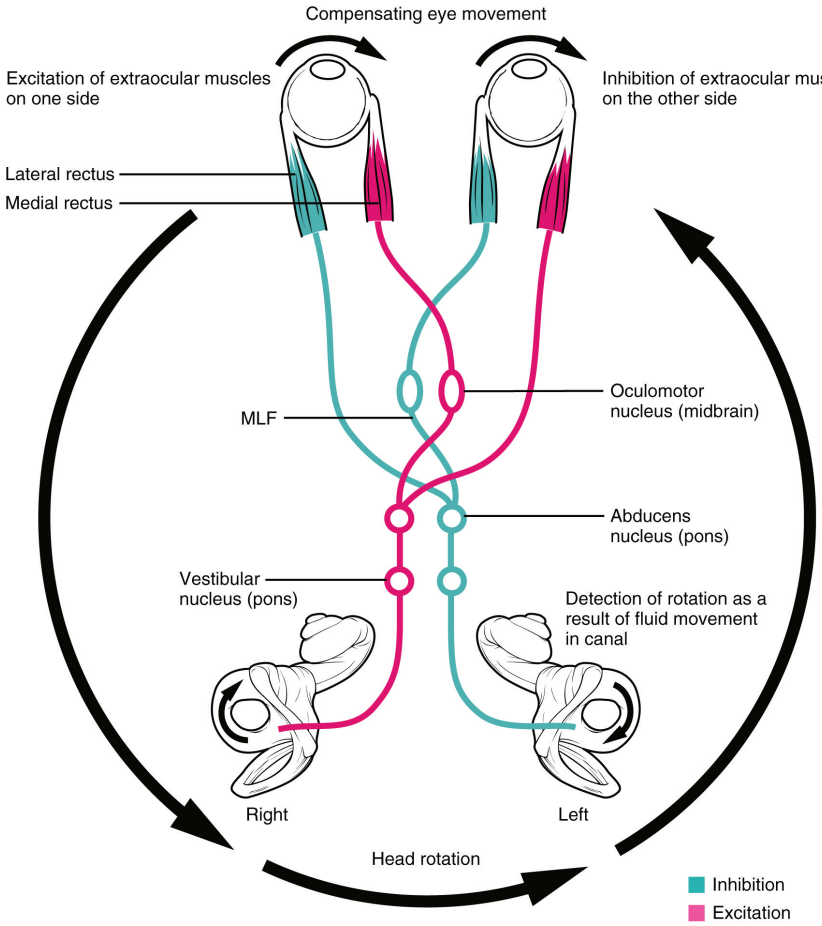


Figure 4. *If the head is turned in one direction, the coordination of that movement with the fixation of the eyes on a visual stimulus involves a circuit that ties the vestibular sense with the eye movement nuclei through the MLF.*

Nerves of the Face and Oral Cavity

An iconic part of a doctor's visit is the inspection of the oral cavity and pharynx, suggested by the directive to "open your mouth and say 'ah.'" This is followed by inspection, with the aid of a tongue depressor, of the back of the mouth, or the opening of the oral cavity into the pharynx known as the **fauces**. Whereas this portion of a medical exam inspects for signs of infection, such as in tonsillitis, it is also the means to test the functions of the cranial nerves that are associated with the oral cavity.

The facial and glossopharyngeal nerves convey gustatory stimulation to the brain. Testing this is as simple as introducing salty, sour, bitter, or sweet stimuli to either side of the tongue. The patient should respond to the taste stimulus before retracting the tongue into the mouth. Stimuli applied to specific locations on the tongue will dissolve into the saliva and may stimulate taste buds connected to either the left or right of the nerves, masking any lateral deficits. Along with taste, the glossopharyngeal nerve relays general sensations from the pharyngeal walls. These sensations, along with certain taste stimuli, can stimulate the gag reflex. If the examiner moves the tongue depressor to contact the lateral wall of the fauces, this should elicit the gag reflex. Stimulation of either side of the fauces should elicit an equivalent response. The motor response, through contraction of the muscles of the pharynx, is mediated through the vagus nerve. Normally, the vagus nerve is considered autonomic in nature. The vagus nerve directly stimulates the contraction of skeletal muscles in the pharynx and larynx to contribute to the swallowing and speech functions. Further testing of vagus motor function has the patient repeating consonant sounds that require movement of the muscles around the fauces. The patient is asked to say "lah-kah-pah" or a similar set of alternating sounds while the examiner observes the movements of the soft palate and arches between the palate and tongue.

The facial and glossopharyngeal nerves are also responsible for the initiation of salivation. Neurons in the salivary nuclei of the medulla project through these two nerves as preganglionic fibers, and synapse in ganglia located in the head. The parasympathetic fibers of the facial nerve synapse in the pterygopalatine ganglion, which projects to the submandibular gland and sublingual gland. The parasympathetic fibers of the glossopharyngeal nerve synapse in the otic ganglion, which projects to the parotid gland. Salivation in response to food in the oral cavity is based on a visceral reflex arc within the facial or glossopharyngeal nerves. Other stimuli that stimulate salivation are coordinated through the hypothalamus, such as the smell and sight of food.

The hypoglossal nerve is the motor nerve that controls the muscles of the tongue, except for the palatoglossus muscle, which is controlled by the vagus nerve. There are two sets of muscles of the tongue. The **extrinsic muscles of the tongue** are connected to other structures, whereas the **intrinsic muscles of the tongue** are completely contained within the lingual tissues. While examining the oral cavity, movement of the tongue will indicate whether hypoglossal function is impaired. The test for hypoglossal function is the "stick out your tongue" part of the exam. The genioglossus muscle is responsible for protrusion of the tongue. If the hypoglossal nerves on both sides are working properly, then the tongue will stick straight out. If the nerve on one side has a deficit, the tongue will stick out to that side—pointing to the side with damage. Loss of function of the tongue can interfere with speech and swallowing. Additionally, because the location of the hypoglossal nerve and nucleus is near the cardiovascular center, inspiratory and expiratory areas for respiration, and the vagus nuclei that regulate digestive functions, a tongue that protrudes incorrectly can suggest damage in adjacent structures that have nothing to do with controlling the tongue.

Watch this short video to see an examination of the facial nerve using some simple tests. The facial

nerve controls the muscles of facial expression. Severe deficits will be obvious in watching someone use those muscles for normal control. One side of the face might not move like the other side. But directed tests, especially for contraction against resistance, require a formal testing of the muscles. The muscles of the upper and lower face need to be tested. The strength test in this video involves the patient squeezing her eyes shut and the examiner trying to pry her eyes open. Why does the examiner ask her to try a second time?

Motor Nerves of the Neck

The accessory nerve, also referred to as the spinal accessory nerve, innervates the sternocleidomastoid and trapezius muscles (Figure 5. Muscles Controlled by the Accessory Nerve). When both the sternocleidomastoids contract, the head flexes forward; individually, they cause rotation to the opposite side. The trapezius can act as an antagonist, causing extension and hyperextension of the neck. These two superficial muscles are important for changing the position of the head. Both muscles also receive input from cervical spinal nerves. Along with the spinal accessory nerve, these nerves contribute to elevating the scapula and clavicle through the trapezius, which is tested by asking the patient to shrug both shoulders, and watching for asymmetry. For the sternocleidomastoid, those spinal nerves are primarily sensory projections, whereas the trapezius also has lateral insertions to the clavicle and scapula, and receives motor input from the spinal cord. Calling the nerve the spinal accessory nerve suggests that it is aiding the spinal nerves. Though that is not precisely how the name originated, it does help make the association between the function of this nerve in controlling these muscles and the role these muscles play in movements of the trunk or shoulders.

Muscles Controlled by the Accessory Nerve

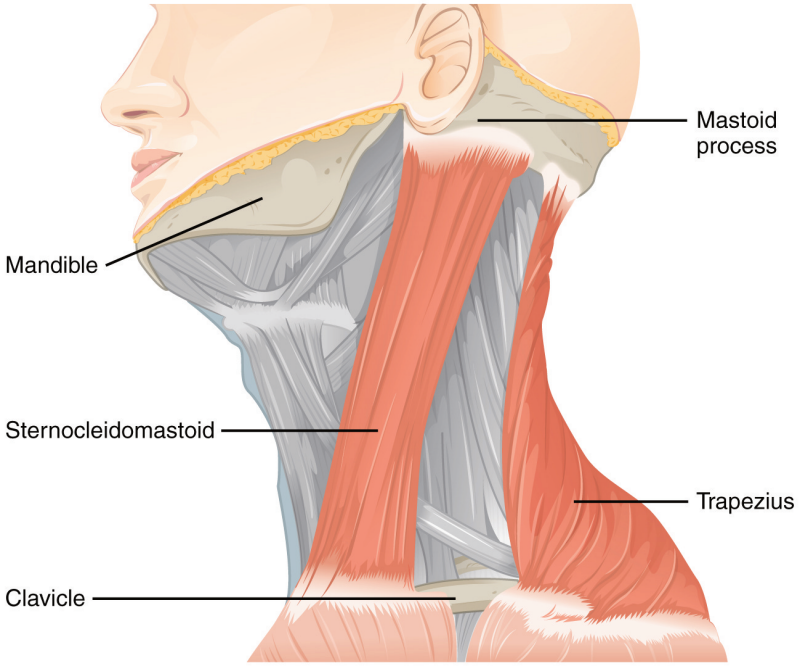


Figure 5. *The accessory nerve innervates the sternocleidomastoid and trapezius muscles, both of which attach to the head and to the trunk and shoulders. They can act as antagonists in head flexion and extension, and as synergists in lateral flexion toward the shoulder.*

To test these muscles, the patient is asked to flex and extend the neck or shrug the shoulders against resistance, testing the strength of the muscles. Lateral flexion of the neck toward the shoulder tests both at the same time. Any difference on one side versus the other would suggest damage on the weaker side. These strength tests are common for the skeletal muscles controlled by spinal nerves and are a significant component of the motor exam. Deficits associated with the accessory nerve may have an effect on orienting the head, as described with the VOR.

HOMEOSTATIC IMBALANCES

The Pupillary Light Response

The autonomic control of pupillary size in response to a bright light involves the sensory input of the optic nerve and the parasympathetic motor output of the oculomotor nerve. When light hits the retina, specialized photosensitive ganglion cells send a signal along the optic nerve to the pretectal nucleus in the superior midbrain. A neuron from this nucleus projects to the Eddinger–Westphal nuclei in the oculomotor complex in both sides of the midbrain. Neurons in this nucleus give rise to the preganglionic parasympathetic fibers that project through the oculomotor nerve to the ciliary ganglion in the posterior orbit. The postganglionic parasympathetic fibers from the ganglion project to the iris, where they release acetylcholine onto circular fibers that constrict the pupil to reduce the amount of light hitting the retina. The sympathetic nervous system is responsible for dilating the pupil when light levels are low.

Shining light in one eye will elicit constriction of both pupils. The efferent limb of the pupillary light reflex is bilateral. Light shined in one eye causes a constriction of that pupil, as well as constriction of the contralateral pupil. Shining a penlight in the eye of a patient is a very artificial situation, as both eyes are normally exposed to the same light sources. Testing this reflex can illustrate whether the optic nerve or the oculomotor nerve is damaged. If shining the light in one eye results in no changes in pupillary size but shining light in the opposite eye elicits a normal, bilateral response, the damage is associated with the optic nerve on the nonresponsive side. If light in either eye elicits a response in only one eye, the problem is with the oculomotor system.

If light in the right eye only causes the left pupil to constrict, the direct reflex is lost and the consensual reflex is intact, which means that the right oculomotor nerve (or Eddinger–Westphal nucleus) is damaged. Damage to the right oculomotor connections will be evident when light is shined in the left eye. In that case, the direct reflex is intact but the consensual reflex is lost, meaning that the left pupil will constrict while the right does not.

The Cranial Nerve Exam

The cranial nerves can be separated into four major groups associated with the subtests of the cranial nerve

exam. First are the sensory nerves, then the nerves that control eye movement, the nerves of the oral cavity and superior pharynx, and the nerve that controls movements of the neck.

The olfactory, optic, and vestibulocochlear nerves are strictly sensory nerves for smell, sight, and balance and hearing, whereas the trigeminal, facial, and glossopharyngeal nerves carry somatosensation of the face, and taste—separated between the anterior two-thirds of the tongue and the posterior one-third. Special senses are tested by presenting the particular stimuli to each receptive organ. General senses can be tested through sensory discrimination of touch versus painful stimuli.

The oculomotor, trochlear, and abducens nerves control the extraocular muscles and are connected by the medial longitudinal fasciculus to coordinate gaze. Testing conjugate gaze is as simple as having the patient follow a visual target, like a pen tip, through the visual field ending with an approach toward the face to test convergence and accommodation. Along with the vestibular functions of the eighth nerve, the vestibulo-ocular reflex stabilizes gaze during head movements by coordinating equilibrium sensations with the eye movement systems.

The trigeminal nerve controls the muscles of chewing, which are tested for stretch reflexes. Motor functions of the facial nerve are usually obvious if facial expressions are compromised, but can be tested by having the patient raise their eyebrows, smile, and frown. Movements of the tongue, soft palate, or superior pharynx can be observed directly while the patient swallows, while the gag reflex is elicited, or while the patient says repetitive consonant sounds. The motor control of the gag reflex is largely controlled by fibers in the vagus nerve and constitutes a test of that nerve because the parasympathetic functions of that nerve are involved in visceral regulation, such as regulating the heartbeat and digestion.

Movement of the head and neck using the sternocleidomastoid and trapezius muscles is controlled by the accessory nerve. Flexing of the neck and strength testing of those muscles reviews the function of that nerve.

The Sensory and Motor Exams

By the end of this section, you will be able to:

- Describe the arrangement of sensory and motor regions in the spinal cord
- Relate damage in the spinal cord to sensory or motor deficits
- Differentiate between upper motor neuron and lower motor neuron diseases
- Describe the clinical indications of common reflexes

Connections between the body and the CNS occur through the spinal cord. The cranial nerves connect the head and neck directly to the brain, but the spinal cord receives sensory input and sends motor commands out to the body through the spinal nerves. Whereas the brain develops into a complex series of nuclei and fiber tracts, the spinal cord remains relatively simple in its configuration (Figure 1. Locations of Spinal Fiber Tracts). From the initial neural tube early in embryonic development, the spinal cord retains a tube-like structure with gray matter surrounding the small central canal and white matter on the surface in three columns. The dorsal, or posterior, horns of the gray matter are mainly devoted to sensory functions whereas the ventral, or anterior, and lateral

horns are associated with motor functions. In the white matter, the dorsal column relays sensory information to the brain, and the anterior column is almost exclusively relaying motor commands to the ventral horn motor neurons. The lateral column, however, conveys both sensory and motor information between the spinal cord and brain.

Locations of Spinal Fiber Tracts

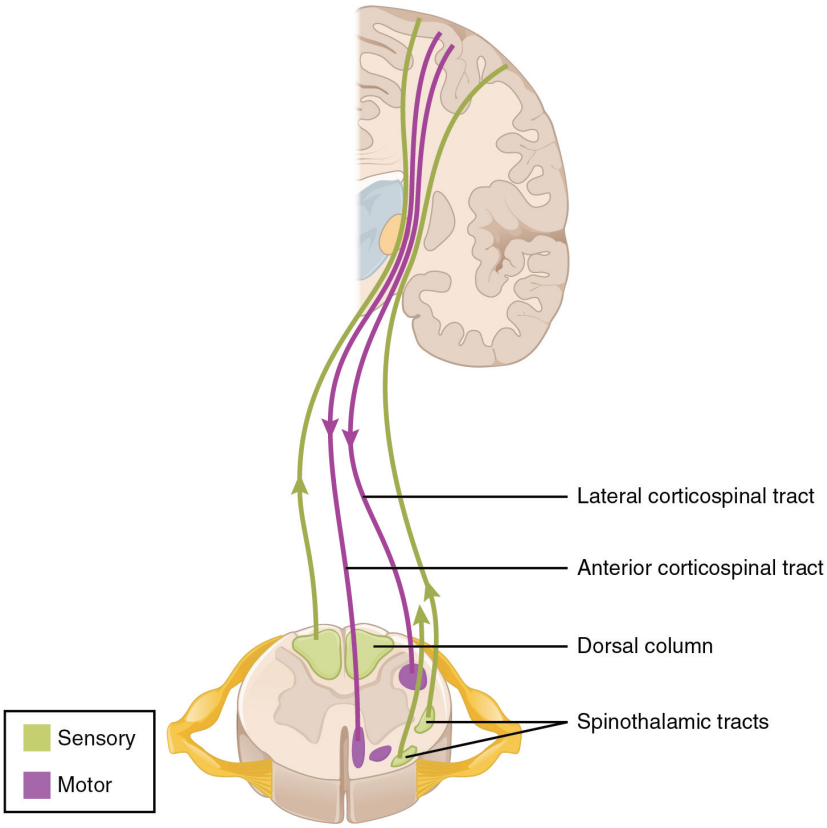


Figure 1.

Sensory Modalities and Location

The general senses are distributed throughout the body, relying on nervous tissue incorporated into various organs. Somatic senses are incorporated mostly into the skin, muscles, or tendons, whereas the visceral senses come from nervous tissue incorporated into the majority of organs such as the heart or stomach. The somatic senses are those that usually make up the conscious perception of the how the body interacts with the environment. The visceral senses are most often below the limit of conscious perception because they are involved in homeostatic regulation through the autonomic nervous system.

The sensory exam tests the somatic senses, meaning those that are consciously perceived. Testing of the senses begins with examining the regions known as dermatomes that connect to the cortical region where somatosensation is perceived in the postcentral gyrus. To test the sensory fields, a simple stimulus of the light touch of the soft end of a cotton-tipped applicator is applied at various locations on the skin. The spinal nerves, which contain sensory fibers with dendritic endings in the skin, connect with the skin in a topographically

organized manner, illustrated as dermatomes (Figure 2. Dermatomes). For example, the fibers of eighth cervical nerve innervate the medial surface of the forearm and extend out to the fingers. In addition to testing perception at different positions on the skin, it is necessary to test sensory perception within the dermatome from distal to proximal locations in the appendages, or lateral to medial locations in the trunk. In testing the eighth cervical nerve, the patient would be asked if the touch of the cotton to the fingers or the medial forearm was perceptible, and whether there were any differences in the sensations.

Dermatomes

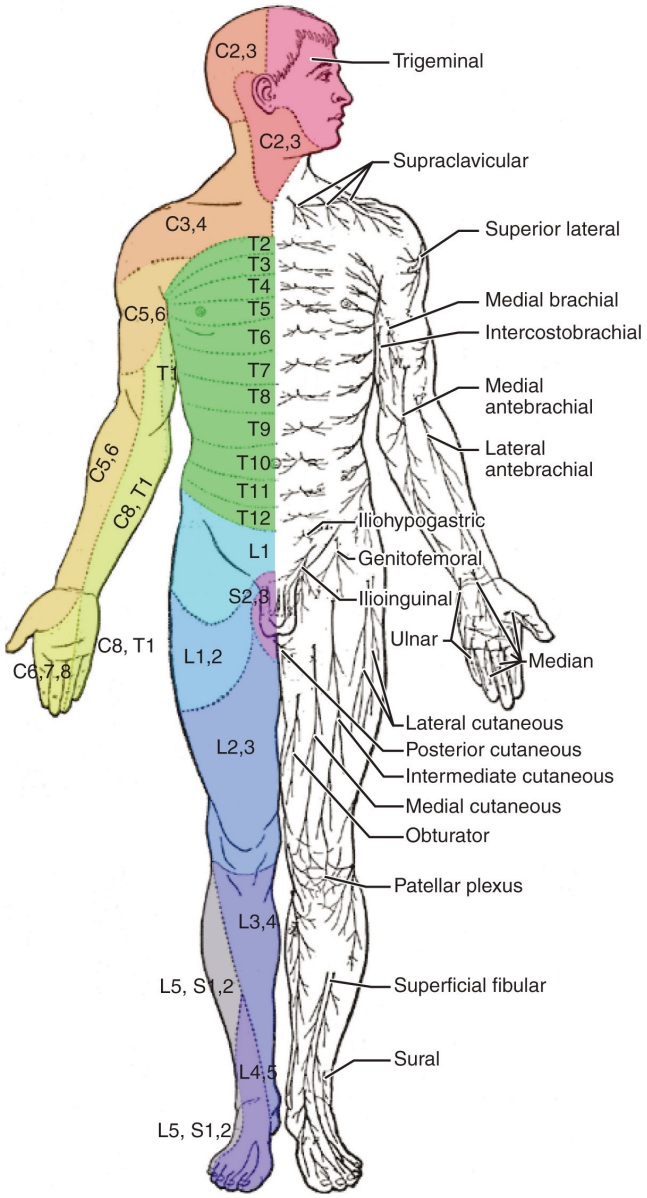


Figure 2. *The surface of the skin can be divided into topographic regions that relate to the location of sensory endings in the skin based on the spinal nerve that contains those fibers. (credit: modification of work by Mikael Häggström)*

Other modalities of somatosensation can be tested using a few simple tools. The perception of pain can be tested using the broken end of the cotton-tipped applicator. The perception of vibratory stimuli can be testing using an

oscillating tuning fork placed against prominent bone features such as the distal head of the ulna on the medial aspect of the elbow. When the tuning fork is still, the metal against the skin can be perceived as a cold stimulus. Using the cotton tip of the applicator, or even just a fingertip, the perception of tactile movement can be assessed as the stimulus is drawn across the skin for approximately 2–3 cm. The patient would be asked in what direction the stimulus is moving. All of these tests are repeated in distal and proximal locations and for different dermatomes to assess the spatial specificity of perception. The sense of position and motion, proprioception, is tested by moving the fingers or toes and asking the patient if they sense the movement. If the distal locations are not perceived, the test is repeated at increasingly proximal joints.

The various stimuli used to test sensory input assess the function of the major ascending tracts of the spinal cord. The dorsal column pathway conveys fine touch, vibration, and proprioceptive information, whereas the spinothalamic pathway primarily conveys pain and temperature. Testing these stimuli provides information about whether these two major ascending pathways are functioning properly. Within the spinal cord, the two systems are segregated. The dorsal column information ascends ipsilateral to the source of the stimulus and decussates in the medulla, whereas the spinothalamic pathway decussates at the level of entry and ascends contralaterally. The differing sensory stimuli are segregated in the spinal cord so that the various subtests for these stimuli can distinguish which ascending pathway may be damaged in certain situations.

Whereas the basic sensory stimuli are assessed in the subtests directed at each submodality of somatosensation, testing the ability to discriminate sensations is important. Pairing the light touch and pain subtests together makes it possible to compare the two submodalities at the same time, and therefore the two major ascending tracts at the same time. Mistaking painful stimuli for light touch, or vice versa, may point to errors in ascending projections, such as in a **hemisection** of the spinal cord that might come from a motor vehicle accident.

Another issue of sensory discrimination is not distinguishing between different submodalities, but rather location. The two-point discrimination subtest highlights the density of sensory endings, and therefore receptive fields in the skin. The sensitivity to fine touch, which can give indications of the texture and detailed shape of objects, is highest in the fingertips. To assess the limit of this sensitivity, two-point discrimination is measured by simultaneously touching the skin in two locations, such as could be accomplished with a pair of forceps. Specialized calipers for precisely measuring the distance between points are also available. The patient is asked to indicate whether one or two stimuli are present while keeping their eyes closed. The examiner will switch between using the two points and a single point as the stimulus. Failure to recognize two points may be an indication of a dorsal column pathway deficit.

Similar to two-point discrimination, but assessing laterality of perception, is double simultaneous stimulation. Two stimuli, such as the cotton tips of two applicators, are touched to the same position on both sides of the body. If one side is not perceived, this may indicate damage to the contralateral posterior parietal lobe. Because there is one of each pathway on either side of the spinal cord, they are not likely to interact. If none of the other subtests suggest particular deficits with the pathways, the deficit is likely to be in the cortex where conscious perception is based. The mental status exam contains subtests that assess other functions that are primarily localized to the parietal cortex, such as stereognosis and graphesthesia.

A final subtest of sensory perception that concentrates on the sense of proprioception is known as the **Romberg test**. The patient is asked to stand straight with feet together. Once the patient has achieved their balance in that position, they are asked to close their eyes. Without visual feedback that the body is in a vertical orientation relative to the surrounding environment, the patient must rely on the proprioceptive stimuli of joint and muscle position, as well as information from the inner ear, to maintain balance. This test can indicate deficits in dorsal column pathway proprioception, as well as problems with proprioceptive projections to the cerebellum through the **spinocerebellar tract**.

Watch this video to see a quick demonstration of two-point discrimination. Touching a specialized caliper to the surface of the skin will measure the distance between two points that are perceived as distinct stimuli versus a single stimulus. The patient keeps their eyes closed while the examiner switches between using both points of the caliper or just one. The patient then must indicate whether one or two stimuli are in contact with the skin. Why is the distance between the caliper points closer on the fingertips as opposed to the palm of the hand? And what do you think the distance would be on the arm, or the shoulder?

Muscle Strength and Voluntary Movement

The skeletomotor system is largely based on the simple, two-cell projection from the precentral gyrus of the frontal lobe to the skeletal muscles. The corticospinal tract represents the neurons that send output from the primary motor cortex. These fibers travel through the deep white matter of the cerebrum, then through the midbrain and pons, into the medulla where most of them decussate, and finally through the spinal cord white matter in the lateral (crossed fibers) or anterior (uncrossed fibers) columns. These fibers synapse on motor neurons in the ventral horn. The ventral horn motor neurons then project to skeletal muscle and cause contraction. These two cells are termed the upper motor neuron (UMN) and the lower motor neuron (LMN). Voluntary movements require these two cells to be active.

The motor exam tests the function of these neurons and the muscles they control. First, the muscles are inspected and palpated for signs of structural irregularities. Movement disorders may be the result of changes to the muscle tissue, such as scarring, and these possibilities need to be ruled out before testing function. Along with this inspection, muscle tone is assessed by moving the muscles through a passive range of motion. The arm is moved at the elbow and wrist, and the leg is moved at the knee and ankle. Skeletal muscle should have a resting tension representing a slight contraction of the fibers. The lack of muscle tone, known as **hypotonicity** or **flaccidity**, may indicate that the LMN is not conducting action potentials that will keep a basal level of acetylcholine in the neuromuscular junction.

If muscle tone is present, muscle strength is tested by having the patient contract muscles against resistance. The examiner will ask the patient to lift the arm, for example, while the examiner is pushing down on it. This is done for both limbs, including shrugging the shoulders. Lateral differences in strength—being able to push against resistance with the right arm but not the left—would indicate a deficit in one corticospinal tract versus the other. An overall loss of strength, without laterality, could indicate a global problem with the motor system. Diseases that result in UMN lesions include cerebral palsy or MS, or it may be the result of a stroke. A sign of UMN lesion is a negative result in the subtest for **pronator drift**. The patient is asked to extend both arms in front of the body with the palms facing up. While keeping the eyes closed, if the patient unconsciously allows one or the other arm to slowly relax, toward the pronated position, this could indicate a failure of the motor system to maintain the supinated position.

Reflexes

Reflexes combine the spinal sensory and motor components with a sensory input that directly generates a motor response. The reflexes that are tested in the neurological exam are classified into two groups. A **deep tendon reflex** is commonly known as a stretch reflex, and is elicited by a strong tap to a tendon, such as in the knee-jerk reflex. A **superficial reflex** is elicited through gentle stimulation of the skin and causes contraction of the associated muscles.

For the arm, the common reflexes to test are of the biceps, brachioradialis, triceps, and flexors for the digits. For the leg, the knee-jerk reflex of the quadriceps is common, as is the ankle reflex for the gastrocnemius and soleus. The tendon at the insertion for each of these muscles is struck with a rubber mallet. The muscle is quickly stretched, resulting in activation of the muscle spindle that sends a signal into the spinal cord through the dorsal root. The fiber synapses directly on the ventral horn motor neuron that activates the muscle, causing contraction. The reflexes are physiologically useful for stability. If a muscle is stretched, it reflexively contracts to return the muscle to compensate for the change in length. In the context of the neurological exam, reflexes indicate that the LMN is functioning properly.

The most common superficial reflex in the neurological exam is the **plantar reflex** that tests for the **Babinski sign** on the basis of the extension or flexion of the toes at the plantar surface of the foot. The plantar reflex is commonly tested in newborn infants to establish the presence of neuromuscular function. To elicit this reflex, an examiner brushes a stimulus, usually the examiner's fingertip, along the plantar surface of the infant's foot. An infant would present a positive Babinski sign, meaning the foot dorsiflexes and the toes extend and splay out. As a person learns to walk, the plantar reflex changes to cause curling of the toes and a moderate plantar flexion. If superficial stimulation of the sole of the foot caused extension of the foot, keeping one's balance would be harder. The descending input of the corticospinal tract modifies the response of the plantar reflex, meaning that a negative Babinski sign is the expected response in testing the reflex. Other superficial reflexes are not commonly tested, though a series of abdominal reflexes can target function in the lower thoracic spinal segments.

> Watch this video to see how to test reflexes in the abdomen. Testing reflexes of the trunk is not commonly performed in the neurological exam, but if findings suggest a problem with the thoracic segments of the spinal cord, a series of superficial reflexes of the abdomen can localize function to those segments. If contraction is not observed when the skin lateral to the umbilicus (belly button) is stimulated, what level of the spinal cord may be damaged?

Comparison of Upper and Lower Motor Neuron Damage

Many of the tests of motor function can indicate differences that will address whether damage to the motor system is in the upper or lower motor neurons. Signs that suggest a UMN lesion include muscle weakness, strong deep tendon reflexes, decreased control of movement or slowness, pronator drift, a positive Babinski sign, **spasticity**, and the **clasp-knife response**. Spasticity is an excess contraction in resistance to stretch. It can

result in **hyperflexia**, which is when joints are overly flexed. The clasp-knife response occurs when the patient initially resists movement, but then releases, and the joint will quickly flex like a pocket knife closing.

A lesion on the LMN would result in paralysis, or at least partial loss of voluntary muscle control, which is known as **paresis**. The paralysis observed in LMN diseases is referred to as **flaccid paralysis**, referring to a complete or partial loss of muscle tone, in contrast to the loss of control in UMN lesions in which tone is retained and spasticity is exhibited. Other signs of an LMN lesion are **fibrillation**, **fasciculation**, and compromised or lost reflexes resulting from the denervation of the muscle fibers.

DISORDERS OF THE...

Spinal Cord

In certain situations, such as a motorcycle accident, only half of the spinal cord may be damaged in what is known as a hemisection. Forceful trauma to the trunk may cause ribs or vertebrae to fracture, and debris can crush or section through part of the spinal cord. The full section of a spinal cord would result in paraplegia, or loss of voluntary motor control of the lower body, as well as loss of sensations from that point down. A hemisection, however, will leave spinal cord tracts intact on one side. The resulting condition would be hemiplegia on the side of the trauma—one leg would be paralyzed. The sensory results are more complicated.

The ascending tracts in the spinal cord are segregated between the dorsal column and spinothalamic pathways. This means that the sensory deficits will be based on the particular sensory information each pathway conveys. Sensory discrimination between touch and painful stimuli will illustrate the difference in how these pathways divide these functions.

On the paralyzed leg, a patient will acknowledge painful stimuli, but not fine touch or proprioceptive sensations. On the functional leg, the opposite is true. The reason for this is that the dorsal column pathway ascends ipsilateral to the sensation, so it would be damaged the same way as the lateral corticospinal tract. The spinothalamic pathway decussates immediately upon entering the spinal cord and ascends contralateral to the source; it would therefore bypass the hemisection.

The motor system can indicate the loss of input to the ventral horn in the lumbar enlargement where motor neurons to the leg are found, but motor function in the trunk is less clear. The left and right anterior corticospinal tracts are directly adjacent to each other. The likelihood of trauma to the spinal cord resulting in a hemisection that affects one anterior column, but not the other, is very unlikely. Either the axial musculature will not be affected at all, or there will be bilateral losses in the trunk.

Sensory discrimination can pinpoint the level of damage in the spinal cord. Below the hemisection, pain stimuli will be perceived in the damaged side, but not fine touch. The opposite is true on the other side. The pain fibers on the side with motor function cross the midline in the spinal cord and ascend in the contralateral lateral column as far as the hemisection. The dorsal column will be intact ipsilateral to the source on the intact side and reach the brain for conscious perception. The trauma would be at the level just before sensory discrimination returns to normal, helping to pinpoint the trauma. Whereas imaging technology, like magnetic resonance imaging (MRI) or computed tomography (CT) scanning, could localize the injury as well, nothing more complicated than

a cotton-tipped applicator can localize the damage. That may be all that is available on the scene when moving the victim requires crucial decisions be made.

Chapter Review

The sensory and motor exams assess function related to the spinal cord and the nerves connected to it. Sensory functions are associated with the dorsal regions of the spinal cord, whereas motor function is associated with the ventral side. Localizing damage to the spinal cord is related to assessments of the peripheral projections mapped to dermatomes.

Sensory tests address the various submodalities of the somatic senses: touch, temperature, vibration, pain, and proprioception. Results of the subtests can point to trauma in the spinal cord gray matter, white matter, or even in connections to the cerebral cortex.

Motor tests focus on the function of the muscles and the connections of the descending motor pathway. Muscle tone and strength are tested for upper and lower extremities. Input to the muscles comes from the descending cortical input of upper motor neurons and the direct innervation of lower motor neurons.

Reflexes can either be based on deep stimulation of tendons or superficial stimulation of the skin. The presence of reflexive contractions helps to differentiate motor disorders between the upper and lower motor neurons. The specific signs associated with motor disorders can establish the difference further, based on the type of paralysis, the state of muscle tone, and specific indicators such as pronator drift or the Babinski sign.

The Coordination and Gait Exams

By the end of this section, you will be able to:

- Explain the relationship between the location of the cerebellum and its function in movement
- Chart the major divisions of the cerebellum
- List the major connections of the cerebellum
- Describe the relationship of the cerebellum to axial and appendicular musculature
- Explain the prevalent causes of cerebellar ataxia

The role of the cerebellum is a subject of debate. There is an obvious connection to motor function based on the clinical implications of cerebellar damage. There is also strong evidence of the cerebellar role in procedural memory. The two are not incompatible; in fact, procedural memory is motor memory, such as learning to ride a bicycle. Significant work has been performed to describe the connections within the cerebellum that result in

learning. A model for this learning is classical conditioning, as shown by the famous dogs from the physiologist Ivan Pavlov's work. This classical conditioning, which can be related to motor learning, fits with the neural connections of the cerebellum. The cerebellum is 10 percent of the mass of the brain and has varied functions that all point to a role in the motor system.

Location and Connections of the Cerebellum

The cerebellum is located in apposition to the dorsal surface of the brain stem, centered on the pons. The name of the pons is derived from its connection to the cerebellum. The word means "bridge" and refers to the thick bundle of myelinated axons that form a bulge on its ventral surface. Those fibers are axons that project from the gray matter of the pons into the contralateral cerebellar cortex. These fibers make up the **middle cerebellar peduncle (MCP)** and are the major physical connection of the cerebellum to the brain stem (Figure 1. Cerebellar Penduncies). Two other white matter bundles connect the cerebellum to the other regions of the brain stem. The **superior cerebellar peduncle (SCP)** is the connection of the cerebellum to the midbrain and forebrain. The **inferior cerebellar peduncle (ICP)** is the connection to the medulla.

Cerebellar Penduncles

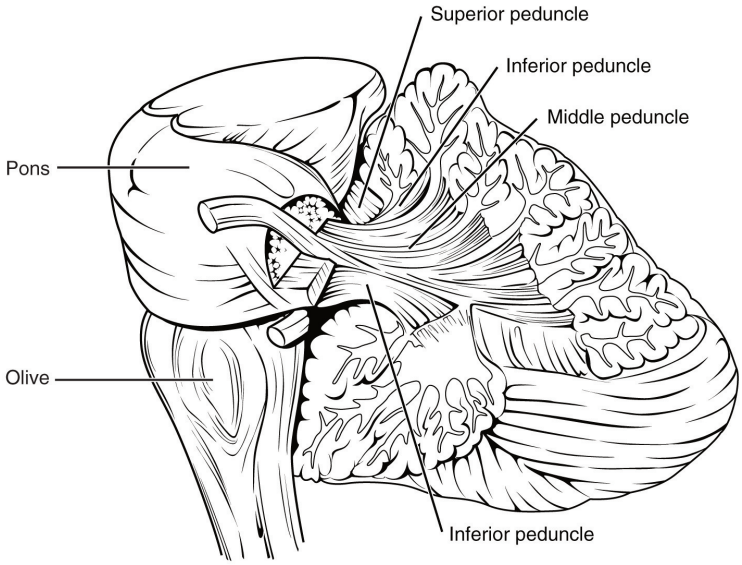


Figure 1. *The connections to the cerebellum are the three cerebellar peduncles, which are close to each other. The ICP arises from the medulla—specifically from the inferior olive, which is visible as a bulge on the ventral surface of the brain stem. The MCP is the ventral surface of the pons. The SCP projects into the midbrain.*

These connections can also be broadly described by their functions. The ICP conveys sensory input to the cerebellum, partially from the spinocerebellar tract, but also through fibers of the **inferior olive**. The MCP is part of the **cortico-ponto-cerebellar pathway** that connects the cerebral cortex with the cerebellum and preferentially targets the lateral regions of the cerebellum. It includes a copy of the motor commands sent from the precentral gyrus through the corticospinal tract, arising from collateral branches that synapse in the gray matter of the pons, along with input from other regions such as the visual cortex. The SCP is the major output of the cerebellum, divided between the **red nucleus** in the midbrain and the thalamus, which will return cerebellar processing to the motor cortex. These connections describe a circuit that compares motor commands and sensory feedback to generate a new output. These comparisons make it possible to coordinate movements.

If the cerebral cortex sends a motor command to initiate walking, that command is copied by the pons and sent into the cerebellum through the MCP. Sensory feedback in the form of proprioception from the spinal cord, as well as vestibular sensations from the inner ear, enters through the ICP. If you take a step and begin to slip on the floor because it is wet, the output from the cerebellum—through the SCP—can correct for that and keep you balanced and moving. The red nucleus sends new motor commands to the spinal cord through the **rubrospinal tract**.

The cerebellum is divided into regions that are based on the particular functions and connections involved. The midline regions of the cerebellum, the **vermis** and **flocculonodular lobe**, are involved in comparing visual information, equilibrium, and proprioceptive feedback to maintain balance and coordinate movements such as walking, or **gait**, through the descending output of the red nucleus (Figure 2. Major Regions of the Cerebellum). The lateral hemispheres are primarily concerned with planning motor functions through frontal lobe inputs that are returned through the thalamic projections back to the premotor and motor cortices. Processing in the midline regions targets movements of the axial musculature, whereas the lateral regions target movements of the appendicular musculature. The vermis is referred to as the **spinocerebellum** because it primarily receives input from the dorsal columns and spinocerebellar pathways. The flocculonodular lobe is referred to as the **vestibulocerebellum** because of the vestibular projection into that region. Finally, the lateral cerebellum is referred to as the **cerebrocerebellum**, reflecting the significant input from the cerebral cortex through the cortico-ponto-cerebellar pathway.

Major Regions of the Cerebellum

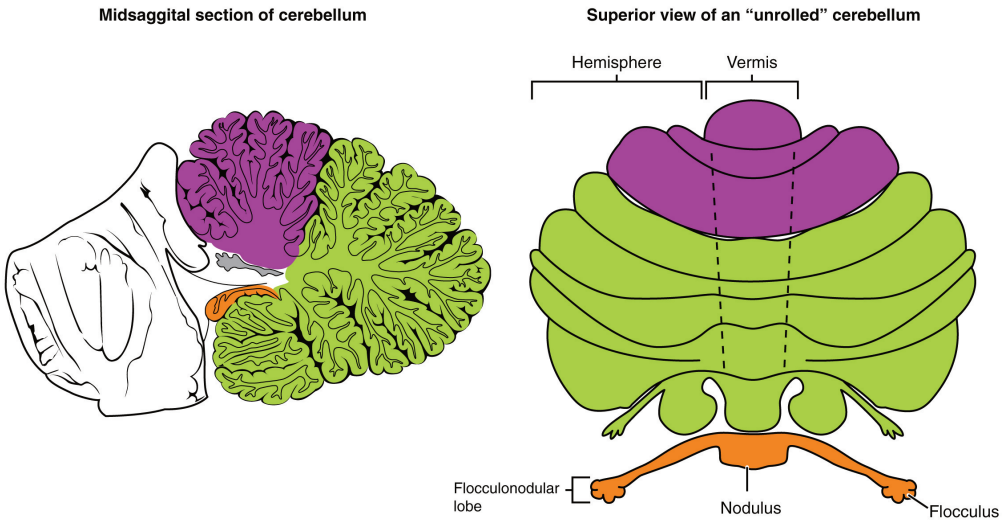


Figure 2. *The cerebellum can be divided into two basic regions: the midline and the hemispheres. The midline is composed of the vermis and the flocculonodular lobe, and the hemispheres are the lateral regions.*

Coordination and Alternating Movement

Testing for cerebellar function is the basis of the coordination exam. The subtests target appendicular musculature, controlling the limbs, and axial musculature for posture and gait. The assessment of cerebellar function will depend on the normal functioning of other systems addressed in previous sections of the neurological exam. Motor control from the cerebrum, as well as sensory input from somatic, visual, and vestibular senses, are important to cerebellar function.

The subtests that address appendicular musculature, and therefore the lateral regions of the cerebellum, begin

with a check for tremor. The patient extends their arms in front of them and holds the position. The examiner watches for the presence of tremors that would not be present if the muscles are relaxed. By pushing down on the arms in this position, the examiner can check for the rebound response, which is when the arms are automatically brought back to the extended position. The extension of the arms is an ongoing motor process, and the tap or push on the arms presents a change in the proprioceptive feedback. The cerebellum compares the cerebral motor command with the proprioceptive feedback and adjusts the descending input to correct. The red nucleus would send an additional signal to the LMN for the arm to increase contraction momentarily to overcome the change and regain the original position.

The **check reflex** depends on cerebellar input to keep increased contraction from continuing after the removal of resistance. The patient flexes the elbow against resistance from the examiner to extend the elbow. When the examiner releases the arm, the patient should be able to stop the increased contraction and keep the arm from moving. A similar response would be seen if you try to pick up a coffee mug that you believe to be full but turns out to be empty. Without checking the contraction, the mug would be thrown from the overexertion of the muscles expecting to lift a heavier object.

Several subtests of the cerebellum assess the ability to alternate movements, or switch between muscle groups that may be antagonistic to each other. In the finger-to-nose test, the patient touches their finger to the examiner's finger and then to their nose, and then back to the examiner's finger, and back to the nose. The examiner moves the target finger to assess a range of movements. A similar test for the lower extremities has the patient touch their toe to a moving target, such as the examiner's finger. Both of these tests involve flexion and extension around a joint—the elbow or the knee and the shoulder or hip—as well as movements of the wrist and ankle. The patient must switch between the opposing muscles, like the biceps and triceps brachii, to move their finger from the target to their nose. Coordinating these movements involves the motor cortex communicating with the cerebellum through the pons and feedback through the thalamus to plan the movements. Visual cortex information is also part of the processing that occurs in the cerebrocerebellum while it is involved in guiding movements of the finger or toe.

Rapid, alternating movements are tested for the upper and lower extremities. The patient is asked to touch each finger to their thumb, or to pat the palm of one hand on the back of the other, and then flip that hand over and alternate back-and-forth. To test similar function in the lower extremities, the patient touches their heel to their shin near the knee and slides it down toward the ankle, and then back again, repetitively. Rapid, alternating movements are part of speech as well. A patient is asked to repeat the nonsense consonants "lah-kah-pah" to alternate movements of the tongue, lips, and palate. All of these rapid alternations require planning from the cerebrocerebellum to coordinate movement commands that control the coordination.

Posture and Gait

Gait can either be considered a separate part of the neurological exam or a subtest of the coordination exam that addresses walking and balance. Testing posture and gait addresses functions of the spinocerebellum and the vestibulocerebellum because both are part of these activities. A subtest called station begins with the patient standing in a normal position to check for the placement of the feet and balance. The patient is asked to hop on one foot to assess the ability to maintain balance and posture during movement. Though the station subtest appears to be similar to the Romberg test, the difference is that the patient's eyes are open during station. The Romberg test has the patient stand still with the eyes closed. Any changes in posture would be the result of proprioceptive deficits, and the patient is able to recover when they open their eyes.

Subtests of walking begin with having the patient walk normally for a distance away from the examiner, and

then turn and return to the starting position. The examiner watches for abnormal placement of the feet and the movement of the arms relative to the movement. The patient is then asked to walk with a few different variations. Tandem gait is when the patient places the heel of one foot against the toe of the other foot and walks in a straight line in that manner. Walking only on the heels or only on the toes will test additional aspects of balance.

Ataxia

A movement disorder of the cerebellum is referred to as **ataxia**. It presents as a loss of coordination in voluntary movements. Ataxia can also refer to sensory deficits that cause balance problems, primarily in proprioception and equilibrium. When the problem is observed in movement, it is ascribed to cerebellar damage. Sensory and vestibular ataxia would likely also present with problems in gait and station.

Ataxia is often the result of exposure to exogenous substances, focal lesions, or a genetic disorder. Focal lesions include strokes affecting the cerebellar arteries, tumors that may impinge on the cerebellum, trauma to the back of the head and neck, or MS. Alcohol intoxication or drugs such as ketamine cause ataxia, but it is often reversible. Mercury in fish can cause ataxia as well. Hereditary conditions can lead to degeneration of the cerebellum or spinal cord, as well as malformation of the brain, or the abnormal accumulation of copper seen in Wilson's disease.

Watch this short video to see a test for station. Station refers to the position a person adopts when they are standing still. The examiner would look for issues with balance, which coordinates proprioceptive, vestibular, and visual information in the cerebellum. To test the ability of a subject to maintain balance, asking them to stand or hop on one foot can be more demanding. The examiner may also push the subject to see if they can maintain balance. An abnormal finding in the test of station is if the feet are placed far apart. Why would a wide stance suggest problems with cerebellar function?

EVERYDAY CONNECTIONS

The Field Sobriety Test

The neurological exam has been described as a clinical tool throughout this chapter. It is also useful in other ways. A variation of the coordination exam is the Field Sobriety Test (FST) used to assess whether drivers are under the influence of alcohol. The cerebellum is crucial for coordinated movements such as keeping balance while walking, or moving appendicular musculature on the basis of proprioceptive feedback. The cerebellum is also very sensitive to ethanol, the particular type of alcohol found in beer, wine, and liquor.

Walking in a straight line involves comparing the motor command from the primary motor cortex to

the proprioceptive and vestibular sensory feedback, as well as following the visual guide of the white line on the side of the road. When the cerebellum is compromised by alcohol, the cerebellum cannot coordinate these movements effectively, and maintaining balance becomes difficult.

Another common aspect of the FST is to have the driver extend their arms out wide and touch their fingertip to their nose, usually with their eyes closed. The point of this is to remove the visual feedback for the movement and force the driver to rely just on proprioceptive information about the movement and position of their fingertip relative to their nose. With eyes open, the corrections to the movement of the arm might be so small as to be hard to see, but proprioceptive feedback is not as immediate and broader movements of the arm will probably be needed, particularly if the cerebellum is affected by alcohol.

Reciting the alphabet backwards is not always a component of the FST, but its relationship to neurological function is interesting. There is a cognitive aspect to remembering how the alphabet goes and how to recite it backwards. That is actually a variation of the mental status subtest of repeating the months backwards. However, the cerebellum is important because speech production is a coordinated activity. The speech rapid alternating movement subtest is specifically using the consonant changes of "lah-kah-pah" to assess coordinated movements of the lips, tongue, pharynx, and palate. But the entire alphabet, especially in the nonrehearsed backwards order, pushes this type of coordinated movement quite far. It is related to the reason that speech becomes slurred when a person is intoxicated.

Chapter Review

The cerebellum is an important part of motor function in the nervous system. It apparently plays a role in procedural learning, which would include motor skills such as riding a bike or throwing a football. The basis for these roles is likely to be tied into the role the cerebellum plays as a comparator for voluntary movement.

The motor commands from the cerebral hemispheres travel along the corticospinal pathway, which passes through the pons. Collateral branches of these fibers synapse on neurons in the pons, which then project into the cerebellar cortex through the middle cerebellar peduncles. Ascending sensory feedback, entering through the inferior cerebellar peduncles, provides information about motor performance. The cerebellar cortex compares the command to the actual performance and can adjust the descending input to compensate for any mismatch. The output from deep cerebellar nuclei projects through the superior cerebellar peduncles to initiate descending signals from the red nucleus to the spinal cord.

The primary role of the cerebellum in relation to the spinal cord is through the spinocerebellum; it controls posture and gait with significant input from the vestibular system. Deficits in cerebellar function result in ataxias, or a specific kind of movement disorder. The root cause of the ataxia may be the sensory input—either the proprioceptive input from the spinal cord or the equilibrium input from the vestibular system, or direct damage to the cerebellum by stroke, trauma, hereditary factors, or toxins.

License

1.7 The Endocrine System

Introduction

A Child Catches a Falling Leaf

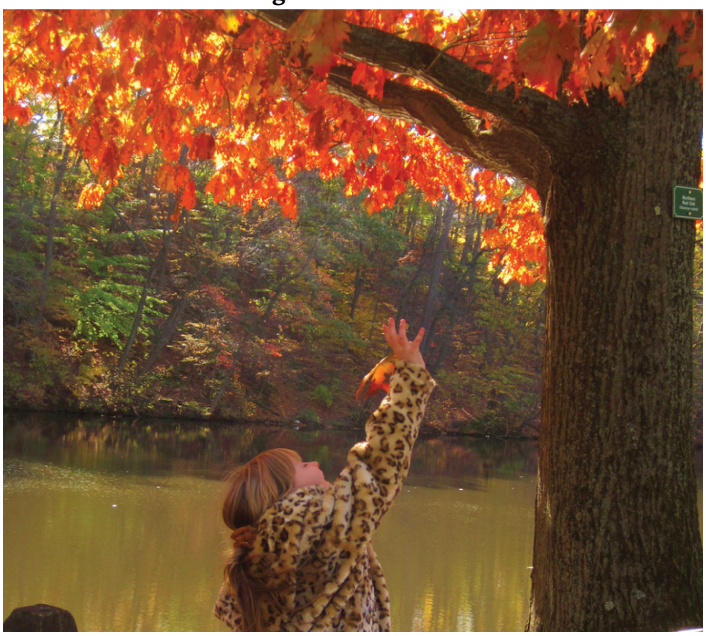


Figure 1. *Hormones of the endocrine system coordinate and control growth, metabolism, temperature regulation, the stress response, reproduction, and many other functions. (credit: "seenthroughmylense"/flickr.com)*

After studying this chapter, you will be able to:

- Identify the contributions of the endocrine system to homeostasis
- Discuss the chemical composition of hormones and the mechanisms of hormone action
- Summarize the site of production, regulation, and effects of the hormones of the pituitary, thyroid, parathyroid, adrenal, and pineal glands
- Discuss the hormonal regulation of the reproductive system
- Explain the role of the pancreatic endocrine cells in the regulation of blood glucose
- Identify the hormones released by the heart, kidneys, and other organs with secondary endocrine functions
- Discuss several common diseases associated with endocrine system dysfunction
- Discuss the embryonic development of, and the effects of aging on, the endocrine system

You may never have thought of it this way, but when you send a text message to two friends to meet you at the dining hall at six, you're sending digital signals that (you hope) will affect their behavior—even though they are some distance away. Similarly, certain cells send chemical signals to other cells in the body that influence their behavior. This long-distance intercellular communication, coordination, and control is critical for homeostasis, and it is the fundamental function of the endocrine system.

An Overview of the Endocrine System

By the end of this section, you will be able to:

- Distinguish the types of intercellular communication, their importance, mechanisms, and effects
- Identify the major organs and tissues of the endocrine system and their location in the body

Communication is a process in which a sender transmits signals to one or more receivers to control and coordinate actions. In the human body, two major organ systems participate in relatively "long distance" communication: the nervous system and the endocrine system. Together, these two systems are primarily responsible for maintaining homeostasis in the body.

Neural and Endocrine Signaling

The nervous system uses two types of intercellular communication—electrical and chemical signaling—either by the direct action of an electrical potential, or in the latter case, through the action of chemical neurotransmitters such as serotonin or norepinephrine. Neurotransmitters act locally and rapidly. When an electrical signal in the form of an action potential arrives at the synaptic terminal, they diffuse across the synaptic cleft (the gap between a sending neuron and a receiving neuron or muscle cell). Once the neurotransmitters interact (bind) with receptors on the receiving (post-synaptic) cell, the receptor stimulation is transduced into a response such as continued electrical signaling or modification of cellular response. The target cell responds within milliseconds of receiving the chemical "message"; this response then ceases very quickly once the neural signaling ends. In this way, neural communication enables body functions that involve quick, brief actions, such as movement, sensation, and cognition.In contrast, the **endocrine system** uses just one method of communication: chemical signaling. These signals are sent by the endocrine organs, which secrete chemicals—the **hormone**—into the extracellular fluid. Hormones are transported primarily via the bloodstream throughout the body, where they bind to receptors on target cells, inducing a characteristic response. As a result, endocrine signaling requires more time than neural signaling to prompt a response in target cells, though the precise amount of time varies with different hormones. For example, the hormones released when you are confronted with a dangerous or frightening situation, called the fight-or-flight response, occur by the release of

adrenal hormones—epinephrine and norepinephrine—within seconds. In contrast, it may take up to 48 hours for target cells to respond to certain reproductive hormones.

> Visit this link to watch an animation of the events that occur when a hormone binds to a cell membrane receptor. What is the secondary messenger made by adenylyl cyclase during the activation of liver cells by epinephrine?

In addition, endocrine signaling is typically less specific than neural signaling. The same hormone may play a role in a variety of different physiological processes depending on the target cells involved. For example, the hormone oxytocin promotes uterine contractions in women in labor. It is also important in breastfeeding, and may be involved in the sexual response and in feelings of emotional attachment in both males and females.

In general, the nervous system involves quick responses to rapid changes in the external environment, and the endocrine system is usually slower acting—taking care of the internal environment of the body, maintaining homeostasis, and controlling reproduction (Table (Endocrine and Nervous Systems)). So how does the fight-or-flight response that was mentioned earlier happen so quickly if hormones are usually slower acting? It is because the two systems are connected. It is the fast action of the nervous system in response to the danger in the environment that stimulates the adrenal glands to secrete their hormones. As a result, the nervous system can cause rapid endocrine responses to keep up with sudden changes in both the external and internal environments when necessary.

Endocrine and Nervous Systems

	Endocrine system	**Nervous system**
Signaling mechanism(s)	Chemical	Chemical/electrical
Primary chemical signal	Hormones	Neurotransmitters
Distance traveled	Long or short	Always short
Response time	Fast or slow	Always fast
Environment targeted	Internal	Internal and external

Structures of the Endocrine System

The endocrine system consists of cells, tissues, and organs that secrete hormones as a primary or secondary function. The **endocrine gland** is the major player in this system. The primary function of these ductless glands is to secrete their hormones directly into the surrounding fluid. The interstitial fluid and the blood vessels then transport the hormones throughout the body. The endocrine system includes the pituitary, thyroid, parathyroid, adrenal, and pineal glands (Figure 1. Endocrine System). Some of these glands have both endocrine and non-endocrine functions. For example, the pancreas contains cells that function in digestion as well as cells that secrete the hormones insulin and glucagon, which regulate blood glucose levels. The hypothalamus, thymus, heart, kidneys, stomach, small intestine, liver, skin, female ovaries, and male testes are other organs that contain cells with endocrine function. Moreover, adipose tissue has long been known to produce hormones, and recent research has revealed that even bone tissue has endocrine functions.

Endocrine System

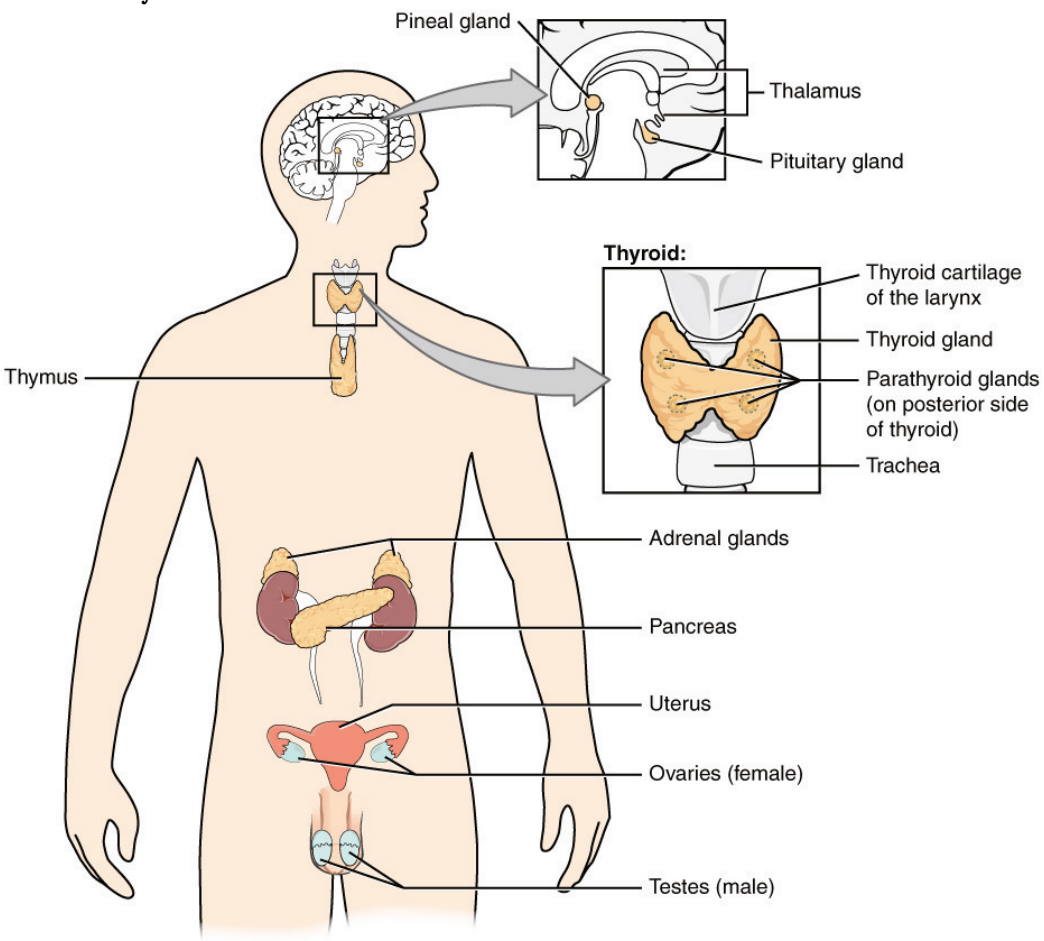


Figure 1. *Endocrine glands and cells are located throughout the body and play an important role in homeostasis.*

The ductless endocrine glands are not to be confused with the body's **exocrine system**, whose glands release their secretions through ducts. Examples of exocrine glands include the sebaceous and sweat glands of the skin. As just noted, the pancreas also has an exocrine function: most of its cells secrete pancreatic juice through the pancreatic and accessory ducts to the lumen of the small intestine.

Other Types of Chemical Signaling

In endocrine signaling, hormones secreted into the extracellular fluid diffuse into the blood or lymph, and can then travel great distances throughout the body. In contrast, autocrine signaling takes place within the same cell. An **autocrine** (auto- = "self") is a chemical that elicits a response in the same cell that secreted it. Interleukin-1, or IL-1, is a signaling molecule that plays an important role in inflammatory response. The cells that secrete IL-1 have receptors on their cell surface that bind these molecules, resulting in autocrine signaling.

Local intercellular communication is the province of the **paracrine**, also called a paracrine factor, which is a chemical that induces a response in neighboring cells. Although paracrines may enter the bloodstream, their concentration is generally too low to elicit a response from distant tissues. A familiar example to those with asthma is histamine, a paracrine that is released by immune cells in the bronchial tree. Histamine causes

the smooth muscle cells of the bronchi to constrict, narrowing the airways. Another example is the neurotransmitters of the nervous system, which act only locally within the synaptic cleft.

CAREER CONNECTIONS

Endocrinologist

Endocrinology is a specialty in the field of medicine that focuses on the treatment of endocrine system disorders. Endocrinologists—medical doctors who specialize in this field—are experts in treating diseases associated with hormonal systems, ranging from thyroid disease to diabetes mellitus. Endocrine surgeons treat endocrine disease through the removal, or resection, of the affected endocrine gland.

Patients who are referred to endocrinologists may have signs and symptoms or blood test results that suggest excessive or impaired functioning of an endocrine gland or endocrine cells. The endocrinologist may order additional blood tests to determine whether the patient's hormonal levels are abnormal, or they may stimulate or suppress the function of the suspect endocrine gland and then have blood taken for analysis. Treatment varies according to the diagnosis. Some endocrine disorders, such as type 2 diabetes, may respond to lifestyle changes such as modest weight loss, adoption of a healthy diet, and regular physical activity. Other disorders may require medication, such as hormone replacement, and routine monitoring by the endocrinologist. These include disorders of the pituitary gland that can affect growth and disorders of the thyroid gland that can result in a variety of metabolic problems.

Some patients experience health problems as a result of the normal decline in hormones that can accompany aging. These patients can consult with an endocrinologist to weigh the risks and benefits of hormone replacement therapy intended to boost their natural levels of reproductive hormones.

In addition to treating patients, endocrinologists may be involved in research to improve the understanding of endocrine system disorders and develop new treatments for these diseases.

Chapter Review

The endocrine system consists of cells, tissues, and organs that secrete hormones critical to homeostasis. The body coordinates its functions through two major types of communication: neural and endocrine. Neural communication includes both electrical and chemical signaling between neurons and target cells. Endocrine communication involves chemical signaling via the release of hormones into the extracellular fluid. From there, hormones diffuse into the bloodstream and may travel to distant body regions, where they elicit a response in target cells. Endocrine glands are ductless glands that secrete hormones. Many organs of the body with other primary functions—such as the heart, stomach, and kidneys—also have hormone-secreting cells.

Hormones

By the end of this section, you will be able to:

- Identify the three major classes of hormones on the basis of chemical structure
- Compare and contrast intracellular and cell membrane hormone receptors
- Describe signaling pathways that involve cAMP and IP3
- Identify several factors that influence a target cell's response
- Discuss the role of feedback loops and humoral, hormonal, and neural stimuli in hormone control

Although a given hormone may travel throughout the body in the bloodstream, it will affect the activity only of its target cells; that is, cells with receptors for that particular hormone. Once the hormone binds to the receptor, a chain of events is initiated that leads to the target cell's response. Hormones play a critical role in the regulation of physiological processes because of the target cell responses they regulate. These responses contribute to human reproduction, growth and development of body tissues, metabolism, fluid, and electrolyte balance, sleep, and many other body functions. The major hormones of the human body and their effects are identified in Table (Endocrine Glands and Their Major Hormones).

Endocrine Glands and Their Major Hormones

Endocrine gland	Associated hormones	Chemical class	Effect
Pituitary (anterior)	Growth hormone (GH)	Protein	Promotes growth of body tissues
Pituitary (anterior)	Prolactin (PRL)	Peptide	Promotes milk production
Pituitary (anterior)	Thyroid-stimulating hormone (TSH)	Glycoprotein	Stimulates thyroid hormone release
Pituitary (anterior)	Adrenocorticotropic hormone (ACTH)	Peptide	Stimulates hormone release by adrenal cortex
Pituitary (anterior)	Follicle-stimulating hormone (FSH)	Glycoprotein	Stimulates gamete production
Pituitary (anterior)	Luteinizing hormone (LH)	Glycoprotein	Stimulates androgen production by gonads
Pituitary (posterior)	Antidiuretic hormone (ADH)	Peptide	Stimulates water reabsorption by kidneys
Pituitary (posterior)	Oxytocin	Peptide	Stimulates uterine contractions during childbirth
Thyroid	Thyroxine (T_4), triiodothyronine (T_3)	Amine	Stimulate basal metabolic rate
Thyroid	Calcitonin	Peptide	Reduces blood Ca^{2+} levels
Parathyroid	Parathyroid hormone (PTH)	Peptide	Increases blood Ca^{2+} levels
Adrenal (cortex)	Aldosterone	Steroid	Increases blood Na^{+} levels
Adrenal (cortex)	Cortisol, corticosterone, cortisone	Steroid	Increase blood glucose levels
Adrenal (medulla)	Epinephrine, norepinephrine	Amine	Stimulate fight-or-flight response
Pineal	Melatonin	Amine	Regulates sleep cycles
Pancreas	Insulin	Protein	Reduces blood glucose levels
Pancreas	Glucagon	Protein	Increases blood glucose levels
Testes	Testosterone	Steroid	Stimulates development of male secondary sex characteristics and sperm production
Ovaries	Estrogens and progesterone	Steroid	Stimulate development of female secondary sex characteristics and prepare the body for childbirth

Types of Hormones

The hormones of the human body can be divided into two major groups on the basis of their chemical structure. Hormones derived from amino acids include amines, peptides, and proteins. Those derived from lipids include steroids (Figure 1. Amine, Peptide, Protein, and Steroid Hormone Structure). These chemical groups affect a hormone's distribution, the type of receptors it binds to, and other aspects of its function.

Amine, Peptide, Protein, and Steroid Hormone Structure

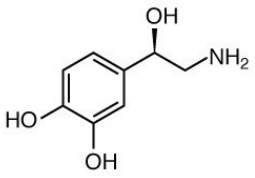
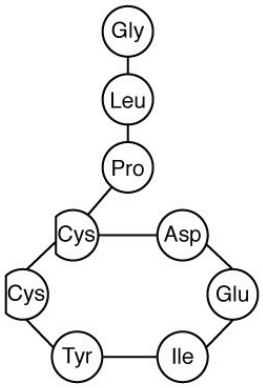
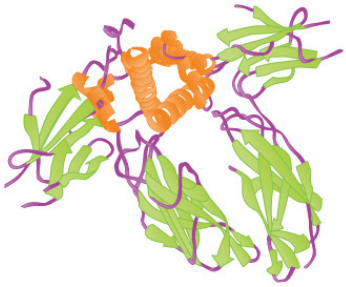
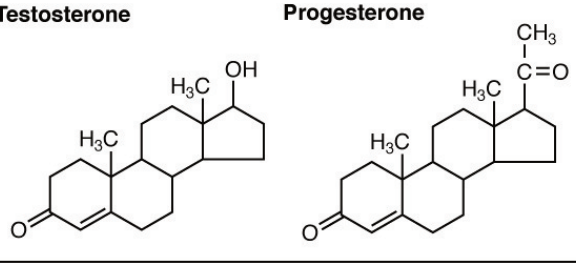
Hormone Class	Components	Example(s)
Amine Hormone	Amino acids with modified groups (e.g. norepinephrine's carboxyl group is replaced with a benzene ring)	**Norepinephrine** 
Peptide Hormone	Short chains of linked amino acids	**Oxytocin** 
Protein Hormone	Long chains of linked amino acids	**Human Growth Hormone** 
Steroid Hormones	Derived from the lipid cholesterol	**Testosterone** **Progesterone** 

Figure 1.

Amine Hormones

Hormones derived from the modification of amino acids are referred to as amine hormones. Typically, the

original structure of the amino acid is modified such that a –COOH, or carboxyl, group is removed, whereas the $-NH_3^+$, or amine, group remains.

Amine hormones are synthesized from the amino acids tryptophan or tyrosine. An example of a hormone derived from tryptophan is melatonin, which is secreted by the pineal gland and helps regulate circadian rhythm. Tyrosine derivatives include the metabolism-regulating thyroid hormones, as well as the catecholamines, such as epinephrine, norepinephrine, and dopamine. Epinephrine and norepinephrine are secreted by the adrenal medulla and play a role in the fight-or-flight response, whereas dopamine is secreted by the hypothalamus and inhibits the release of certain anterior pituitary hormones.

Peptide and Protein Hormones

Whereas the amine hormones are derived from a single amino acid, peptide and protein hormones consist of multiple amino acids that link to form an amino acid chain. Peptide hormones consist of short chains of amino acids, whereas protein hormones are longer polypeptides. Both types are synthesized like other body proteins: DNA is transcribed into mRNA, which is translated into an amino acid chain.

Examples of peptide hormones include antidiuretic hormone (ADH), a pituitary hormone important in fluid balance, and atrial-natriuretic peptide, which is produced by the heart and helps to decrease blood pressure. Some examples of protein hormones include growth hormone, which is produced by the pituitary gland, and follicle-stimulating hormone (FSH), which has an attached carbohydrate group and is thus classified as a glycoprotein. FSH helps stimulate the maturation of eggs in the ovaries and sperm in the testes.

Steroid Hormones

The primary hormones derived from lipids are steroids. Steroid hormones are derived from the lipid cholesterol. For example, the reproductive hormones testosterone and the estrogens—which are produced by the gonads (testes and ovaries)—are steroid hormones. The adrenal glands produce the steroid hormone aldosterone, which is involved in osmoregulation, and cortisol, which plays a role in metabolism.

Like cholesterol, steroid hormones are not soluble in water (they are hydrophobic). Because blood is water-based, lipid-derived hormones must travel to their target cell bound to a transport protein. This more complex structure extends the half-life of steroid hormones much longer than that of hormones derived from amino acids. A hormone's half-life is the time required for half the concentration of the hormone to be degraded. For example, the lipid-derived hormone cortisol has a half-life of approximately 60 to 90 minutes. In contrast, the amino acid–derived hormone epinephrine has a half-life of approximately one minute.

Pathways of Hormone Action

The message a hormone sends is received by a **hormone receptor**, a protein located either inside the cell or within the cell membrane. The receptor will process the message by initiating other signaling events or cellular mechanisms that result in the target cell's response. Hormone receptors recognize molecules with specific shapes and side groups, and respond only to those hormones that are recognized. The same type of receptor

may be located on cells in different body tissues, and trigger somewhat different responses. Thus, the response triggered by a hormone depends not only on the hormone, but also on the target cell.

Once the target cell receives the hormone signal, it can respond in a variety of ways. The response may include the stimulation of protein synthesis, activation or deactivation of enzymes, alteration in the permeability of the cell membrane, altered rates of mitosis and cell growth, and stimulation of the secretion of products. Moreover, a single hormone may be capable of inducing different responses in a given cell.

Pathways Involving Intracellular Hormone Receptors

Intracellular hormone receptors are located inside the cell. Hormones that bind to this type of receptor must be able to cross the cell membrane. Steroid hormones are derived from cholesterol and therefore can readily diffuse through the lipid bilayer of the cell membrane to reach the intracellular receptor (Figure 2. Binding of Lipid-Soluble Hormones). Thyroid hormones, which contain benzene rings studded with iodine, are also lipid-soluble and can enter the cell.

The location of steroid and thyroid hormone binding differs slightly: a steroid hormone may bind to its receptor within the cytosol or within the nucleus. In either case, this binding generates a hormone-receptor complex that moves toward the chromatin in the cell nucleus and binds to a particular segment of the cell's DNA. In contrast, thyroid hormones bind to receptors already bound to DNA. For both steroid and thyroid hormones, binding of the hormone-receptor complex with DNA triggers transcription of a target gene to mRNA, which moves to the cytosol and directs protein synthesis by ribosomes.

Binding of Lipid-Soluble Hormones

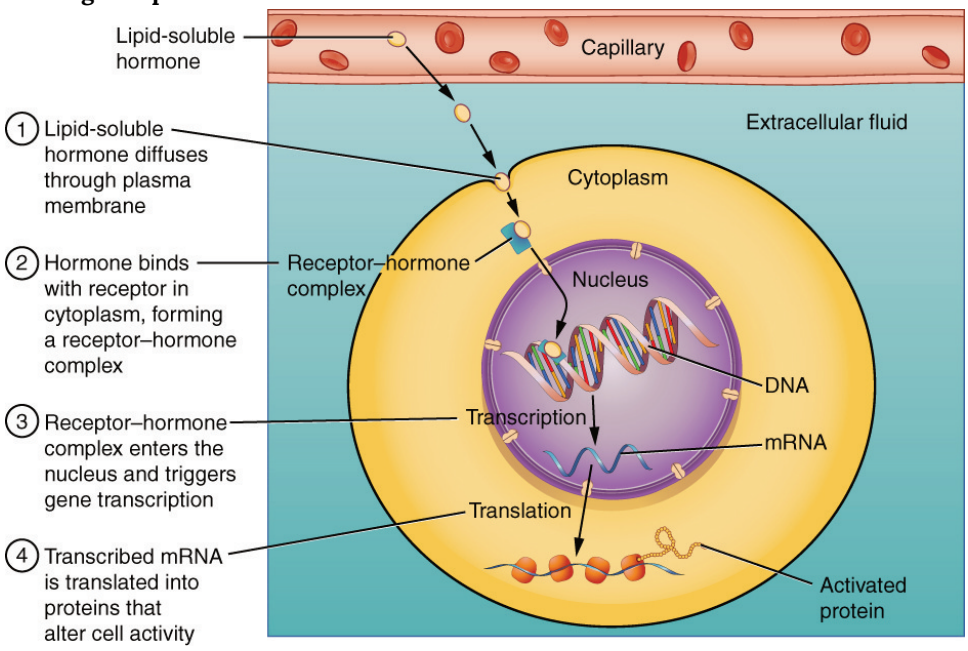


Figure 2. *A steroid hormone directly initiates the production of proteins within a target cell. Steroid hormones easily diffuse through the cell membrane. The hormone binds to its receptor in the cytosol, forming a receptor–hormone complex. The receptor–hormone complex then enters the nucleus and binds to the target gene on the DNA. Transcription of the gene creates a messenger RNA that is translated into the desired protein within the cytoplasm.*

Pathways Involving Cell Membrane Hormone Receptors

Hydrophilic, or water-soluble, hormones are unable to diffuse through the lipid bilayer of the cell membrane and must therefore pass on their message to a receptor located at the surface of the cell. Except for thyroid hormones, which are lipid-soluble, all amino acid–derived hormones bind to cell membrane receptors that are located, at least in part, on the extracellular surface of the cell membrane. Therefore, they do not directly affect the transcription of target genes, but instead initiate a signaling cascade that is carried out by a molecule called a **second messenger**. In this case, the hormone is called a **first messenger**.

The second messenger used by most hormones is **cyclic adenosine monophosphate (cAMP)**. In the cAMP second messenger system, a water-soluble hormone binds to its receptor in the cell membrane (Step 1 in Figure 3. (Binding of Water-Soluble Hormones)). This receptor is associated with an intracellular component called a **G protein**, and binding of the hormone activates the G-protein component (Step 2). The activated G protein in turn activates an enzyme called **adenylyl cyclase**, also known as adenylate cyclase (Step 3), which converts adenosine triphosphate (ATP) to cAMP (Step 4). As the second messenger, cAMP activates a type of enzyme called a **protein kinase** that is present in the cytosol (Step 5). Activated protein kinases initiate a **phosphorylation cascade**, in which multiple protein kinases phosphorylate (add a phosphate group to) numerous and various cellular proteins, including other enzymes (Step 6).

Binding of Water-Soluble Hormones

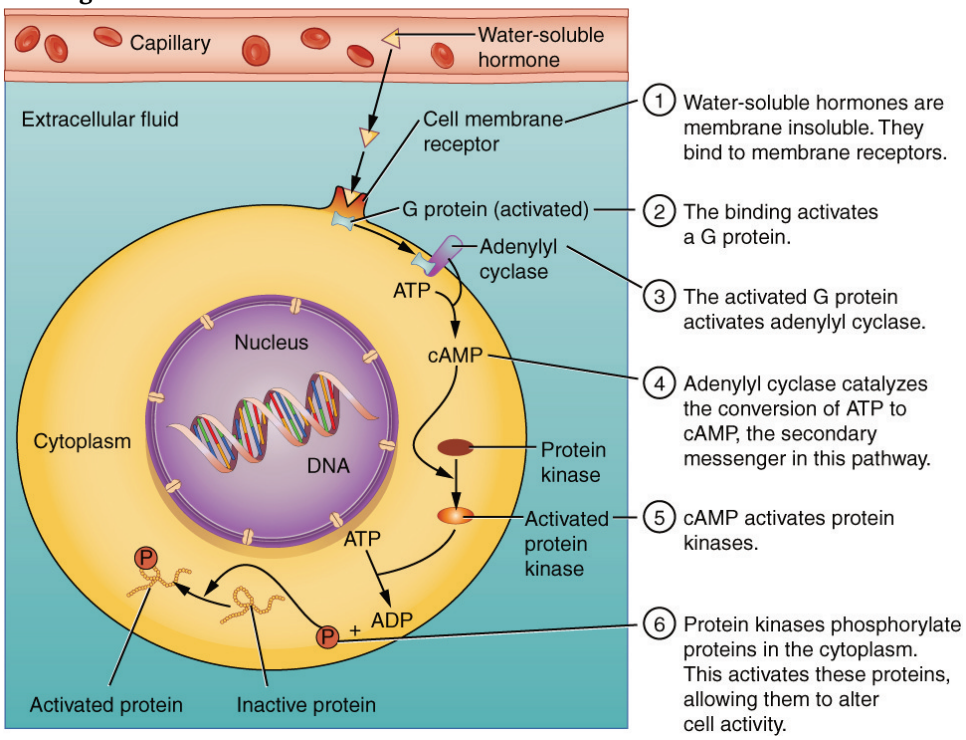


Figure 3. *Water-soluble hormones cannot diffuse through the cell membrane. These hormones must bind to a surface cell-membrane receptor. The receptor then initiates a cell-signaling pathway within the cell involving G proteins, adenylyl cyclase, the secondary messenger cyclic AMP (cAMP), and protein kinases. In the final step, these protein kinases phosphorylate proteins in the cytoplasm. This activates proteins in the cell that carry out the changes specified by the hormone.*

The phosphorylation of cellular proteins can trigger a wide variety of effects, from nutrient metabolism to the

synthesis of different hormones and other products. The effects vary according to the type of target cell, the G proteins and kinases involved, and the phosphorylation of proteins. Examples of hormones that use cAMP as a second messenger include calcitonin, which is important for bone construction and regulating blood calcium levels; glucagon, which plays a role in blood glucose levels; and thyroid-stimulating hormone, which causes the release of T_3 and T_4 from the thyroid gland.

Overall, the phosphorylation cascade significantly increases the efficiency, speed, and specificity of the hormonal response, as thousands of signaling events can be initiated simultaneously in response to a very low concentration of hormone in the bloodstream. However, the duration of the hormone signal is short, as cAMP is quickly deactivated by the enzyme **phosphodiesterase (PDE)**, which is located in the cytosol. The action of PDE helps to ensure that a target cell's response ceases quickly unless new hormones arrive at the cell membrane.

Importantly, there are also G proteins that decrease the levels of cAMP in the cell in response to hormone binding. For example, when growth hormone–inhibiting hormone (GHIH), also known as somatostatin, binds to its receptors in the pituitary gland, the level of cAMP decreases, thereby inhibiting the secretion of human growth hormone.

Not all water-soluble hormones initiate the cAMP second messenger system. One common alternative system uses calcium ions as a second messenger. In this system, G proteins activate the enzyme phospholipase C (PLC), which functions similarly to adenylyl cyclase. Once activated, PLC cleaves a membrane-bound phospholipid into two molecules: **diacylglycerol (DAG)** and inositol triphosphate (IP_3). Like cAMP, DAG activates protein kinases that initiate a phosphorylation cascade. At the same time, IP_3causes calcium ions to be released from storage sites within the cytosol, such as from within the smooth endoplasmic reticulum. The calcium ions then act as second messengers in two ways: they can influence enzymatic and other cellular activities directly, or they can bind to calcium-binding proteins, the most common of which is calmodulin. Upon binding calcium, calmodulin is able to modulate protein kinase within the cell. Examples of hormones that use calcium ions as a second messenger system include angiotensin II, which helps regulate blood pressure through vasoconstriction, and growth hormone–releasing hormone (GHRH), which causes the pituitary gland to release growth hormones.

Factors Affecting Target Cell Response

You will recall that target cells must have receptors specific to a given hormone if that hormone is to trigger a response. But several other factors influence the target cell response. For example, the presence of a significant level of a hormone circulating in the bloodstream can cause its target cells to decrease their number of receptors for that hormone. This process is called **downregulation**, and it allows cells to become less reactive to the excessive hormone levels. When the level of a hormone is chronically reduced, target cells engage in **upregulation** to increase their number of receptors. This process allows cells to be more sensitive to the hormone that is present. Cells can also alter the sensitivity of the receptors themselves to various hormones.

Two or more hormones can interact to affect the response of cells in a variety of ways. The three most common types of interaction are as follows:

- The permissive effect, in which the presence of one hormone enables another hormone to act. For example, thyroid hormones have complex permissive relationships with certain reproductive hormones. A dietary deficiency of iodine, a component of thyroid hormones, can therefore affect reproductive system development and functioning.
- The synergistic effect, in which two hormones with similar effects produce an amplified response. In some cases, two hormones are required for an adequate response. For example, two different reproductive

hormones—FSH from the pituitary gland and estrogens from the ovaries—are required for the maturation of female ova (egg cells).
- The antagonistic effect, in which two hormones have opposing effects. A familiar example is the effect of two pancreatic hormones, insulin and glucagon. Insulin increases the liver's storage of glucose as glycogen, decreasing blood glucose, whereas glucagon stimulates the breakdown of glycogen stores, increasing blood glucose.

Regulation of Hormone Secretion

To prevent abnormal hormone levels and a potential disease state, hormone levels must be tightly controlled. The body maintains this control by balancing hormone production and degradation. Feedback loops govern the initiation and maintenance of most hormone secretion in response to various stimuli.

Role of Feedback Loops

The contribution of feedback loops to homeostasis will only be briefly reviewed here. Positive feedback loops are characterized by the release of additional hormone in response to an original hormone release. The release of oxytocin during childbirth is a positive feedback loop. The initial release of oxytocin begins to signal the uterine muscles to contract, which pushes the fetus toward the cervix, causing it to stretch. This, in turn, signals the pituitary gland to release more oxytocin, causing labor contractions to intensify. The release of oxytocin decreases after the birth of the child.

The more common method of hormone regulation is the negative feedback loop. Negative feedback is characterized by the inhibition of further secretion of a hormone in response to adequate levels of that hormone. This allows blood levels of the hormone to be regulated within a narrow range. An example of a negative feedback loop is the release of glucocorticoid hormones from the adrenal glands, as directed by the hypothalamus and pituitary gland. As glucocorticoid concentrations in the blood rise, the hypothalamus and pituitary gland reduce their signaling to the adrenal glands to prevent additional glucocorticoid secretion (Figure 4. Negative Feedback Loop).

Negative Feedback Loop

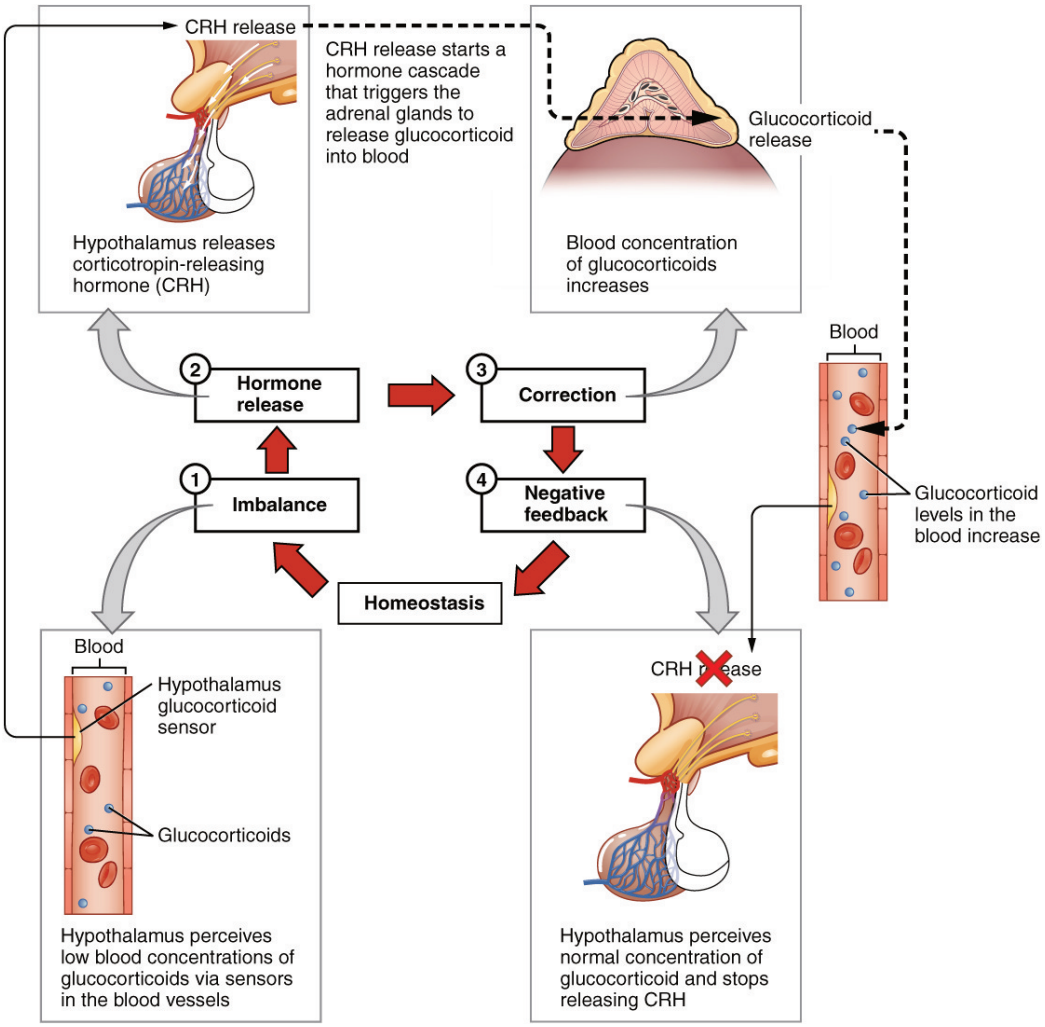


Figure 4. *The release of adrenal glucocorticoids is stimulated by the release of hormones from the hypothalamus and pituitary gland. This signaling is inhibited when glucocorticoid levels become elevated by causing negative signals to the pituitary gland and hypothalamus.*

Role of Endocrine Gland Stimuli

Reflexes triggered by both chemical and neural stimuli control endocrine activity. These reflexes may be simple, involving only one hormone response, or they may be more complex and involve many hormones, as is the case with the hypothalamic control of various anterior pituitary–controlled hormones.

Humoral stimuli are changes in blood levels of non-hormone chemicals, such as nutrients or ions, which cause the release or inhibition of a hormone to, in turn, maintain homeostasis. For example, osmoreceptors in the hypothalamus detect changes in blood osmolarity (the concentration of solutes in the blood plasma). If blood osmolarity is too high, meaning that the blood is not dilute enough, osmoreceptors signal the hypothalamus to release ADH. The hormone causes the kidneys to reabsorb more water and reduce the volume of urine produced. This reabsorption causes a reduction of the osmolarity of the blood, diluting the blood to the appropriate level.

The regulation of blood glucose is another example. High blood glucose levels cause the release of insulin from the pancreas, which increases glucose uptake by cells and liver storage of glucose as glycogen.

An endocrine gland may also secrete a hormone in response to the presence of another hormone produced by a different endocrine gland. Such hormonal stimuli often involve the hypothalamus, which produces releasing and inhibiting hormones that control the secretion of a variety of pituitary hormones.

In addition to these chemical signals, hormones can also be released in response to neural stimuli. A common example of neural stimuli is the activation of the fight-or-flight response by the sympathetic nervous system. When an individual perceives danger, sympathetic neurons signal the adrenal glands to secrete norepinephrine and epinephrine. The two hormones dilate blood vessels, increase the heart and respiratory rate, and suppress the digestive and immune systems. These responses boost the body's transport of oxygen to the brain and muscles, thereby improving the body's ability to fight or flee.

EVERYDAY CONNECTIONS

Bisphenol A and Endocrine Disruption

You may have heard news reports about the effects of a chemical called bisphenol A (BPA) in various types of food packaging. BPA is used in the manufacturing of hard plastics and epoxy resins. Common food-related items that may contain BPA include the lining of aluminum cans, plastic food-storage containers, drinking cups, as well as baby bottles and "sippy" cups. Other uses of BPA include medical equipment, dental fillings, and the lining of water pipes.

Research suggests that BPA is an endocrine disruptor, meaning that it negatively interferes with the endocrine system, particularly during the prenatal and postnatal development period. In particular, BPA mimics the hormonal effects of estrogens and has the opposite effect—that of androgens. The U.S. Food and Drug Administration (FDA) notes in their statement about BPA safety that although traditional toxicology studies have supported the safety of low levels of exposure to BPA, recent studies using novel approaches to test for subtle effects have led to some concern about the potential effects of BPA on the brain, behavior, and prostate gland in fetuses, infants, and young children. The FDA is currently facilitating decreased use of BPA in food-related materials. Many US companies have voluntarily removed BPA from baby bottles, "sippy" cups, and the linings of infant formula cans, and most plastic reusable water bottles sold today boast that they are "BPA free." In contrast, both Canada and the European Union have completely banned the use of BPA in baby products.

The potential harmful effects of BPA have been studied in both animal models and humans and include a large variety of health effects, such as developmental delay and disease. For example, prenatal exposure to BPA during the first trimester of human pregnancy may be associated with wheezing and aggressive behavior during childhood. Adults exposed to high levels of BPA may experience altered thyroid signaling and male sexual dysfunction. BPA exposure during the prenatal or postnatal period of development in animal models has been observed to cause neurological delays, changes in brain structure and function, sexual dysfunction, asthma, and increased risk for multiple cancers. In vitro studies have also shown that BPA exposure causes molecular changes that initiate the development of cancers of the breast, prostate, and brain. Although these studies have implicated BPA in numerous ill health effects, some experts caution that some of these studies may be flawed and that more research needs to be done. In the meantime, the FDA recommends that consumers take precautions to limit their exposure to BPA. In addition to purchasing foods in packaging free of

BPA, consumers should avoid carrying or storing foods or liquids in bottles with the recycling code 3 or 7. Foods and liquids should not be microwave-heated in any form of plastic: use paper, glass, or ceramics instead.

Chapter Review

Hormones are derived from amino acids or lipids. Amine hormones originate from the amino acids tryptophan or tyrosine. Larger amino acid hormones include peptides and protein hormones. Steroid hormones are derived from cholesterol.

Steroid hormones and thyroid hormone are lipid soluble. All other amino acid–derived hormones are water soluble. Hydrophobic hormones are able to diffuse through the membrane and interact with an intracellular receptor. In contrast, hydrophilic hormones must interact with cell membrane receptors. These are typically associated with a G protein, which becomes activated when the hormone binds the receptor. This initiates a signaling cascade that involves a second messenger, such as cyclic adenosine monophosphate (cAMP). Second messenger systems greatly amplify the hormone signal, creating a broader, more efficient, and faster response.

Hormones are released upon stimulation that is of either chemical or neural origin. Regulation of hormone release is primarily achieved through negative feedback. Various stimuli may cause the release of hormones, but there are three major types. Humoral stimuli are changes in ion or nutrient levels in the blood. Hormonal stimuli are changes in hormone levels that initiate or inhibit the secretion of another hormone. Finally, a neural stimulus occurs when a nerve impulse prompts the secretion or inhibition of a hormone.

The Pituitary Gland and Hypothalamus

By the end of this section, you will be able to:

- Explain the interrelationships of the anatomy and functions of the hypothalamus and the posterior and anterior lobes of the pituitary gland
- Identify the two hormones released from the posterior pituitary, their target cells, and their principal actions
- Identify the six hormones produced by the anterior lobe of the pituitary gland, their target cells, their principal actions, and their regulation by the hypothalamus

The hypothalamus–pituitary complex can be thought of as the “command center” of the endocrine system. This complex secretes several hormones that directly produce responses in target tissues, as well as hormones

that regulate the synthesis and secretion of hormones of other glands. In addition, the hypothalamus–pituitary complex coordinates the messages of the endocrine and nervous systems. In many cases, a stimulus received by the nervous system must pass through the hypothalamus–pituitary complex to be translated into hormones that can initiate a response.

The **hypothalamus** is a structure of the diencephalon of the brain located anterior and inferior to the thalamus (Figure 1. Hypothalamus-Pituitary Complex). It has both neural and endocrine functions, producing and secreting many hormones. In addition, the hypothalamus is anatomically and functionally related to the **pituitary gland** (or hypophysis), a bean-sized organ suspended from it by a stem called the **infundibulum** (or pituitary stalk). The pituitary gland is cradled within the sellaturcica of the sphenoid bone of the skull. It consists of two lobes that arise from distinct parts of embryonic tissue: the posterior pituitary (neurohypophysis) is neural tissue, whereas the anterior pituitary (also known as the adenohypophysis) is glandular tissue that develops from the primitive digestive tract. The hormones secreted by the posterior and anterior pituitary, and the intermediate zone between the lobes are summarized in Table (Pituitary Hormones).

Hypothalamus–Pituitary Complex

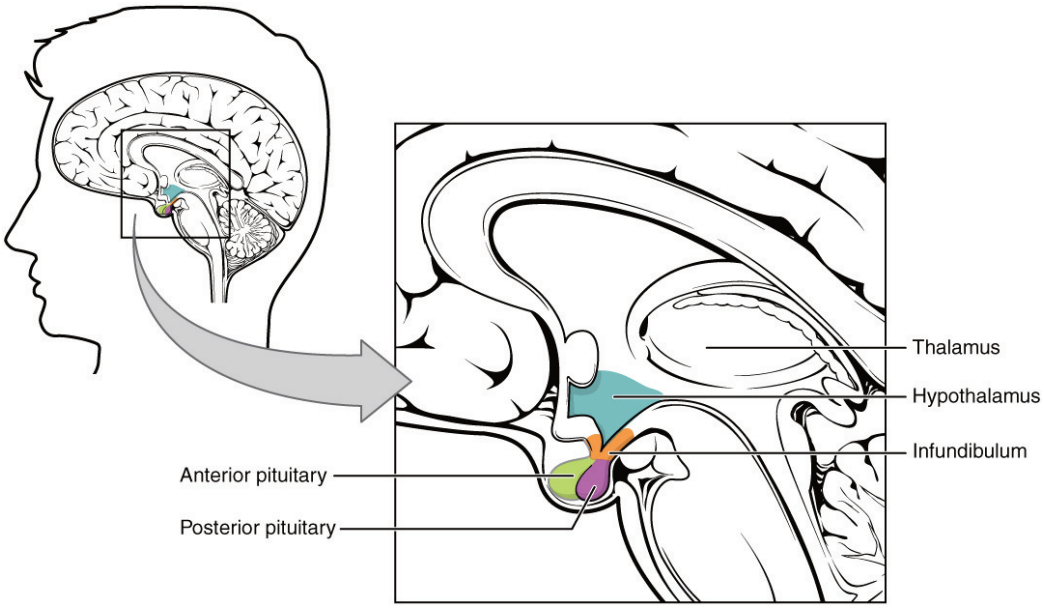


Figure 1. *The hypothalamus region lies inferior and anterior to the thalamus. It connects to the pituitary gland by the stalk-like infundibulum. The pituitary gland consists of an anterior and posterior lobe, with each lobe secreting different hormones in response to signals from the hypothalamus.*

Pituitary Hormones

Pituitary lobe	Associated hormones	Chemical class	Effect
Anterior	Growth hormone (GH)	Protein	Promotes growth of body tissues
Anterior	Prolactin (PRL)	Peptide	Promotes milk production from mammary glands
Anterior	Thyroid-stimulating hormone (TSH)	Glycoprotein	Stimulates thyroid hormone release from thyroid
Anterior	Adrenocorticotropic hormone (ACTH)	Peptide	Stimulates hormone release by adrenal cortex
Anterior	Follicle-stimulating hormone (FSH)	Glycoprotein	Stimulates gamete production in gonads
Anterior	Luteinizing hormone (LH)	Glycoprotein	Stimulates androgen production by gonads
Posterior	Antidiuretic hormone (ADH)	Peptide	Stimulates water reabsorption by kidneys
Posterior	Oxytocin	Peptide	Stimulates uterine contractions during childbirth
Intermediate zone	Melanocyte-stimulating hormone	Peptide	Stimulates melanin formation in melanocytes

Posterior Pituitary

The posterior pituitary is actually an extension of the neurons of the paraventricular and supraoptic nuclei of the hypothalamus. The cell bodies of these regions rest in the hypothalamus, but their axons descend as the hypothalamic–hypophyseal tract within the infundibulum, and end in axon terminals that comprise the posterior pituitary (Figure 2. Posterior Pituitary).

Posterior Pituitary

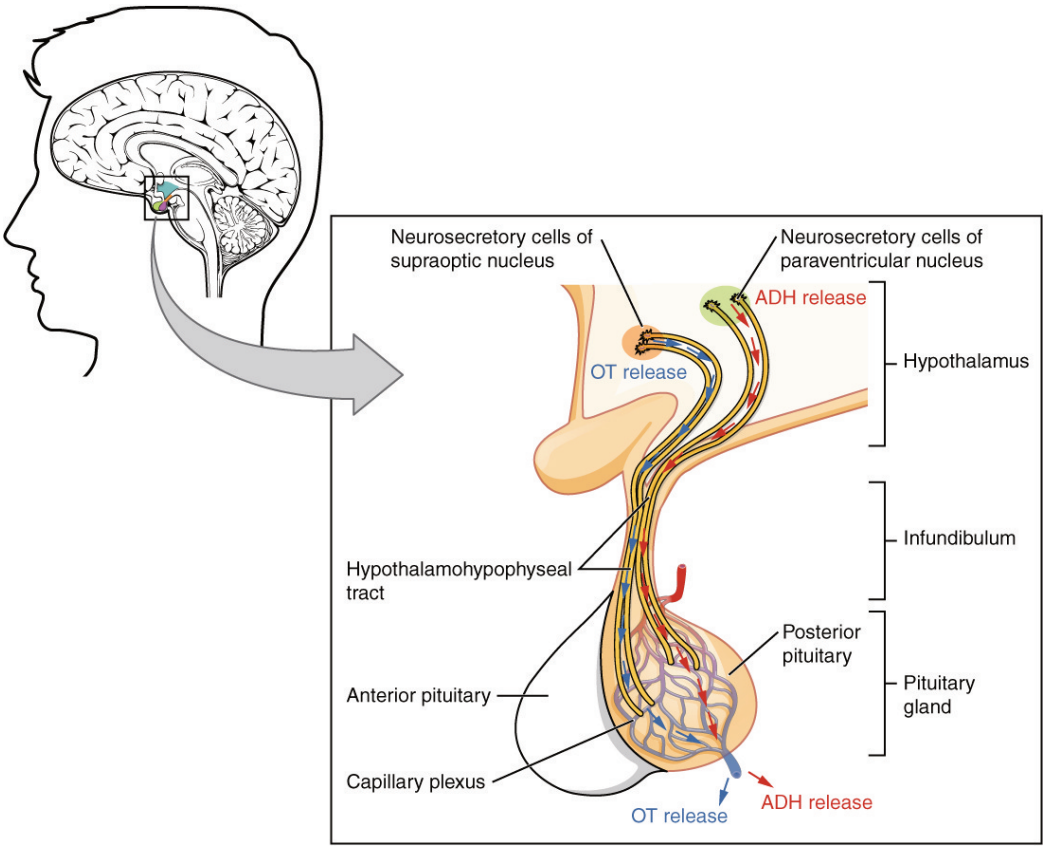


Figure 2. *Neurosecretory cells in the hypothalamus release oxytocin (OT) or ADH into the posterior lobe of the pituitary gland. These hormones are stored or released into the blood via the capillary plexus.*

The posterior pituitary gland does not produce hormones, but rather stores and secretes hormones produced by the hypothalamus. The paraventricular nuclei produce the hormone oxytocin, whereas the supraoptic nuclei produce ADH. These hormones travel along the axons into storage sites in the axon terminals of the posterior pituitary. In response to signals from the same hypothalamic neurons, the hormones are released from the axon terminals into the bloodstream.

Oxytocin

When fetal development is complete, the peptide-derived hormone **oxytocin** (tocia- = "childbirth") stimulates uterine contractions and dilation of the cervix. Throughout most of pregnancy, oxytocin hormone receptors are not expressed at high levels in the uterus. Toward the end of pregnancy, the synthesis of oxytocin receptors in the uterus increases, and the smooth muscle cells of the uterus become more sensitive to its effects. Oxytocin is continually released throughout childbirth through a positive feedback mechanism. As noted earlier, oxytocin prompts uterine contractions that push the fetal head toward the cervix. In response, cervical stretching stimulates additional oxytocin to be synthesized by the hypothalamus and released from the pituitary. This increases the intensity and effectiveness of uterine contractions and prompts additional dilation of the cervix. The feedback loop continues until birth.

Although the mother's high blood levels of oxytocin begin to decrease immediately following birth, oxytocin

continues to play a role in maternal and newborn health. First, oxytocin is necessary for the milk ejection reflex (commonly referred to as "let-down") in breastfeeding women. As the newborn begins suckling, sensory receptors in the nipples transmit signals to the hypothalamus. In response, oxytocin is secreted and released into the bloodstream. Within seconds, cells in the mother's milk ducts contract, ejecting milk into the infant's mouth. Secondly, in both males and females, oxytocin is thought to contribute to parent–newborn bonding, known as attachment. Oxytocin is also thought to be involved in feelings of love and closeness, as well as in the sexual response.

Antidiuretic Hormone (ADH)

The solute concentration of the blood, or blood osmolarity, may change in response to the consumption of certain foods and fluids, as well as in response to disease, injury, medications, or other factors. Blood osmolarity is constantly monitored by **osmoreceptors**—specialized cells within the hypothalamus that are particularly sensitive to the concentration of sodium ions and other solutes.

In response to high blood osmolarity, which can occur during dehydration or following a very salty meal, the osmoreceptors signal the posterior pituitary to release **antidiuretic hormone (ADH)**. The target cells of ADH are located in the tubular cells of the kidneys. Its effect is to increase epithelial permeability to water, allowing increased water reabsorption. The more water reabsorbed from the filtrate, the greater the amount of water that is returned to the blood and the less that is excreted in the urine. A greater concentration of water results in a reduced concentration of solutes. ADH is also known as vasopressin because, in very high concentrations, it causes constriction of blood vessels, which increases blood pressure by increasing peripheral resistance. The release of ADH is controlled by a negative feedback loop. As blood osmolarity decreases, the hypothalamic osmoreceptors sense the change and prompt a corresponding decrease in the secretion of ADH. As a result, less water is reabsorbed from the urine filtrate.

Interestingly, drugs can affect the secretion of ADH. For example, alcohol consumption inhibits the release of ADH, resulting in increased urine production that can eventually lead to dehydration and a hangover. A disease called diabetes insipidus is characterized by chronic underproduction of ADH that causes chronic dehydration. Because little ADH is produced and secreted, not enough water is reabsorbed by the kidneys. Although patients feel thirsty, and increase their fluid consumption, this doesn't effectively decrease the solute concentration in their blood because ADH levels are not high enough to trigger water reabsorption in the kidneys. Electrolyte imbalances can occur in severe cases of diabetes insipidus.

Anterior Pituitary

The anterior pituitary originates from the digestive tract in the embryo and migrates toward the brain during fetal development. There are three regions: the pars distalis is the most anterior, the pars intermedia is adjacent to the posterior pituitary, and the pars tuberalis is a slender "tube" that wraps the infundibulum.

Recall that the posterior pituitary does not synthesize hormones, but merely stores them. In contrast, the anterior pituitary does manufacture hormones. However, the secretion of hormones from the anterior pituitary is regulated by two classes of hormones. These hormones—secreted by the hypothalamus—are the releasing hormones that stimulate the secretion of hormones from the anterior pituitary and the inhibiting hormones that inhibit secretion.

Hypothalamic hormones are secreted by neurons, but enter the anterior pituitary through blood vessels (Figure 3. Anterior Pituitary). Within the infundibulum is a bridge of capillaries that connects the hypothalamus to the anterior pituitary. This network, called the **hypophyseal portal system**, allows hypothalamic hormones to be transported to the anterior pituitary without first entering the systemic circulation. The system originates from the superior hypophyseal artery, which branches off the carotid arteries and transports blood to the hypothalamus. The branches of the superior hypophyseal artery form the hypophyseal portal system (see Figure 3. Anterior Pituitary). Hypothalamic releasing and inhibiting hormones travel through a primary capillary plexus to the portal veins, which carry them into the anterior pituitary. Hormones produced by the anterior pituitary (in response to releasing hormones) enter a secondary capillary plexus, and from there drain into the circulation.

Anterior Pituitary

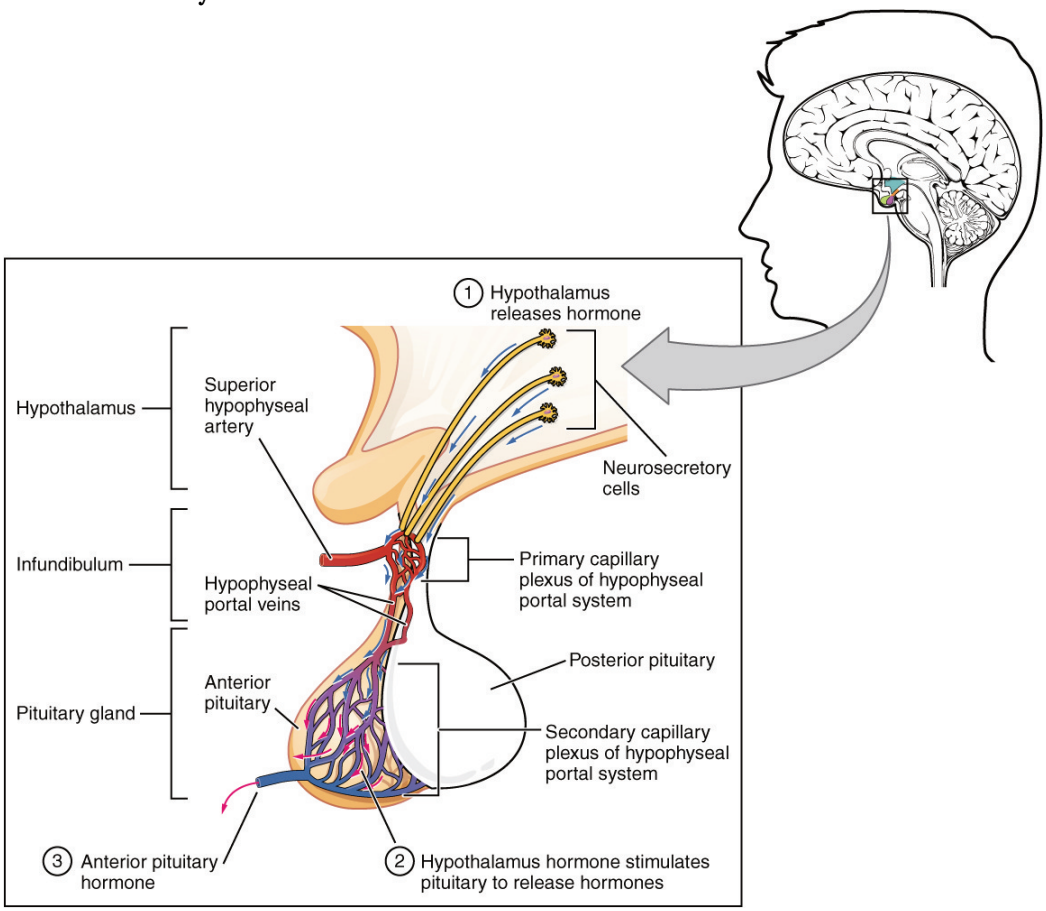


Figure 3. *The anterior pituitary manufactures seven hormones. The hypothalamus produces separate hormones that stimulate or inhibit hormone production in the anterior pituitary. Hormones from the hypothalamus reach the anterior pituitary via the hypophyseal portal system.*

The anterior pituitary produces seven hormones. These are the growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), beta endorphin, and prolactin. Of the hormones of the anterior pituitary, TSH, ACTH, FSH, and LH are collectively referred to as tropic hormones (trope- = "turning") because they turn on or off the function of other endocrine glands.

Growth Hormone

The endocrine system regulates the growth of the human body, protein synthesis, and cellular replication. A major hormone involved in this process is **growth hormone (GH)**, also called somatotropin—a protein hormone produced and secreted by the anterior pituitary gland. Its primary function is anabolic; it promotes protein synthesis and tissue building through direct and indirect mechanisms (Figure 4. Hormonal Regulation of Growth). GH levels are controlled by the release of GHRH and GHIH (also known as somatostatin) from the hypothalamus.

Hormonal Regulation of Growth

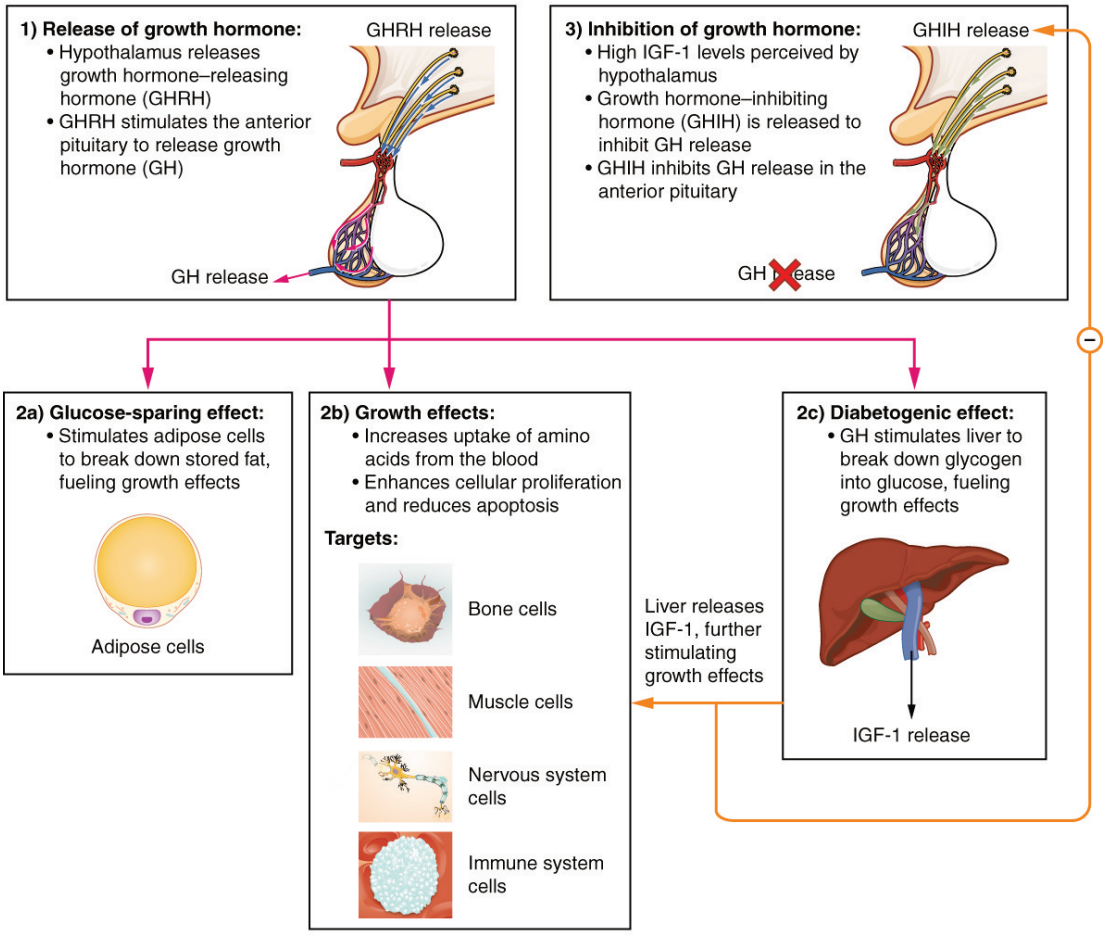


Figure 4. *Growth hormone (GH) directly accelerates the rate of protein synthesis in skeletal muscle and bones. Insulin-like growth factor 1 (IGF-1) is activated by growth hormone and indirectly supports the formation of new proteins in muscle cells and bone.*

A glucose-sparing effect occurs when GH stimulates lipolysis, or the breakdown of adipose tissue, releasing fatty acids into the blood. As a result, many tissues switch from glucose to fatty acids as their main energy source, which means that less glucose is taken up from the bloodstream.

GH also initiates the diabetogenic effect in which GH stimulates the liver to break down glycogen to glucose, which is then deposited into the blood. The name "diabetogenic" is derived from the similarity in elevated blood glucose levels observed between individuals with untreated diabetes mellitus and individuals experiencing GH excess. Blood glucose levels rise as the result of a combination of glucose-sparing and diabetogenic effects.

GH indirectly mediates growth and protein synthesis by triggering the liver and other tissues to produce a

group of proteins called **insulin-like growth factors (IGFs)**. These proteins enhance cellular proliferation and inhibit apoptosis, or programmed cell death. IGFs stimulate cells to increase their uptake of amino acids from the blood for protein synthesis. Skeletal muscle and cartilage cells are particularly sensitive to stimulation from IGFs.

Dysfunction of the endocrine system's control of growth can result in several disorders. For example, **gigantism** is a disorder in children that is caused by the secretion of abnormally large amounts of GH, resulting in excessive growth. A similar condition in adults is **acromegaly**, a disorder that results in the growth of bones in the face, hands, and feet in response to excessive levels of GH in individuals who have stopped growing. Abnormally low levels of GH in children can cause growth impairment—a disorder called **pituitary dwarfism** (also known as growth hormone deficiency).

Thyroid-Stimulating Hormone

The activity of the thyroid gland is regulated by **thyroid-stimulating hormone (TSH)**, also called thyrotropin. TSH is released from the anterior pituitary in response to thyrotropin-releasing hormone (TRH) from the hypothalamus. As discussed shortly, it triggers the secretion of thyroid hormones by the thyroid gland. In a classic negative feedback loop, elevated levels of thyroid hormones in the bloodstream then trigger a drop in production of TRH and subsequently TSH.

Adrenocorticotropic Hormone

The **adrenocorticotropic hormone (ACTH)**, also called corticotropin, stimulates the adrenal cortex (the more superficial "bark" of the adrenal glands) to secrete corticosteroid hormones such as cortisol. ACTH come from a precursor molecule known as pro-opiomelanotropin (POMC) which produces several biologically active molecules when cleaved, including ACTH, melanocyte-stimulating hormone, and the brain opioid peptides known as endorphins.

The release of ACTH is regulated by the corticotropin-releasing hormone (CRH) from the hypothalamus in response to normal physiologic rhythms. A variety of stressors can also influence its release, and the role of ACTH in the stress response is discussed later in this chapter.

Follicle-Stimulating Hormone and Luteinizing Hormone

The endocrine glands secrete a variety of hormones that control the development and regulation of the reproductive system (these glands include the anterior pituitary, the adrenal cortex, and the gonads—the testes in males and the ovaries in females). Much of the development of the reproductive system occurs during puberty and is marked by the development of sex-specific characteristics in both male and female adolescents. Puberty is initiated by gonadotropin-releasing hormone (GnRH), a hormone produced and secreted by the hypothalamus. GnRH stimulates the anterior pituitary to secrete **gonadotropins**—hormones that regulate the function of the gonads. The levels of GnRH are regulated through a negative feedback loop; high levels of reproductive hormones

inhibit the release of GnRH. Throughout life, gonadotropins regulate reproductive function and, in the case of women, the onset and cessation of reproductive capacity.

The gonadotropins include two glycoprotein hormones: **follicle-stimulating hormone (FSH)** stimulates the production and maturation of sex cells, or gametes, including ova in women and sperm in men. FSH also promotes follicular growth; these follicles then release estrogens in the female ovaries. **Luteinizing hormone (LH)** triggers ovulation in women, as well as the production of estrogens and progesterone by the ovaries. LH stimulates production of testosterone by the male testes.

Prolactin

As its name implies, **prolactin (PRL)** promotes lactation (milk production) in women. During pregnancy, it contributes to development of the mammary glands, and after birth, it stimulates the mammary glands to produce breast milk. However, the effects of prolactin depend heavily upon the permissive effects of estrogens, progesterone, and other hormones. And as noted earlier, the let-down of milk occurs in response to stimulation from oxytocin.

In a non-pregnant woman, prolactin secretion is inhibited by prolactin-inhibiting hormone (PIH), which is actually the neurotransmitter dopamine, and is released from neurons in the hypothalamus. Only during pregnancy do prolactin levels rise in response to prolactin-releasing hormone (PRH) from the hypothalamus.

Intermediate Pituitary: Melanocyte-Stimulating Hormone

The cells in the zone between the pituitary lobes secrete a hormone known as melanocyte-stimulating hormone (MSH) that is formed by cleavage of the pro-opiomelanocortin (POMC) precursor protein. Local production of MSH in the skin is responsible for melanin production in response to UV light exposure. The role of MSH made by the pituitary is more complicated. For instance, people with lighter skin generally have the same amount of MSH as people with darker skin. Nevertheless, this hormone is capable of darkening of the skin by inducing melanin production in the skin's melanocytes. Women also show increased MSH production during pregnancy; in combination with estrogens, it can lead to darker skin pigmentation, especially the skin of the areolas and labia minora. Figure 5. (Major Pituitary Hormones) is a summary of the pituitary hormones and their principal effects.
Major Pituitary Hormones

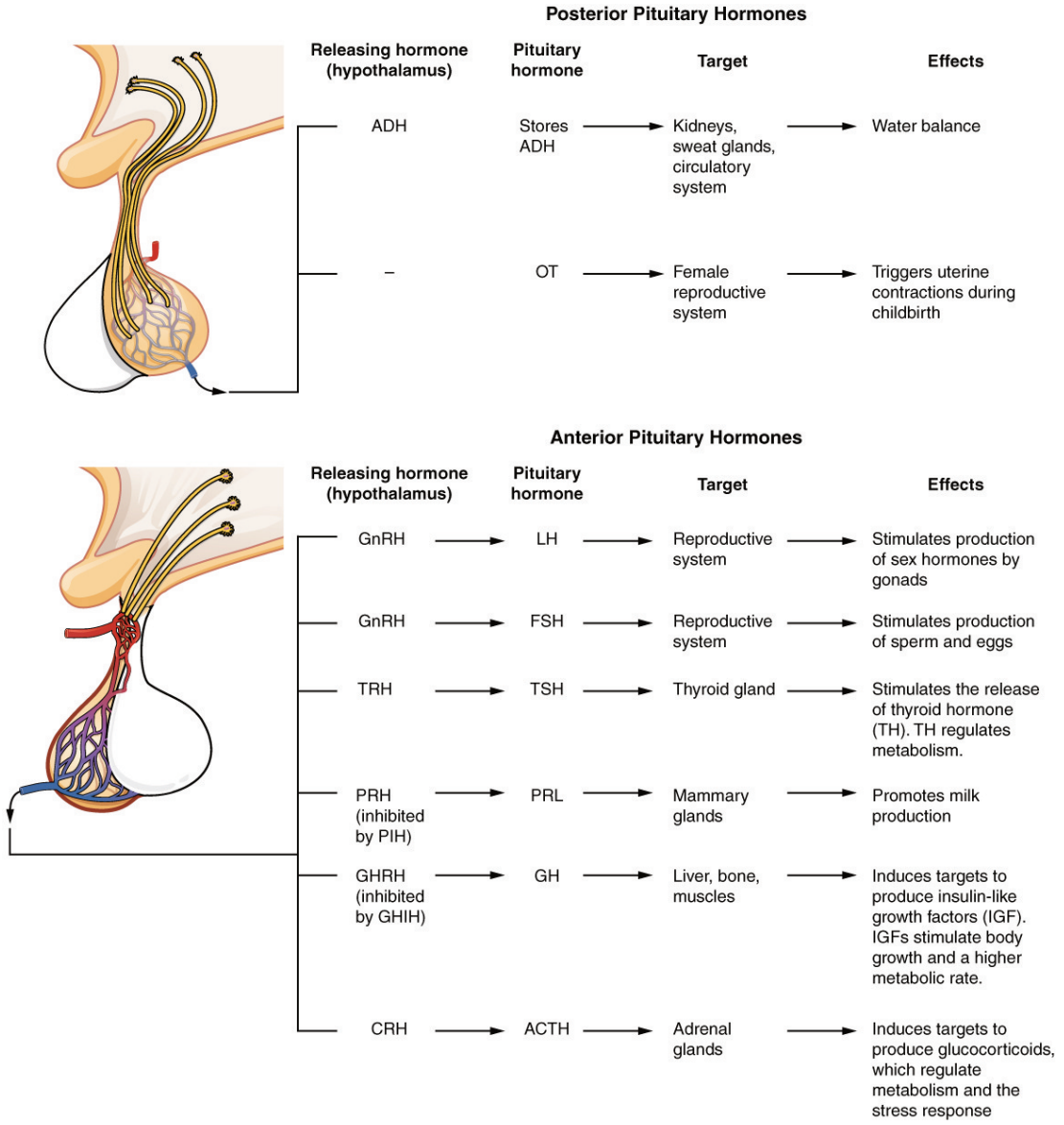


Figure 5. *Major pituitary hormones and their target organs.*

Visit this link to watch an animation showing the role of the hypothalamus and the pituitary gland. Which hormone is released by the pituitary to stimulate the thyroid gland?

Chapter Review

The hypothalamus–pituitary complex is located in the diencephalon of the brain. The hypothalamus and the pituitary gland are connected by a structure called the infundibulum, which contains vasculature and nerve axons. The pituitary gland is divided into two distinct structures with different embryonic origins. The posterior

lobe houses the axon terminals of hypothalamic neurons. It stores and releases into the bloodstream two hypothalamic hormones: oxytocin and antidiuretic hormone (ADH). The anterior lobe is connected to the hypothalamus by vasculature in the infundibulum and produces and secretes six hormones. Their secretion is regulated, however, by releasing and inhibiting hormones from the hypothalamus. The six anterior pituitary hormones are: growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), and prolactin (PRL).

The Thyroid Gland

By the end of this section, you will be able to:

- Describe the location and anatomy of the thyroid gland
- Discuss the synthesis of triiodothyronine and thyroxine
- Explain the role of thyroid hormones in the regulation of basal metabolism
- Identify the hormone produced by the parafollicular cells of the thyroid

A butterfly-shaped organ, the **thyroid gland** is located anterior to the trachea, just inferior to the larynx (Figure 1. Thyroid Gland). The medial region, called the isthmus, is flanked by wing-shaped left and right lobes. Each of the thyroid lobes are embedded with parathyroid glands, primarily on their posterior surfaces. The tissue of the thyroid gland is composed mostly of thyroid follicles. The follicles are made up of a central cavity filled with a sticky fluid called colloid. Surrounded by a wall of epithelial follicle cells, the colloid is the center of thyroid hormone production, and that production is dependent on the hormones' essential and unique component: iodine.

Thyroid Gland

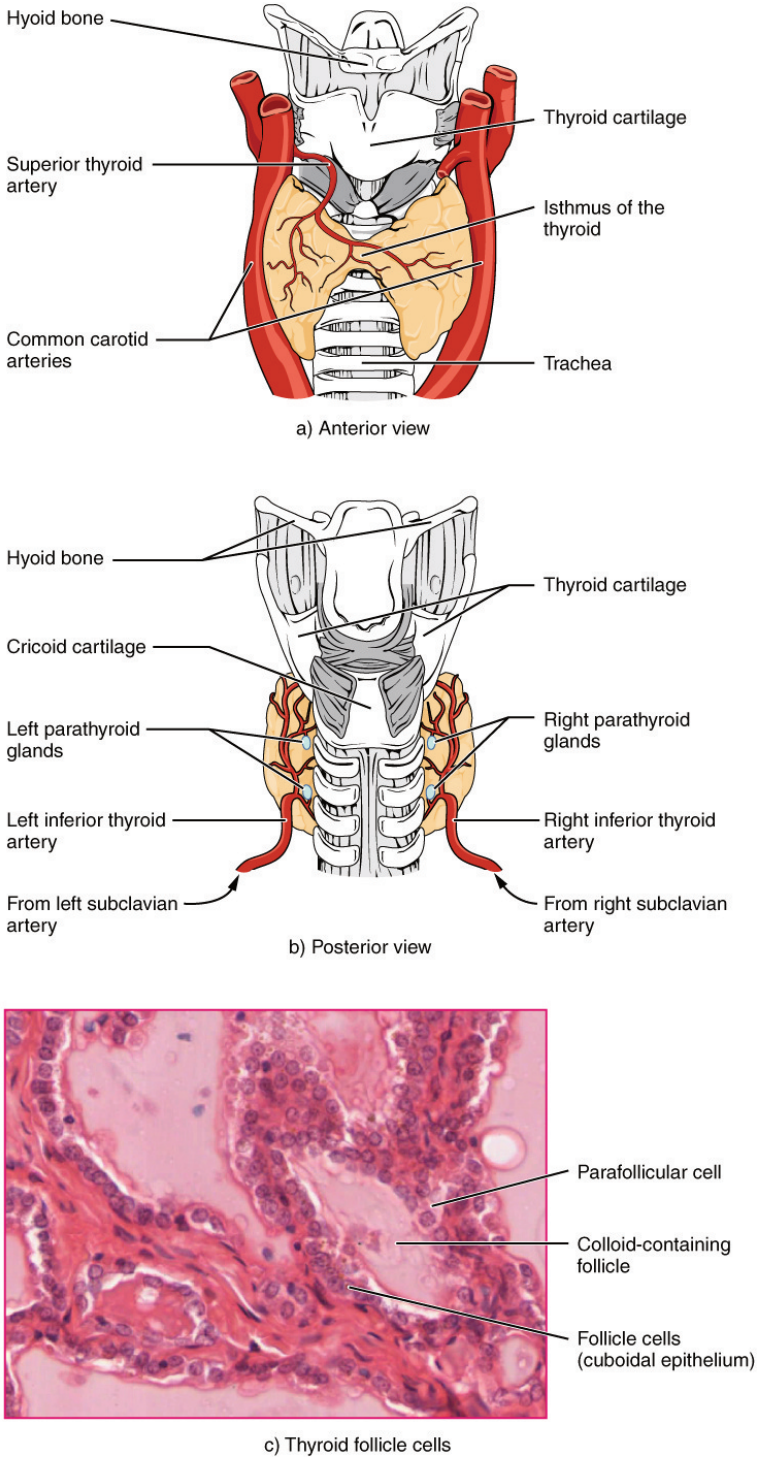


Figure 1. *The thyroid gland is located in the neck where it wraps around the trachea. (a) Anterior view of the thyroid gland. (b) Posterior view of the thyroid gland. (c) The glandular tissue is composed primarily of thyroid follicles. The larger parafollicular cells often appear within the matrix of follicle cells.* LM × 1332. *(Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

Synthesis and Release of Thyroid Hormones

Hormones are produced in the colloid when atoms of the mineral iodine attach to a glycoprotein, called thyroglobulin, that is secreted into the colloid by the follicle cells. The following steps outline the hormones' assembly:

1. Binding of TSH to its receptors in the follicle cells of the thyroid gland causes the cells to actively transport iodide ions (I^-) across their cell membrane, from the bloodstream into the cytosol. As a result, the concentration of iodide ions "trapped" in the follicular cells is many times higher than the concentration in the bloodstream.
2. Iodide ions then move to the lumen of the follicle cells that border the colloid. There, the ions undergo oxidation (their negatively charged electrons are removed). The oxidation of two iodide ions ($2\ I^-$) results in iodine (I_2), which passes through the follicle cell membrane into the colloid.
3. In the colloid, peroxidase enzymes link the iodine to the tyrosine amino acids in thyroglobulin to produce two intermediaries: a tyrosine attached to one iodine and a tyrosine attached to two iodines. When one of each of these intermediaries is linked by covalent bonds, the resulting compound is **triiodothyronine** (T_3), a thyroid hormone with three iodines. Much more commonly, two copies of the second intermediary bond, forming tetraiodothyronine, also known as **thyroxine** (T_4), a thyroid hormone with four iodines.

These hormones remain in the colloid center of the thyroid follicles until TSH stimulates endocytosis of colloid back into the follicle cells. There, lysosomal enzymes break apart the thyroglobulin colloid, releasing free T_3 and T_4, which diffuse across the follicle cell membrane and enter the bloodstream.

In the bloodstream, less than one percent of the circulating T_3 and T_4 remains unbound. This free T_3 and T_4can cross the lipid bilayer of cell membranes and be taken up by cells. The remaining 99 percent of circulating T_3 and T_4 is bound to specialized transport proteins called thyroxine-binding globulins (TBGs), to albumin, or to other plasma proteins. This "packaging" prevents their free diffusion into body cells. When blood levels of T_3 and T_4 begin to decline, bound T_3 and T_4 are released from these plasma proteins and readily cross the membrane of target cells. T_3 is more potent than T_4, and many cells convert T_4 to T_3through the removal of an iodine atom.

Regulation of TH Synthesis

The release of T_3 and T_4 from the thyroid gland is regulated by thyroid-stimulating hormone (TSH). As shown in Figure 2. (Classic Negative Feedback Loop), low blood levels of T_3 and T_4 stimulate the release of thyrotropin-releasing hormone (TRH) from the hypothalamus, which triggers secretion of TSH from the anterior pituitary. In turn, TSH stimulates the thyroid gland to secrete T_3 and T_4. The levels of TRH, TSH, T_3, and T_4 are regulated by a negative feedback system in which increasing levels of T_3 and T_4 decrease the production and secretion of TSH.
Classic Negative Feedback Loop

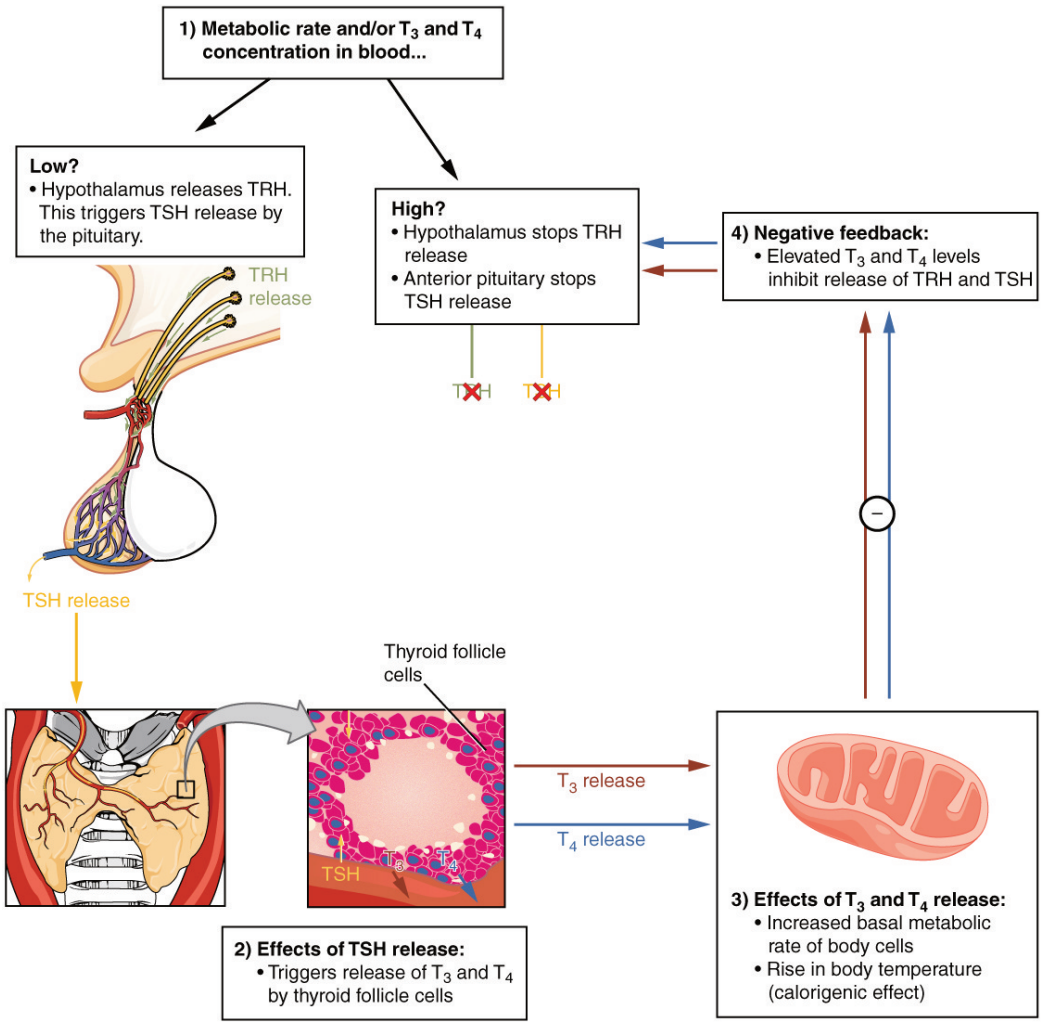


Figure 2. *A classic negative feedback loop controls the regulation of thyroid hormone levels.*

Functions of Thyroid Hormones

The thyroid hormones, T_3 and T_4, are often referred to as metabolic hormones because their levels influence the body's basal metabolic rate, the amount of energy used by the body at rest. When T_3 and T_4 bind to intracellular receptors located on the mitochondria, they cause an increase in nutrient breakdown and the use of oxygen to produce ATP. In addition, T_3 and T_4 initiate the transcription of genes involved in glucose oxidation. Although these mechanisms prompt cells to produce more ATP, the process is inefficient, and an abnormally increased level of heat is released as a byproduct of these reactions. This so-called calorigenic effect (calor- = "heat") raises body temperature.

Adequate levels of thyroid hormones are also required for protein synthesis and for fetal and childhood tissue development and growth. They are especially critical for normal development of the nervous system both in utero and in early childhood, and they continue to support neurological function in adults. As noted earlier, these thyroid hormones have a complex interrelationship with reproductive hormones, and deficiencies can influence libido, fertility, and other aspects of reproductive function. Finally, thyroid hormones increase the

body's sensitivity to catecholamines (epinephrine and norepinephrine) from the adrenal medulla by upregulation of receptors in the blood vessels. When levels of T_3 and T_4 hormones are excessive, this effect accelerates the heart rate, strengthens the heartbeat, and increases blood pressure. Because thyroid hormones regulate metabolism, heat production, protein synthesis, and many other body functions, thyroid disorders can have severe and widespread consequences.

DISORDERS OF THE...

Endocrine System: Iodine Deficiency, Hypothyroidism, and Hyperthyroidism

As discussed above, dietary iodine is required for the synthesis of T_3 and T_4. But for much of the world's population, foods do not provide adequate levels of this mineral, because the amount varies according to the level in the soil in which the food was grown, as well as the irrigation and fertilizers used. Marine fish and shrimp tend to have high levels because they concentrate iodine from seawater, but many people in landlocked regions lack access to seafood. Thus, the primary source of dietary iodine in many countries is iodized salt. Fortification of salt with iodine began in the United States in 1924, and international efforts to iodize salt in the world's poorest nations continue today.

Dietary iodine deficiency can result in the impaired ability to synthesize T_3 and T_4, leading to a variety of severe disorders. When T_3 and T_4 cannot be produced, TSH is secreted in increasing amounts. As a result of this hyperstimulation, thyroglobulin accumulates in the thyroid gland follicles, increasing their deposits of colloid. The accumulation of colloid increases the overall size of the thyroid gland, a condition called a **goiter** (Figure 3. Goiter). A goiter is only a visible indication of the deficiency. Other iodine deficiency disorders include impaired growth and development, decreased fertility, and prenatal and infant death. Moreover, iodine deficiency is the primary cause of preventable mental retardation worldwide. **Neonatal hypothyroidism** (cretinism) is characterized by cognitive deficits, short stature, and sometimes deafness and muteness in children and adults born to mothers who were iodine-deficient during pregnancy.

Goiter

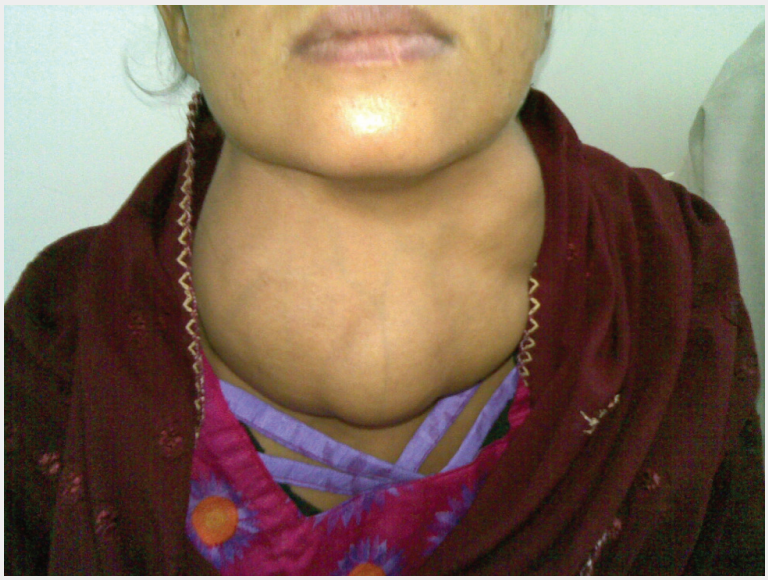


Figure 3. *(credit: "Almazi"/Wikimedia Commons)*

In areas of the world with access to iodized salt, dietary deficiency is rare. Instead, inflammation of the thyroid gland is the more common cause of low blood levels of thyroid hormones. Called **hypothyroidism**, the condition is characterized by a low metabolic rate, weight gain, cold extremities, constipation, reduced libido, menstrual irregularities, and reduced mental activity. In contrast, **hyperthyroidism**—an abnormally elevated blood level of thyroid hormones—is often caused by a pituitary or thyroid tumor. In Graves' disease, the hyperthyroid state results from an autoimmune reaction in which antibodies overstimulate the follicle cells of the thyroid gland. Hyperthyroidism can lead to an increased metabolic rate, excessive body heat and sweating, diarrhea, weight loss, tremors, and increased heart rate. The person's eyes may bulge (called exophthalmos) as antibodies produce inflammation in the soft tissues of the orbits. The person may also develop a goiter.

Calcitonin

The thyroid gland also secretes a hormone called **calcitonin** that is produced by the parafollicular cells (also called C cells) that stud the tissue between distinct follicles. Calcitonin is released in response to a rise in blood calcium levels. It appears to have a function in decreasing blood calcium concentrations by:

- Inhibiting the activity of osteoclasts, bone cells that release calcium into the circulation by degrading bone matrix
- Increasing osteoblastic activity
- Decreasing calcium absorption in the intestines
- Increasing calcium loss in the urine

However, these functions are usually not significant in maintaining calcium homeostasis, so the importance of calcitonin is not entirely understood. Pharmaceutical preparations of calcitonin are sometimes prescribed to reduce osteoclast activity in people with osteoporosis and to reduce the degradation of cartilage in people with osteoarthritis. The hormones secreted by thyroid are summarized in Table (Thyroid Hormones).

Thyroid Hormones

Associated hormones	**Chemical class**	**Effect**
Thyroxine (T_4), triiodothyronine (T_3)	Amine	Stimulate basal metabolic rate
Calcitonin	Peptide	Reduces blood Ca^{2+} levels

Of course, calcium is critical for many other biological processes. It is a second messenger in many signaling pathways, and is essential for muscle contraction, nerve impulse transmission, and blood clotting. Given these roles, it is not surprising that blood calcium levels are tightly regulated by the endocrine system. The organs involved in the regulation are the parathyroid glands.

Chapter Review

The thyroid gland is a butterfly-shaped organ located in the neck anterior to the trachea. Its hormones regulate basal metabolism, oxygen use, nutrient metabolism, the production of ATP, and calcium homeostasis. They also contribute to protein synthesis and the normal growth and development of body tissues, including maturation of the nervous system, and they increase the body's sensitivity to catecholamines. The thyroid hormones triiodothyronine (T_3) and thyroxine (T_4) are produced and secreted by the thyroid gland in response to thyroid-stimulating hormone (TSH) from the anterior pituitary. Synthesis of the amino acid–derived T_3 and T_4 hormones requires iodine. Insufficient amounts of iodine in the diet can lead to goiter, cretinism, and many other disorders.

The Parathyroid Glands

By the end of this section, you will be able to:

- Describe the location and structure of the parathyroid glands
- Describe the hormonal control of blood calcium levels
- Discuss the physiological response of parathyroid dysfunction

The **parathyroid glands** are tiny, round structures usually found embedded in the posterior surface of the thyroid gland (Figure 1. Parathyroid Glands). A thick connective tissue capsule separates the glands from the thyroid tissue. Most people have four parathyroid glands, but occasionally there are more in tissues of the neck or chest. The function of one type of parathyroid cells, the oxyphil cells, is not clear. The primary functional cells of the parathyroid glands are the chief cells. These epithelial cells produce and secrete the **parathyroid hormone (PTH)**, the major hormone involved in the regulation of blood calcium levels.

Parathyroid Glands

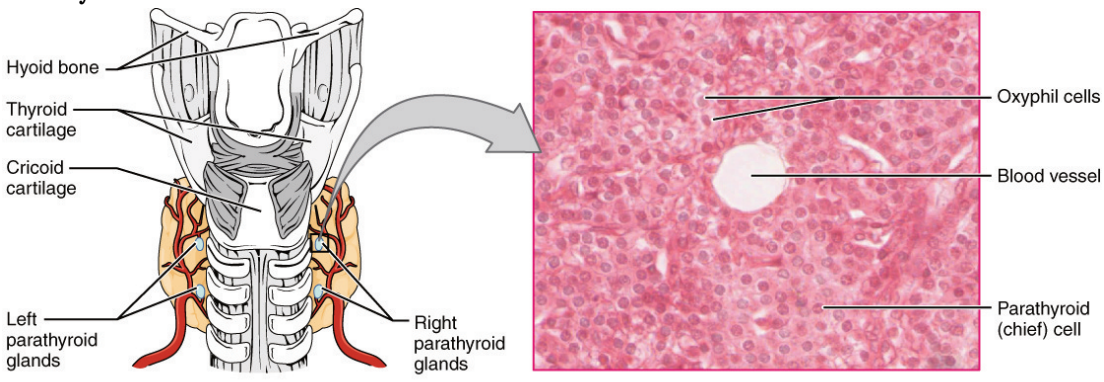


Figure 1. *The small parathyroid glands are embedded in the posterior surface of the thyroid gland. LM × 760. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://141.214.65.171/Histology/Endocrine%20System/217_HISTO_40X.svs/view.apml to explore the tissue sample in greater detail.

The parathyroid glands produce and secrete PTH, a peptide hormone, in response to low blood calcium levels (Figure 2. Parathyroid Hormone in Maintaining Blood Calcium Homeostasis). PTH secretion causes the release of calcium from the bones by stimulating osteoclasts, which secrete enzymes that degrade bone and release calcium into the interstitial fluid. PTH also inhibits osteoblasts, the cells involved in bone deposition, thereby sparing blood calcium. PTH causes increased reabsorption of calcium (and magnesium) in the kidney tubules from the urine filtrate. In addition, PTH initiates the production of the steroid hormone calcitriol (also known as 1,25-dihydroxyvitamin D), which is the active form of vitamin D_3, in the kidneys. Calcitriol then stimulates increased absorption of dietary calcium by the intestines. A negative feedback loop regulates the levels of PTH, with rising blood calcium levels inhibiting further release of PTH.

Parathyroid Hormone in Maintaining Blood Calcium Homeostasis

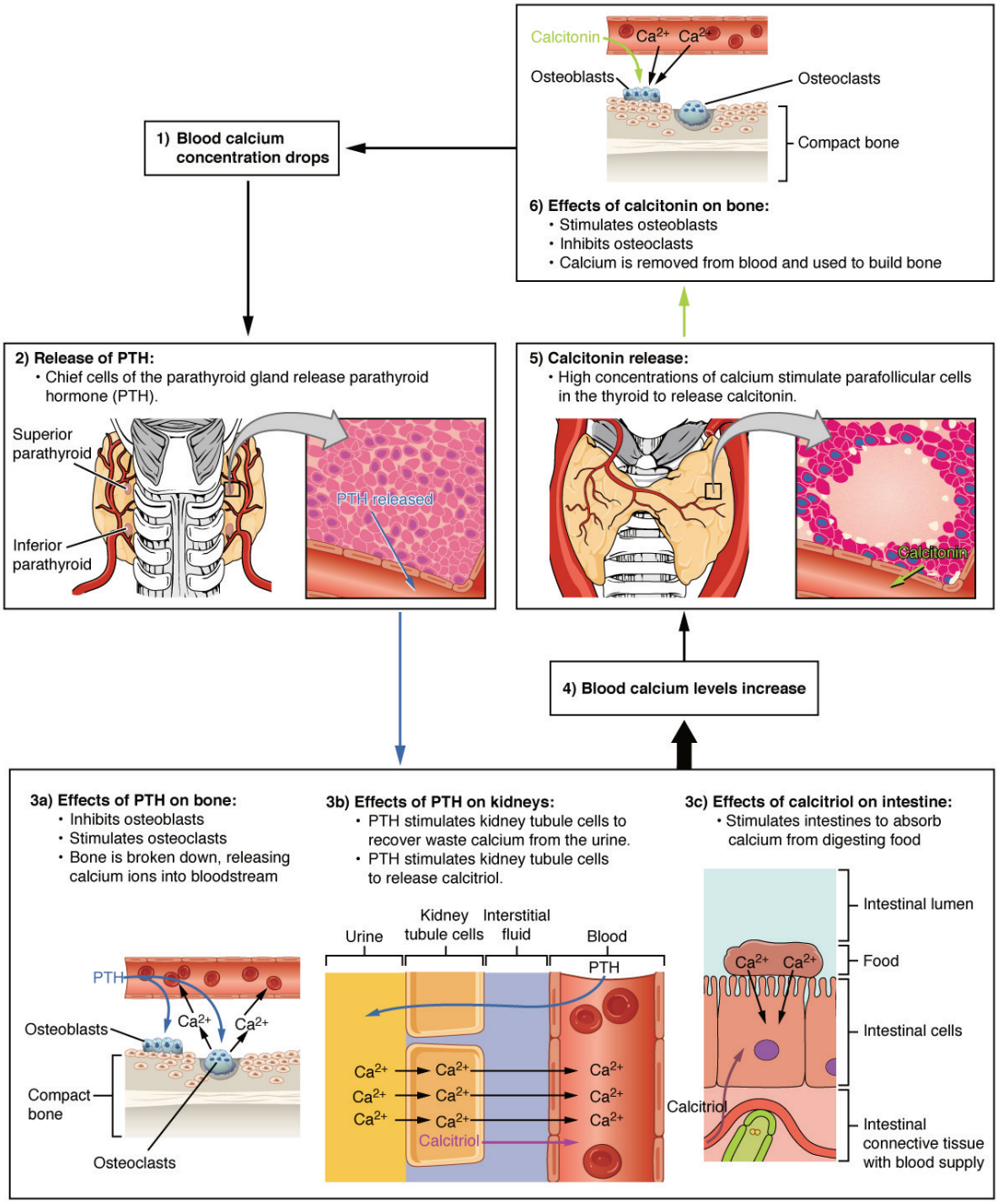


Figure 2. *Parathyroid hormone increases blood calcium levels when they drop too low. Conversely, calcitonin, which is released from the thyroid gland, decreases blood calcium levels when they become too high. These two mechanisms constantly maintain blood calcium concentration at homeostasis.*

Abnormally high activity of the parathyroid gland can cause **hyperparathyroidism**, a disorder caused by an overproduction of PTH that results in excessive calcium reabsorption from bone. Hyperparathyroidism can significantly decrease bone density, leading to spontaneous fractures or deformities. As blood calcium levels rise, cell membrane permeability to sodium is decreased, and the responsiveness of the nervous system is reduced. At the same time, calcium deposits may collect in the body's tissues and organs, impairing their functioning.

In contrast, abnormally low blood calcium levels may be caused by parathyroid hormone deficiency,

called **hypoparathyroidism**, which may develop following injury or surgery involving the thyroid gland. Low blood calcium increases membrane permeability to sodium, resulting in muscle twitching, cramping, spasms, or convulsions. Severe deficits can paralyze muscles, including those involved in breathing, and can be fatal.

When blood calcium levels are high, calcitonin is produced and secreted by the parafollicular cells of the thyroid gland. As discussed earlier, calcitonin inhibits the activity of osteoclasts, reduces the absorption of dietary calcium in the intestine, and signals the kidneys to reabsorb less calcium, resulting in larger amounts of calcium excreted in the urine.

Chapter Review

Calcium is required for a variety of important physiologic processes, including neuromuscular functioning; thus, blood calcium levels are closely regulated. The parathyroid glands are small structures located on the posterior thyroid gland that produce parathyroid hormone (PTH), which regulates blood calcium levels. Low blood calcium levels cause the production and secretion of PTH. In contrast, elevated blood calcium levels inhibit secretion of PTH and trigger secretion of the thyroid hormone calcitonin. Underproduction of PTH can result in hypoparathyroidism. In contrast, overproduction of PTH can result in hyperparathyroidism.

The Adrenal Glands

By the end of this section, you will be able to:

- Describe the location and structure of the adrenal glands
- Identify the hormones produced by the adrenal cortex and adrenal medulla, and summarize their target cells and effects

The **adrenal glands** are wedges of glandular and neuroendocrine tissue adhering to the top of the kidneys by a fibrous capsule (Figure 1. Adrenal Glands). The adrenal glands have a rich blood supply and experience one of the highest rates of blood flow in the body. They are served by several arteries branching off the aorta, including the suprarenal and renal arteries. Blood flows to each adrenal gland at the adrenal cortex and then drains into the adrenal medulla. Adrenal hormones are released into the circulation via the left and right suprarenal veins.

Adrenal Glands

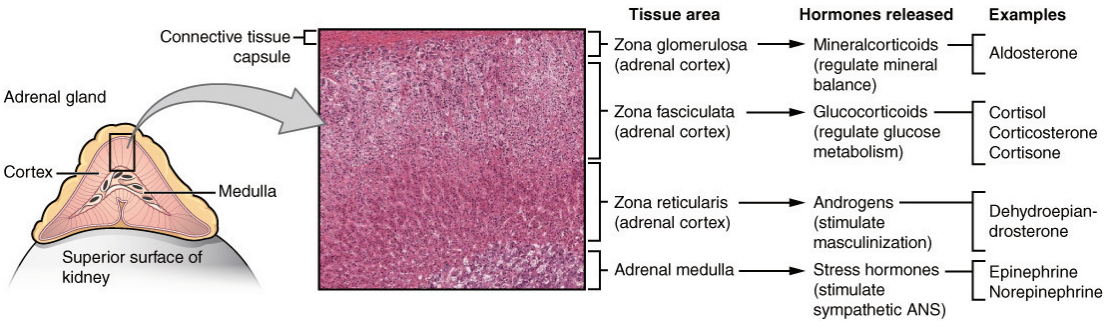


Figure 1. *Both adrenal glands sit atop the kidneys and are composed of an outer cortex and an inner medulla, all surrounded by a connective tissue capsule. The cortex can be subdivided into additional zones, all of which produce different types of hormones. LM × 204. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://141.214.65.171/Histology/Endocrine%20System/New%20Scans/230_HISTO_40x.svs/view.apmlto explore the tissue sample in greater detail.

The adrenal gland consists of an outer cortex of glandular tissue and an inner medulla of nervous tissue. The cortex itself is divided into three zones: the **zona glomerulosa**, the **zona fasciculata**, and the **zona reticularis**. Each region secretes its own set of hormones.

The **adrenal cortex**, as a component of the hypothalamic-pituitary-adrenal (HPA) axis, secretes steroid hormones important for the regulation of the long-term stress response, blood pressure and blood volume, nutrient uptake and storage, fluid and electrolyte balance, and inflammation. The HPA axis involves the stimulation of hormone release of adrenocorticotropic hormone (ACTH) from the pituitary by the hypothalamus. ACTH then stimulates the adrenal cortex to produce the hormone cortisol. This pathway will be discussed in more detail below.

The **adrenal medulla** is neuroendocrine tissue composed of postganglionic sympathetic nervous system (SNS) neurons. It is really an extension of the autonomic nervous system, which regulates homeostasis in the body. The sympathomedullary (SAM) pathway involves the stimulation of the medulla by impulses from the hypothalamus via neurons from the thoracic spinal cord. The medulla is stimulated to secrete the amine hormones epinephrine and norepinephrine.

One of the major functions of the adrenal gland is to respond to stress. Stress can be either physical or psychological or both. Physical stresses include exposing the body to injury, walking outside in cold and wet conditions without a coat on, or malnutrition. Psychological stresses include the perception of a physical threat, a fight with a loved one, or just a bad day at school.

The body responds in different ways to short-term stress and long-term stress following a pattern known as the **general adaptation syndrome (GAS)**. Stage one of GAS is called the **alarm reaction**. This is short-term stress, the fight-or-flight response, mediated by the hormones epinephrine and norepinephrine from the adrenal medulla via the SAM pathway. Their function is to prepare the body for extreme physical exertion. Once this stress is relieved, the body quickly returns to normal. The section on the adrenal medulla covers this response in more detail.

If the stress is not soon relieved, the body adapts to the stress in the second stage called the **stage of**

resistance. If a person is starving for example, the body may send signals to the gastrointestinal tract to maximize the absorption of nutrients from food.

If the stress continues for a longer term however, the body responds with symptoms quite different than the fight-or-flight response. During the **stage of exhaustion**, individuals may begin to suffer depression, the suppression of their immune response, severe fatigue, or even a fatal heart attack. These symptoms are mediated by the hormones of the adrenal cortex, especially cortisol, released as a result of signals from the HPA axis.

Adrenal hormones also have several non–stress-related functions, including the increase of blood sodium and glucose levels, which will be described in detail below.

Adrenal Cortex

The adrenal cortex consists of multiple layers of lipid-storing cells that occur in three structurally distinct regions. Each of these regions produces different hormones.

> Visit this link to view an animation describing the location and function of the adrenal glands. Which hormone produced by the adrenal glands is responsible for the mobilization of energy stores?

Hormones of the Zona Glomerulosa

The most superficial region of the adrenal cortex is the zona glomerulosa, which produces a group of hormones collectively referred to as **mineralocorticoids** because of their effect on body minerals, especially sodium and potassium. These hormones are essential for fluid and electrolyte balance.

Aldosterone is the major mineralocorticoid. It is important in the regulation of the concentration of sodium and potassium ions in urine, sweat, and saliva. For example, it is released in response to elevated blood K^+, low blood Na^+, low blood pressure, or low blood volume. In response, aldosterone increases the excretion of K^+ and the retention of Na^+, which in turn increases blood volume and blood pressure. Its secretion is prompted when CRH from the hypothalamus triggers ACTH release from the anterior pituitary.

Aldosterone is also a key component of the renin-angiotensin-aldosterone system (RAAS) in which specialized cells of the kidneys secrete the enzyme renin in response to low blood volume or low blood pressure. Renin then catalyzes the conversion of the blood protein angiotensinogen, produced by the liver, to the hormone angiotensin I. Angiotensin I is converted in the lungs to angiotensin II by **angiotensin-converting enzyme** (ACE). Angiotensin II has three major functions:

1. Initiating vasoconstriction of the arterioles, decreasing blood flow
2. Stimulating kidney tubules to reabsorb NaCl and water, increasing blood volume
3. Signaling the adrenal cortex to secrete aldosterone, the effects of which further contribute to fluid retention, restoring blood pressure and blood volume

For individuals with hypertension, or high blood pressure, drugs are available that block the production of

angiotensin II. These drugs, known as ACE inhibitors, block the ACE enzyme from converting angiotensin I to angiotensin II, thus mitigating the latter's ability to increase blood pressure.

Hormones of the Zona Fasciculata

The intermediate region of the adrenal cortex is the zona fasciculata, named as such because the cells form small fascicles (bundles) separated by tiny blood vessels. The cells of the zona fasciculata produce hormones called **glucocorticoids** because of their role in glucose metabolism. The most important of these is **cortisol**, some of which the liver converts to cortisone. A glucocorticoid produced in much smaller amounts is corticosterone. In response to long-term stressors, the hypothalamus secretes CRH, which in turn triggers the release of ACTH by the anterior pituitary. ACTH triggers the release of the glucocorticoids. Their overall effect is to inhibit tissue building while stimulating the breakdown of stored nutrients to maintain adequate fuel supplies. In conditions of long-term stress, for example, cortisol promotes the catabolism of glycogen to glucose, the catabolism of stored triglycerides into fatty acids and glycerol, and the catabolism of muscle proteins into amino acids. These raw materials can then be used to synthesize additional glucose and ketones for use as body fuels. The hippocampus, which is part of the temporal lobe of the cerebral cortices and important in memory formation, is highly sensitive to stress levels because of its many glucocorticoid receptors.

You are probably familiar with prescription and over-the-counter medications containing glucocorticoids, such as cortisone injections into inflamed joints, prednisone tablets and steroid-based inhalers used to manage severe asthma, and hydrocortisone creams applied to relieve itchy skin rashes. These drugs reflect another role of cortisol—the downregulation of the immune system, which inhibits the inflammatory response.

Hormones of the Zona Reticularis

The deepest region of the adrenal cortex is the zona reticularis, which produces small amounts of a class of steroid sex hormones called androgens. During puberty and most of adulthood, androgens are produced in the gonads. The androgens produced in the zona reticularis supplement the gonadal androgens. They are produced in response to ACTH from the anterior pituitary and are converted in the tissues to testosterone or estrogens. In adult women, they may contribute to the sex drive, but their function in adult men is not well understood. In post-menopausal women, as the functions of the ovaries decline, the main source of estrogens becomes the androgens produced by the zona reticularis.

Adrenal Medulla

As noted earlier, the adrenal cortex releases glucocorticoids in response to long-term stress such as severe illness. In contrast, the adrenal medulla releases its hormones in response to acute, short-term stress mediated by the sympathetic nervous system (SNS).

The medullary tissue is composed of unique postganglionic SNS neurons called **chromaffin** cells, which are large and irregularly shaped, and produce the neurotransmitters **epinephrine** (also called adrenaline) and **norepinephrine** (or noradrenaline). Epinephrine is produced in greater quantities—approximately a 4 to 1

ratio with norepinephrine—and is the more powerful hormone. Because the chromaffin cells release epinephrine and norepinephrine into the systemic circulation, where they travel widely and exert effects on distant cells, they are considered hormones. Derived from the amino acid tyrosine, they are chemically classified as catecholamines.

The secretion of medullary epinephrine and norepinephrine is controlled by a neural pathway that originates from the hypothalamus in response to danger or stress (the SAM pathway). Both epinephrine and norepinephrine signal the liver and skeletal muscle cells to convert glycogen into glucose, resulting in increased blood glucose levels. These hormones increase the heart rate, pulse, and blood pressure to prepare the body to fight the perceived threat or flee from it. In addition, the pathway dilates the airways, raising blood oxygen levels. It also prompts vasodilation, further increasing the oxygenation of important organs such as the lungs, brain, heart, and skeletal muscle. At the same time, it triggers vasoconstriction to blood vessels serving less essential organs such as the gastrointestinal tract, kidneys, and skin, and downregulates some components of the immune system. Other effects include a dry mouth, loss of appetite, pupil dilation, and a loss of peripheral vision. The major hormones of the adrenal glands are summarized in Table (Hormones of the Adrenal Glands).

Hormones of the Adrenal Glands

Adrenal gland	Associated hormones	Chemical class	Effect
Adrenal cortex	Aldosterone	Steroid	Increases blood Na^+ levels
Adrenal cortex	Cortisol, corticosterone, cortisone	Steroid	Increase blood glucose levels
Adrenal medulla	Epinephrine, norepinephrine	Amine	Stimulate fight-or-flight response

Disorders Involving the Adrenal Glands

Several disorders are caused by the dysregulation of the hormones produced by the adrenal glands. For example, Cushing's disease is a disorder characterized by high blood glucose levels and the accumulation of lipid deposits on the face and neck. It is caused by hypersecretion of cortisol. The most common source of Cushing's disease is a pituitary tumor that secretes cortisol or ACTH in abnormally high amounts. Other common signs of Cushing's disease include the development of a moon-shaped face, a buffalo hump on the back of the neck, rapid weight gain, and hair loss. Chronically elevated glucose levels are also associated with an elevated risk of developing type 2 diabetes. In addition to hyperglycemia, chronically elevated glucocorticoids compromise immunity, resistance to infection, and memory, and can result in rapid weight gain and hair loss.

In contrast, the hyposecretion of corticosteroids can result in Addison's disease, a rare disorder that causes low blood glucose levels and low blood sodium levels. The signs and symptoms of Addison's disease are vague and are typical of other disorders as well, making diagnosis difficult. They may include general weakness, abdominal pain, weight loss, nausea, vomiting, sweating, and cravings for salty food.

Chapter Review

The adrenal glands, located superior to each kidney, consist of two regions: the adrenal cortex and adrenal medulla. The adrenal cortex—the outer layer of the gland—produces mineralocorticoids, glucocorticoids, and androgens. The adrenal medulla at the core of the gland produces epinephrine and norepinephrine.

The adrenal glands mediate a short-term stress response and a long-term stress response. A perceived threat results in the secretion of epinephrine and norepinephrine from the adrenal medulla, which mediate the fight-or-flight response. The long-term stress response is mediated by the secretion of CRH from the hypothalamus, which triggers ACTH, which in turn stimulates the secretion of corticosteroids from the adrenal cortex. The mineralocorticoids, chiefly aldosterone, cause sodium and fluid retention, which increases blood volume and blood pressure.

The Pineal Gland

By the end of this section, you will be able to:

- Describe the location and structure of the pineal gland
- Discuss the function of melatonin

Recall that the hypothalamus, part of the diencephalon of the brain, sits inferior and somewhat anterior to the thalamus. Inferior but somewhat posterior to the thalamus is the **pineal gland**, a tiny endocrine gland whose functions are not entirely clear. The **pinealocyte** cells that make up the pineal gland are known to produce and secrete the amine hormone **melatonin**, which is derived from serotonin.

The secretion of melatonin varies according to the level of light received from the environment. When photons of light stimulate the retinas of the eyes, a nerve impulse is sent to a region of the hypothalamus called the suprachiasmatic nucleus (SCN), which is important in regulating biological rhythms. From the SCN, the nerve signal is carried to the spinal cord and eventually to the pineal gland, where the production of melatonin is inhibited. As a result, blood levels of melatonin fall, promoting wakefulness. In contrast, as light levels decline—such as during the evening—melatonin production increases, boosting blood levels and causing drowsiness.

Visit this link to view an animation describing the function of the hormone melatonin. What should you avoid doing in the middle of your sleep cycle that would lower melatonin?

The secretion of melatonin may influence the body's circadian rhythms, the dark-light fluctuations that affect not only sleepiness and wakefulness, but also appetite and body temperature. Interestingly, children have higher melatonin levels than adults, which may prevent the release of gonadotropins from the anterior pituitary, thereby inhibiting the onset of puberty. Finally, an antioxidant role of melatonin is the subject of current research.

Jet lag occurs when a person travels across several time zones and feels sleepy during the day or wakeful at night. Traveling across multiple time zones significantly disturbs the light-dark cycle regulated by melatonin. It can take up to several days for melatonin synthesis to adjust to the light-dark patterns in the new environment, resulting in jet lag. Some air travelers take melatonin supplements to induce sleep.

Chapter Review

The pineal gland is an endocrine structure of the diencephalon of the brain, and is located inferior and posterior to the thalamus. It is made up of pinealocytes. These cells produce and secrete the hormone melatonin in response to low light levels. High blood levels of melatonin induce drowsiness. Jet lag, caused by traveling across several time zones, occurs because melatonin synthesis takes several days to readjust to the light-dark patterns in the new environment.

Gonadal and Placental Hormones

By the end of this section, you will be able to:

- Identify the most important hormones produced by the testes and ovaries
- Name the hormones produced by the placenta and state their functions

This section briefly discusses the hormonal role of the gonads—the male testes and female ovaries—which produce the sex cells (sperm and ova) and secrete the gonadal hormones. The roles of the gonadotropins released from the anterior pituitary (FSH and LH) were discussed earlier.

The primary hormone produced by the male testes is **testosterone**, a steroid hormone important in the development of the male reproductive system, the maturation of sperm cells, and the development of male secondary sex characteristics such as a deepened voice, body hair, and increased muscle mass. Interestingly, testosterone is also produced in the female ovaries, but at a much reduced level. In addition, the testes produce the peptide hormone **inhibin**, which inhibits the secretion of FSH from the anterior pituitary gland. FSH stimulates spermatogenesis.

The primary hormones produced by the ovaries are **estrogens**, which include estradiol, estriol, and estrone. Estrogens play an important role in a larger number of physiological processes, including the development of the female reproductive system, regulation of the menstrual cycle, the development of female secondary sex characteristics such as increased adipose tissue and the development of breast tissue, and the maintenance of pregnancy. Another significant ovarian hormone is **progesterone**, which contributes to regulation of the menstrual cycle and is important in preparing the body for pregnancy as well as maintaining pregnancy. In addition, the granulosa cells of the ovarian follicles produce inhibin, which—as in males—inhibits the secretion of FSH.During the initial stages of pregnancy, an organ called the placenta develops within the uterus. The placenta supplies oxygen and nutrients to the fetus, excretes waste products, and produces and secretes estrogens and progesterone. The placenta produces human chorionic gonadotropin (hCG) as well. The hCG hormone promotes progesterone synthesis and reduces the mother's immune function to protect the fetus from immune rejection. It also secretes human placental lactogen (hPL), which plays a role in preparing the breasts for lactation, and relaxin, which is thought to help soften and widen the pubic symphysis in preparation for childbirth. The hormones controlling reproduction are summarized in Table (Reproductive Hormones).

Reproductive Hormones

Gonad	Associated hormones	Chemical class	Effect
Testes	Testosterone	Steroid	Stimulates development of male secondary sex characteristics and sperm production
Testes	Inhibin	Protein	Inhibits FSH release from pituitary
Ovaries	Estrogens and progesterone	Steroid	Stimulate development of female secondary sex characteristics and prepare the body for childbirth
Placenta	Human chorionic gonadotropin	Protein	Promotes progesterone synthesis during pregnancy and inhibits immune response against fetus

EVERYDAY CONNECTIONS

Anabolic Steroids

The endocrine system can be exploited for illegal or unethical purposes. A prominent example of this is the use of steroid drugs by professional athletes.

Commonly used for performance enhancement, anabolic steroids are synthetic versions of the male sex hormone, testosterone. By boosting natural levels of this hormone, athletes experience increased muscle mass. Synthetic versions of human growth hormone are also used to build muscle mass.

The use of performance-enhancing drugs is banned by all major collegiate and professional sports organizations in the United States because they impart an unfair advantage to athletes who take them. In addition, the drugs can cause significant and dangerous side effects. For example, anabolic steroid use can increase cholesterol levels, raise blood pressure, and damage the liver. Altered testosterone levels (both too low or too high) have been implicated in causing structural damage to the heart, and increasing the risk for cardiac arrhythmias, heart attacks, congestive heart failure, and sudden death. Paradoxically, steroids can have a feminizing effect in males, including shriveled testicles and enlarged breast tissue. In females, their use can cause masculinizing effects such as an enlarged clitoris and growth of facial hair. In both sexes, their use can promote increased aggression (commonly known as "roid-rage"), depression, sleep disturbances, severe acne, and infertility.

Chapter Review

The male and female reproductive system is regulated by follicle-stimulating hormone (FSH) and luteinizing hormone (LH) produced by the anterior lobe of the pituitary gland in response to gonadotropin-releasing hormone (GnRH) from the hypothalamus. In males, FSH stimulates sperm maturation, which is inhibited by the hormone inhibin. The steroid hormone testosterone, a type of androgen, is released in response to LH and is responsible for the maturation and maintenance of the male reproductive system, as well as the development of male secondary sex characteristics. In females, FSH promotes egg maturation and LH signals the secretion of the female sex hormones, the estrogens and progesterone. Both of these hormones are important in the development and maintenance of the female reproductive system, as well as maintaining pregnancy. The

placenta develops during early pregnancy, and secretes several hormones important for maintaining the pregnancy.

The Endocrine Pancreas

By the end of this section, you will be able to:

- Describe the location and structure of the pancreas, and the morphology and function of the pancreatic islets
- Compare and contrast the functions of insulin and glucagon

The **pancreas** is a long, slender organ, most of which is located posterior to the bottom half of the stomach (Figure 1. Pancreas). Although it is primarily an exocrine gland, secreting a variety of digestive enzymes, the pancreas has an endocrine function. Its **pancreatic islets**—clusters of cells formerly known as the islets of Langerhans—secrete the hormones glucagon, insulin, somatostatin, and pancreatic polypeptide (PP).

Pancreas

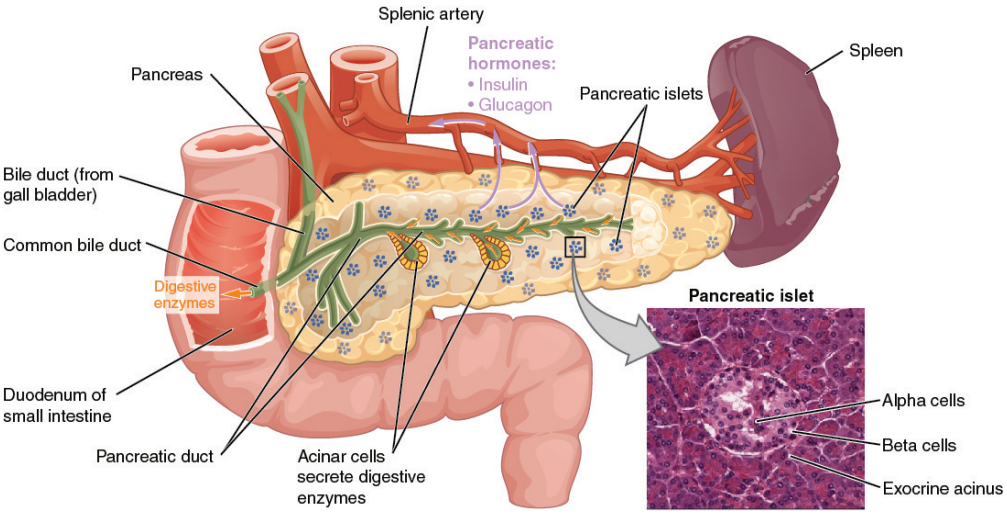


Figure 1. *The pancreatic exocrine function involves the acinar cells secreting digestive enzymes that are transported into the small intestine by the pancreatic duct. Its endocrine function involves the secretion of insulin (produced by beta cells) and glucagon (produced by alpha cells) within the pancreatic islets. These two hormones regulate the rate of glucose metabolism in the body. The micrograph reveals pancreatic islets. LM × 760. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)*

View the University of Michigan WebScope at http://141.214.65.171/Histology/Digestive%20System/Liver%20and%20Pancreas/188B_HISTO_40X.svs/view.apml to explore the tissue sample in greater detail.

Cells and Secretions of the Pancreatic Islets

The pancreatic islets each contain four varieties of cells:

- The **alpha cell** produces the hormone glucagon and makes up approximately 20 percent of each islet. Glucagon plays an important role in blood glucose regulation; low blood glucose levels stimulate its release.
- The **beta cell** produces the hormone insulin and makes up approximately 75 percent of each islet. Elevated blood glucose levels stimulate the release of insulin.
- The **delta cell** accounts for four percent of the islet cells and secretes the peptide hormone somatostatin. Recall that somatostatin is also released by the hypothalamus (as GHIH), and the stomach and intestines also secrete it. An inhibiting hormone, pancreatic somatostatin inhibits the release of both glucagon and insulin.
- The **PP cell** accounts for about one percent of islet cells and secretes the pancreatic polypeptide hormone. It is thought to play a role in appetite, as well as in the regulation of pancreatic exocrine and endocrine secretions. Pancreatic polypeptide released following a meal may reduce further food consumption; however, it is also released in response to fasting.

Regulation of Blood Glucose Levels by Insulin and Glucagon

Glucose is required for cellular respiration and is the preferred fuel for all body cells. The body derives glucose from the breakdown of the carbohydrate-containing foods and drinks we consume. Glucose not immediately taken up by cells for fuel can be stored by the liver and muscles as glycogen, or converted to triglycerides and stored in the adipose tissue. Hormones regulate both the storage and the utilization of glucose as required. Receptors located in the pancreas sense blood glucose levels, and subsequently the pancreatic cells secrete glucagon or insulin to maintain normal levels.

Glucagon

Receptors in the pancreas can sense the decline in blood glucose levels, such as during periods of fasting or during prolonged labor or exercise (Figure 2. Homeostatic Regulation of Blood Glucose Levels). In response, the alpha cells of the pancreas secrete the hormone **glucagon**, which has several effects:

- It stimulates the liver to convert its stores of glycogen back into glucose. This response is known as

glycogenolysis. The glucose is then released into the circulation for use by body cells.
- It stimulates the liver to take up amino acids from the blood and convert them into glucose. This response is known as gluconeogenesis.
- It stimulates lipolysis, the breakdown of stored triglycerides into free fatty acids and glycerol. Some of the free glycerol released into the bloodstream travels to the liver, which converts it into glucose. This is also a form of gluconeogenesis.

Taken together, these actions increase blood glucose levels. The activity of glucagon is regulated through a negative feedback mechanism; rising blood glucose levels inhibit further glucagon production and secretion.

Homeostatic Regulation of Blood Glucose Levels

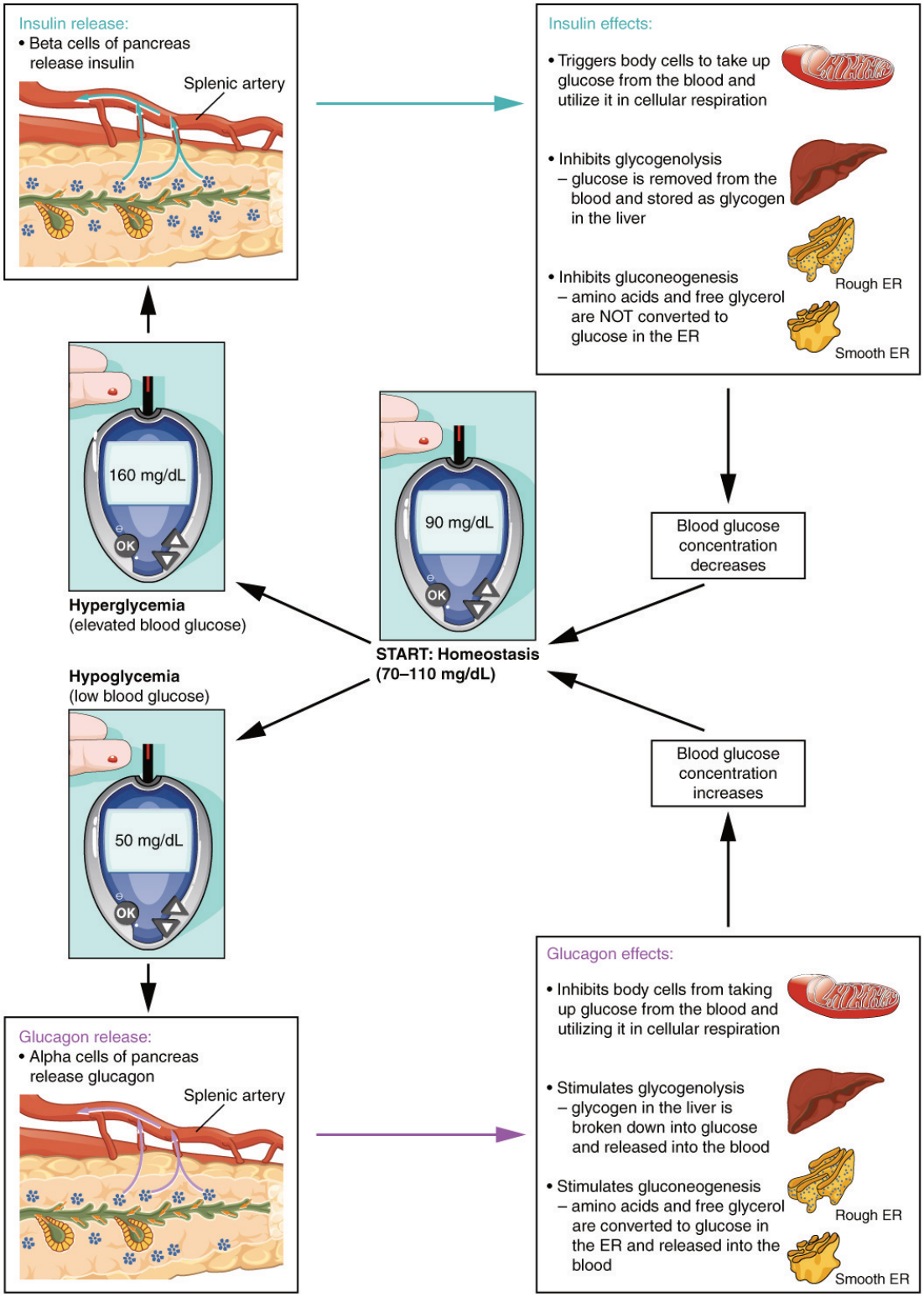


Figure 2. *Blood glucose concentration is tightly maintained between 70 mg/dL and 110 mg/dL. If blood glucose concentration rises above this range, insulin is released, which stimulates body cells to remove glucose from the blood. If blood glucose concentration drops below this range, glucagon is released, which stimulates body cells to release glucose into the blood.*

Insulin

The primary function of **insulin** is to facilitate the uptake of glucose into body cells. Red blood cells, as well as cells of the brain, liver, kidneys, and the lining of the small intestine, do not have insulin receptors on their cell membranes and do not require insulin for glucose uptake. Although all other body cells do require insulin if they are to take glucose from the bloodstream, skeletal muscle cells and adipose cells are the primary targets of insulin.

The presence of food in the intestine triggers the release of gastrointestinal tract hormones such as glucose-dependent insulinotropic peptide (previously known as gastric inhibitory peptide). This is in turn the initial trigger for insulin production and secretion by the beta cells of the pancreas. Once nutrient absorption occurs, the resulting surge in blood glucose levels further stimulates insulin secretion.

Precisely how insulin facilitates glucose uptake is not entirely clear. However, insulin appears to activate a tyrosine kinase receptor, triggering the phosphorylation of many substrates within the cell. These multiple biochemical reactions converge to support the movement of intracellular vesicles containing facilitative glucose transporters to the cell membrane. In the absence of insulin, these transport proteins are normally recycled slowly between the cell membrane and cell interior. Insulin triggers the rapid movement of a pool of glucose transporter vesicles to the cell membrane, where they fuse and expose the glucose transporters to the extracellular fluid. The transporters then move glucose by facilitated diffusion into the cell interior.

Visit this link to view an animation describing the location and function of the pancreas. What goes wrong in the function of insulin in type 2 diabetes?

Insulin also reduces blood glucose levels by stimulating glycolysis, the metabolism of glucose for generation of ATP. Moreover, it stimulates the liver to convert excess glucose into glycogen for storage, and it inhibits enzymes involved in glycogenolysis and gluconeogenesis. Finally, insulin promotes triglyceride and protein synthesis. The secretion of insulin is regulated through a negative feedback mechanism. As blood glucose levels decrease, further insulin release is inhibited. The pancreatic hormones are summarized in Table (Hormones of the Pancreas).

Hormones of the Pancreas

Associated hormones	**Chemical class**	**Effect**
Insulin (beta cells)	Protein	Reduces blood glucose levels
Glucagon (alpha cells)	Protein	Increases blood glucose levels
Somatostatin (delta cells)	Protein	Inhibits insulin and glucagon release
Pancreatic polypeptide (PP cells)	Protein	Role in appetite

DISORDERS OF THE…

Endocrine System: Diabetes Mellitus

Dysfunction of insulin production and secretion, as well as the target cells' responsiveness to insulin, can lead to a condition called **diabetes mellitus**. An increasingly common disease, diabetes mellitus has been diagnosed in more than 18 million adults in the United States, and more than 200,000 children. It is estimated that up to 7 million more adults have the condition but have not been diagnosed. In addition, approximately 79 million people in the US are estimated to have pre-diabetes, a condition in which blood glucose levels are abnormally high, but not yet high enough to be classified as diabetes.

There are two main forms of diabetes mellitus. Type 1 diabetes is an autoimmune disease affecting the beta cells of the pancreas. Certain genes are recognized to increase susceptibility. The beta cells of people with type 1 diabetes do not produce insulin; thus, synthetic insulin must be administered by injection or infusion. This form of diabetes accounts for less than five percent of all diabetes cases.

Type 2 diabetes accounts for approximately 95 percent of all cases. It is acquired, and lifestyle factors such as poor diet, inactivity, and the presence of pre-diabetes greatly increase a person's risk. About 80 to 90 percent of people with type 2 diabetes are overweight or obese. In type 2 diabetes, cells become resistant to the effects of insulin. In response, the pancreas increases its insulin secretion, but over time, the beta cells become exhausted. In many cases, type 2 diabetes can be reversed by moderate weight loss, regular physical activity, and consumption of a healthy diet; however, if blood glucose levels cannot be controlled, the diabetic will eventually require insulin.

Two of the early manifestations of diabetes are excessive urination and excessive thirst. They demonstrate how the out-of-control levels of glucose in the blood affect kidney function. The kidneys are responsible for filtering glucose from the blood. Excessive blood glucose draws water into the urine, and as a result the person eliminates an abnormally large quantity of sweet urine. The use of body water to dilute the urine leaves the body dehydrated, and so the person is unusually and continually thirsty. The person may also experience persistent hunger because the body cells are unable to access the glucose in the bloodstream.

Over time, persistently high levels of glucose in the blood injure tissues throughout the body, especially those of the blood vessels and nerves. Inflammation and injury of the lining of arteries lead to atherosclerosis and an increased risk of heart attack and stroke. Damage to the microscopic blood vessels of the kidney impairs kidney function and can lead to kidney failure. Damage to blood vessels that serve the eyes can lead to blindness. Blood vessel damage also reduces circulation to the limbs, whereas nerve damage leads to a loss of sensation, called neuropathy, particularly in the hands and feet. Together, these changes increase the risk of injury, infection, and tissue death (necrosis), contributing to a high rate of toe, foot, and lower leg amputations in people with diabetes. Uncontrolled diabetes can also lead to a dangerous form of metabolic acidosis called ketoacidosis. Deprived of glucose, cells increasingly rely on fat stores for fuel. However, in a glucose-deficient state, the liver is forced to use an alternative lipid metabolism pathway that results in the increased production of ketone bodies (or ketones), which are acidic. The build-up of ketones in the blood causes ketoacidosis, which—if left untreated—may lead to a life-threatening "diabetic coma." Together, these complications make diabetes the seventh leading cause of death in the United States.

Diabetes is diagnosed when lab tests reveal that blood glucose levels are higher than normal, a condition called **hyperglycemia**. The treatment of diabetes depends on the type, the severity of

the condition, and the ability of the patient to make lifestyle changes. As noted earlier, moderate weight loss, regular physical activity, and consumption of a healthful diet can reduce blood glucose levels. Some patients with type 2 diabetes may be unable to control their disease with these lifestyle changes, and will require medication. Historically, the first-line treatment of type 2 diabetes was insulin. Research advances have resulted in alternative options, including medications that enhance pancreatic function.

Visit this link to view an animation describing the role of insulin and the pancreas in diabetes.

Chapter Review

The pancreas has both exocrine and endocrine functions. The pancreatic islet cell types include alpha cells, which produce glucagon; beta cells, which produce insulin; delta cells, which produce somatostatin; and PP cells, which produce pancreatic polypeptide. Insulin and glucagon are involved in the regulation of glucose metabolism. Insulin is produced by the beta cells in response to high blood glucose levels. It enhances glucose uptake and utilization by target cells, as well as the storage of excess glucose for later use. Dysfunction of the production of insulin or target cell resistance to the effects of insulin causes diabetes mellitus, a disorder characterized by high blood glucose levels. The hormone glucagon is produced and secreted by the alpha cells of the pancreas in response to low blood glucose levels. Glucagon stimulates mechanisms that increase blood glucose levels, such as the catabolism of glycogen into glucose.

Organs with Secondary Endocrine Functions

By the end of this section, you will be able to:

- Identify the organs with a secondary endocrine function, the hormone they produce, and its effects

In your study of anatomy and physiology, you have already encountered a few of the many organs of the body that have secondary endocrine functions. Here, you will learn about the hormone-producing activities of the heart, gastrointestinal tract, kidneys, skeleton, adipose tissue, skin, and thymus.

Heart

When the body experiences an increase in blood volume or pressure, the cells of the heart's atrial wall stretch. In response, specialized cells in the wall of the atria produce and secrete the peptide hormone **atrial natriuretic peptide (ANP)**. ANP signals the kidneys to reduce sodium reabsorption, thereby decreasing the amount of water reabsorbed from the urine filtrate and reducing blood volume. Other actions of ANP include the inhibition of renin secretion and the initiation of the renin-angiotensin-aldosterone system (RAAS) and vasodilation. Therefore, ANP aids in decreasing blood pressure, blood volume, and blood sodium levels.

Gastrointestinal Tract

The endocrine cells of the GI tract are located in the mucosa of the stomach and small intestine. Some of these hormones are secreted in response to eating a meal and aid in digestion. An example of a hormone secreted by the stomach cells is gastrin, a peptide hormone secreted in response to stomach distention that stimulates the release of hydrochloric acid. Secretin is a peptide hormone secreted by the small intestine as acidic chyme (partially digested food and fluid) moves from the stomach. It stimulates the release of bicarbonate from the pancreas, which buffers the acidic chyme, and inhibits the further secretion of hydrochloric acid by the stomach. Cholecystokinin (CCK) is another peptide hormone released from the small intestine. It promotes the secretion of pancreatic enzymes and the release of bile from the gallbladder, both of which facilitate digestion. Other hormones produced by the intestinal cells aid in glucose metabolism, such as by stimulating the pancreatic beta cells to secrete insulin, reducing glucagon secretion from the alpha cells, or enhancing cellular sensitivity to insulin.

Kidneys

The kidneys participate in several complex endocrine pathways and produce certain hormones. A decline in blood flow to the kidneys stimulates them to release the enzyme renin, triggering the renin-angiotensin-aldosterone (RAAS) system, and stimulating the reabsorption of sodium and water. The reabsorption increases blood flow and blood pressure. The kidneys also play a role in regulating blood calcium levels through the production of calcitriol from vitamin D_3, which is released in response to the secretion of parathyroid hormone (PTH). In addition, the kidneys produce the hormone **erythropoietin (EPO)** in response to low oxygen levels. EPO stimulates the production of red blood cells (erythrocytes) in the bone marrow, thereby increasing oxygen delivery to tissues. You may have heard of EPO as a performance-enhancing drug (in a synthetic form).

Skeleton

Although bone has long been recognized as a target for hormones, only recently have researchers recognized that the skeleton itself produces at least two hormones. Fibroblast growth factor 23 (FGF23) is produced by bone cells in response to increased blood levels of vitamin D_3 or phosphate. It triggers the kidneys to inhibit

the formation of calcitriol from vitamin D_3 and to increase phosphorus excretion. Osteocalcin, produced by osteoblasts, stimulates the pancreatic beta cells to increase insulin production. It also acts on peripheral tissues to increase their sensitivity to insulin and their utilization of glucose.

Adipose Tissue

Adipose tissue produces and secretes several hormones involved in lipid metabolism and storage. One important example is **leptin**, a protein manufactured by adipose cells that circulates in amounts directly proportional to levels of body fat. Leptin is released in response to food consumption and acts by binding to brain neurons involved in energy intake and expenditure. Binding of leptin produces a feeling of satiety after a meal, thereby reducing appetite. It also appears that the binding of leptin to brain receptors triggers the sympathetic nervous system to regulate bone metabolism, increasing deposition of cortical bone. Adiponectin—another hormone synthesized by adipose cells—appears to reduce cellular insulin resistance and to protect blood vessels from inflammation and atherosclerosis. Its levels are lower in people who are obese, and rise following weight loss.

Skin

The skin functions as an endocrine organ in the production of the inactive form of vitamin D_3, cholecalciferol. When cholesterol present in the epidermis is exposed to ultraviolet radiation, it is converted to cholecalciferol, which then enters the blood. In the liver, cholecalciferol is converted to an intermediate that travels to the kidneys and is further converted to calcitriol, the active form of vitamin D_3. Vitamin D is important in a variety of physiological processes, including intestinal calcium absorption and immune system function. In some studies, low levels of vitamin D have been associated with increased risks of cancer, severe asthma, and multiple sclerosis. Vitamin D deficiency in children causes rickets, and in adults, osteomalacia—both of which are characterized by bone deterioration.

Thymus

The **thymus** is an organ of the immune system that is larger and more active during infancy and early childhood, and begins to atrophy as we age. Its endocrine function is the production of a group of hormones called **thymosins** that contribute to the development and differentiation of T lymphocytes, which are immune cells. Although the role of thymosins is not yet well understood, it is clear that they contribute to the immune response. Thymosins have been found in tissues other than the thymus and have a wide variety of functions, so the thymosins cannot be strictly categorized as thymic hormones.

Liver

The liver is responsible for secreting at least four important hormones or hormone precursors: insulin-like

growth factor (somatomedin), angiotensinogen, thrombopoetin, and hepcidin. Insulin-like growth factor-1 is the immediate stimulus for growth in the body, especially of the bones. Angiotensinogen is the precursor to angiotensin, mentioned earlier, which increases blood pressure. Thrombopoetin stimulates the production of the blood's platelets. Hepcidins block the release of iron from cells in the body, helping to regulate iron homeostasis in our body fluids. The major hormones of these other organs are summarized in Table (Organs with Secondary Endocrine Functions and Their Major Hormones).

Organs with Secondary Endocrine Functions and Their Major Hormones

Organ	Major hormones	Effects
Heart	Atrial natriuretic peptide (ANP)	Reduces blood volume, blood pressure, and Na^+ concentration
Gastrointestinal tract	Gastrin, secretin, and cholecystokinin	Aid digestion of food and buffering of stomach acids
Gastrointestinal tract	Glucose-dependent insulinotropic peptide (GIP) and glucagon-like peptide 1 (GLP-1)	Stimulate beta cells of the pancreas to release insulin
Kidneys	Renin	Stimulates release of aldosterone
Kidneys	Calcitriol	Aids in the absorption of Ca^{2+}
Kidneys	Erythropoietin	Triggers the formation of red blood cells in the bone marrow
Skeleton	FGF23	Inhibits production of calcitriol and increases phosphate excretion
Skeleton	Osteocalcin	Increases insulin production
Adipose tissue	Leptin	Promotes satiety signals in the brain
Adipose tissue	Adiponectin	Reduces insulin resistance
Skin	Cholecalciferol	Modified to form vitamin D
Thymus (and other organs)	Thymosins	Among other things, aids in the development of T lymphocytes of the immune system
Liver	Insulin-like growth factor-1	Stimulates bodily growth
Liver	Angiotensinogen	Raises blood pressure
Liver	Thrombopoetin	Causes increase in platelets
Liver	Hepcidin	Blocks release of iron into body fluids

Chapter Review

Some organs have a secondary endocrine function. For example, the walls of the atria of the heart produce the hormone atrial natriuretic peptide (ANP), the gastrointestinal tract produces the hormones gastrin, secretin, and cholecystokinin, which aid in digestion, and the kidneys produce erythropoietin (EPO), which stimulates the formation of red blood cells. Even bone, adipose tissue, and the skin have secondary endocrine functions.

Development and Aging of the Endocrine System

By the end of this section, you will be able to:

- Describe the embryonic origins of the endocrine system
- Discuss the effects of aging on the endocrine system

The endocrine system arises from all three embryonic germ layers. The endocrine glands that produce the steroid hormones, such as the gonads and adrenal cortex, arise from the mesoderm. In contrast, endocrine glands that arise from the endoderm and ectoderm produce the amine, peptide, and protein hormones. The pituitary gland arises from two distinct areas of the ectoderm: the anterior pituitary gland arises from the oral ectoderm, whereas the posterior pituitary gland arises from the neural ectoderm at the base of the hypothalamus. The pineal gland also arises from the ectoderm. The two structures of the adrenal glands arise from two different germ layers: the adrenal cortex from the mesoderm and the adrenal medulla from ectoderm neural cells. The endoderm gives rise to the thyroid and parathyroid glands, as well as the pancreas and the thymus.

As the body ages, changes occur that affect the endocrine system, sometimes altering the production, secretion, and catabolism of hormones. For example, the structure of the anterior pituitary gland changes as vascularization decreases and the connective tissue content increases with increasing age. This restructuring affects the gland's hormone production. For example, the amount of human growth hormone that is produced declines with age, resulting in the reduced muscle mass commonly observed in the elderly.

The adrenal glands also undergo changes as the body ages; as fibrous tissue increases, the production of cortisol and aldosterone decreases. Interestingly, the production and secretion of epinephrine and norepinephrine remain normal throughout the aging process.

A well-known example of the aging process affecting an endocrine gland is menopause and the decline of ovarian function. With increasing age, the ovaries decrease in both size and weight and become progressively less sensitive to gonadotropins. This gradually causes a decrease in estrogen and progesterone levels, leading to menopause and the inability to reproduce. Low levels of estrogens and progesterone are also associated with some disease states, such as osteoporosis, atherosclerosis, and hyperlipidemia, or abnormal blood lipid levels.

Testosterone levels also decline with age, a condition called andropause (or viropause); however, this decline is much less dramatic than the decline of estrogens in women, and much more gradual, rarely affecting sperm production until very old age. Although this means that males maintain their ability to father children for decades longer than females, the quantity, quality, and motility of their sperm is often reduced.

As the body ages, the thyroid gland produces less of the thyroid hormones, causing a gradual decrease in the basal metabolic rate. The lower metabolic rate reduces the production of body heat and increases levels of body fat. Parathyroid hormones, on the other hand, increase with age. This may be because of reduced dietary calcium levels, causing a compensatory increase in parathyroid hormone. However, increased parathyroid hormone levels combined with decreased levels of calcitonin (and estrogens in women) can lead to osteoporosis as PTH stimulates demineralization of bones to increase blood calcium levels. Notice that osteoporosis is common in both elderly males and females.

Increasing age also affects glucose metabolism, as blood glucose levels spike more rapidly and take longer

to return to normal in the elderly. In addition, increasing glucose intolerance may occur because of a gradual decline in cellular insulin sensitivity. Almost 27 percent of Americans aged 65 and older have diabetes.

Chapter Review

The endocrine system originates from all three germ layers of the embryo, including the endoderm, ectoderm, and mesoderm. In general, different hormone classes arise from distinct germ layers. Aging affects the endocrine glands, potentially affecting hormone production and secretion, and can cause disease. The production of hormones, such as human growth hormone, cortisol, aldosterone, sex hormones, and the thyroid hormones, decreases with age.

License

1.8 The Circulatory System

CHARLES MOLNAR AND JANE GAIR

Figure 21.1. *Just as highway systems transport people and goods through a complex network, the circulatory system transports nutrients, gases, and wastes throughout the animal body. (credit: modification of work by Andrey Belenko)*

Introduction

Most animals are complex multicellular organisms that require a mechanism for transporting nutrients throughout their bodies and removing waste products. The circulatory system has evolved over time from simple diffusion through cells in the early evolution of animals to a complex network of blood vessels that reach all parts of the human body. This extensive network supplies the cells, tissues, and organs with oxygen and nutrients, and removes carbon dioxide and waste, which are byproducts of respiration.

At the core of the human circulatory system is the heart. The size of a clenched fist, the human heart is protected beneath the rib cage. Made of specialized and unique cardiac muscle, it pumps blood throughout the body and to the heart itself. Heart contractions are driven by intrinsic electrical impulses that the brain and endocrine hormones help to regulate. Understanding the heart's basic anatomy and function is important to understanding the body's circulatory and respiratory systems.

Gas exchange is one essential function of the circulatory system. A circulatory system is not needed in organisms with no specialized respiratory organs because oxygen and carbon dioxide diffuse directly between their body tissues and the external environment. However, in organisms that possess lungs and gills, oxygen must be transported from these specialized respiratory organs to the body tissues via a circulatory system. Therefore,

circulatory systems have had to evolve to accommodate the great diversity of body sizes and body types present among animals.

Overview of the Circulatory System

By the end of this section, you will be able to:

- Describe an open and closed circulatory system
- Describe interstitial fluid and hemolymph
- Compare and contrast the organization and evolution of the vertebrate circulatory system.

In all animals, except a few simple types, the circulatory system is used to transport nutrients and gases through the body. Simple diffusion allows some water, nutrient, waste, and gas exchange into primitive animals that are only a few cell layers thick; however, bulk flow is the only method by which the entire body of larger more complex organisms is accessed.

Circulatory System Architecture

The circulatory system is effectively a network of cylindrical vessels: the arteries, veins, and capillaries that emanate from a pump, the heart. In all vertebrate organisms, as well as some invertebrates, this is a closed-loop system, in which the blood is not free in a cavity. In a **closed circulatory system**, blood is contained inside blood vessels and circulates **unidirectionally** from the heart around the systemic circulatory route, then returns to the heart again, as illustrated in Figure 21.2a. As opposed to a closed system, arthropods—including insects, crustaceans, and most mollusks—have an open circulatory system, as illustrated in Figure 21.2b. In an **open circulatory system**, the blood is not enclosed in the blood vessels but is pumped into a cavity called a **hemocoel** and is called **hemolymph** because the blood mixes with the **interstitial fluid**. As the heart beats and the animal moves, the hemolymph circulates around the organs within the body cavity and then reenters the hearts through openings called **ostia**. This movement allows for gas and nutrient exchange. An open circulatory system does not use as much energy as a closed system to operate or to maintain; however, there is a trade-off with the amount of blood that can be moved to metabolically active organs and tissues that require high levels of oxygen. In fact, one reason that insects with wing spans of up to two feet wide (70 cm) are not around today is probably because they were outcompeted by the arrival of birds 150 million years ago. Birds, having a closed circulatory system, are thought to have moved more agilely, allowing them to get food faster and possibly to prey on the insects.

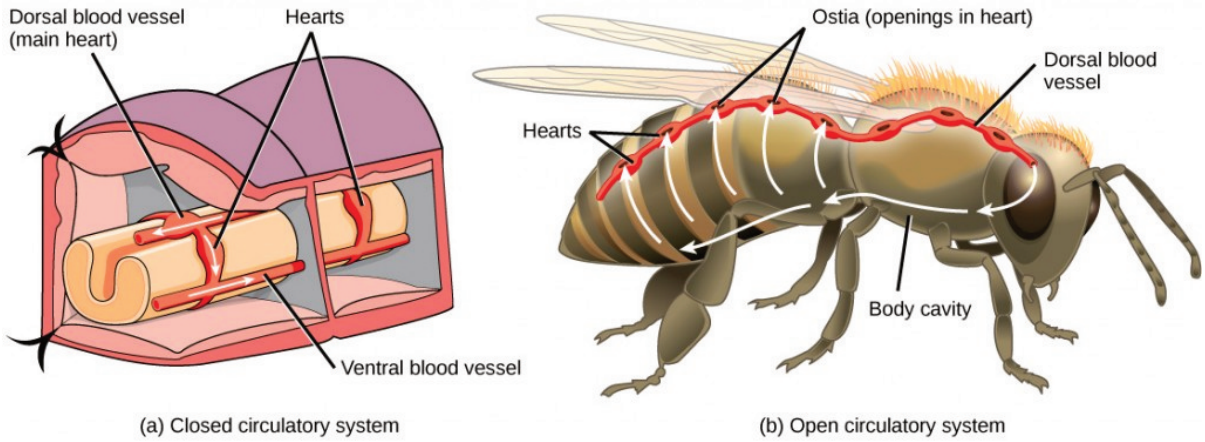


Figure 21.2. *In (a) closed circulatory systems, the heart pumps blood through vessels that are separate from the interstitial fluid of the body. Most vertebrates and some invertebrates, like this annelid earthworm, have a closed circulatory system. In (b) open circulatory systems, a fluid called hemolymph is pumped through a blood vessel that empties into the body cavity. Hemolymph returns to the blood vessel through openings called ostia. Arthropods like this bee and most mollusks have open circulatory systems.*

Circulatory System Variation in Animals

The circulatory system varies from simple systems in invertebrates to more complex systems in vertebrates. The simplest animals, such as the sponges (Porifera) and rotifers (Rotifera), do not need a circulatory system because diffusion allows adequate exchange of water, nutrients, and waste, as well as dissolved gases, as shown in Figure 21.3a. Organisms that are more complex but still only have two layers of cells in their body plan, such as jellies (Cnidaria) and comb jellies (Ctenophora) also use diffusion through their epidermis and internally through the gastrovascular compartment. Both their internal and external tissues are bathed in an aqueous environment and exchange fluids by diffusion on both sides, as illustrated in Figure 21.3b. Exchange of fluids is assisted by the pulsing of the jellyfish body.

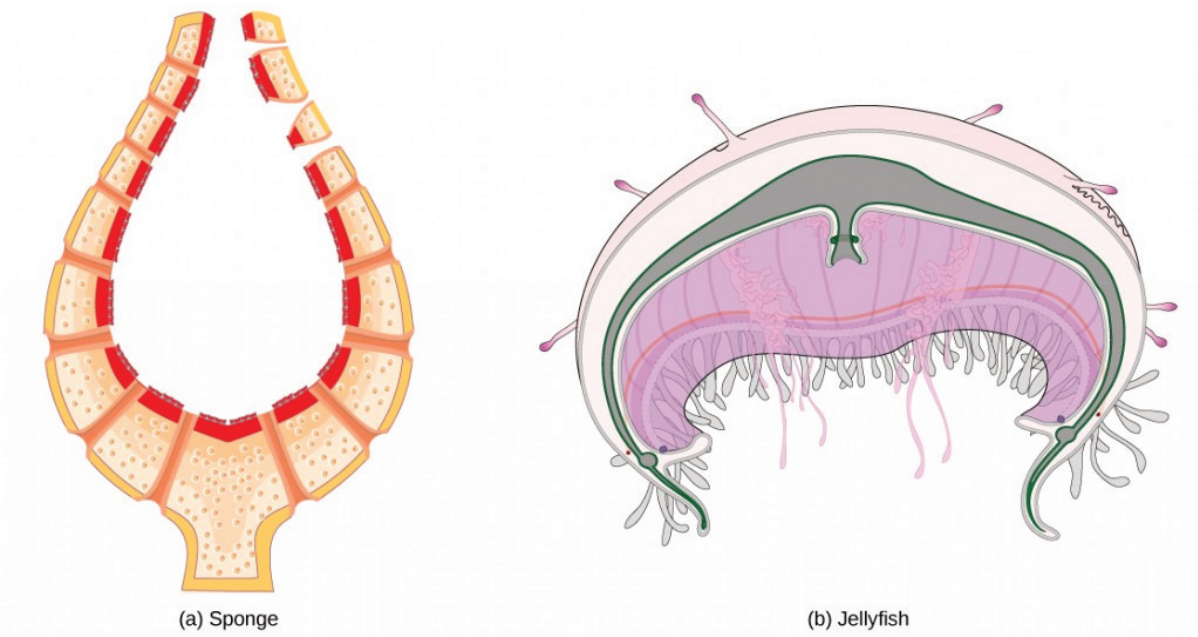


Figure 21.3. *Simple animals consisting of a single cell layer such as the (a) sponge or only a few cell layers such as the (b) jellyfish do not have a circulatory system. Instead, gases, nutrients, and wastes are exchanged by diffusion.*

For more complex organisms, diffusion is not efficient for cycling gases, nutrients, and waste effectively through the body; therefore, more complex circulatory systems evolved. Most arthropods and many mollusks have open circulatory systems. In an open system, an elongated beating heart pushes the hemolymph through the body and muscle contractions help to move fluids. The larger more complex crustaceans, including lobsters, have developed arterial-like vessels to push blood through their bodies, and the most active mollusks, such as squids, have evolved a closed circulatory system and are able to move rapidly to catch prey. Closed circulatory systems are a characteristic of vertebrates; however, there are significant differences in the structure of the heart and the circulation of blood between the different vertebrate groups due to adaptation during evolution and associated differences in anatomy. Figure 21.4 illustrates the basic circulatory systems of some vertebrates: fish, amphibians, reptiles, and mammals.

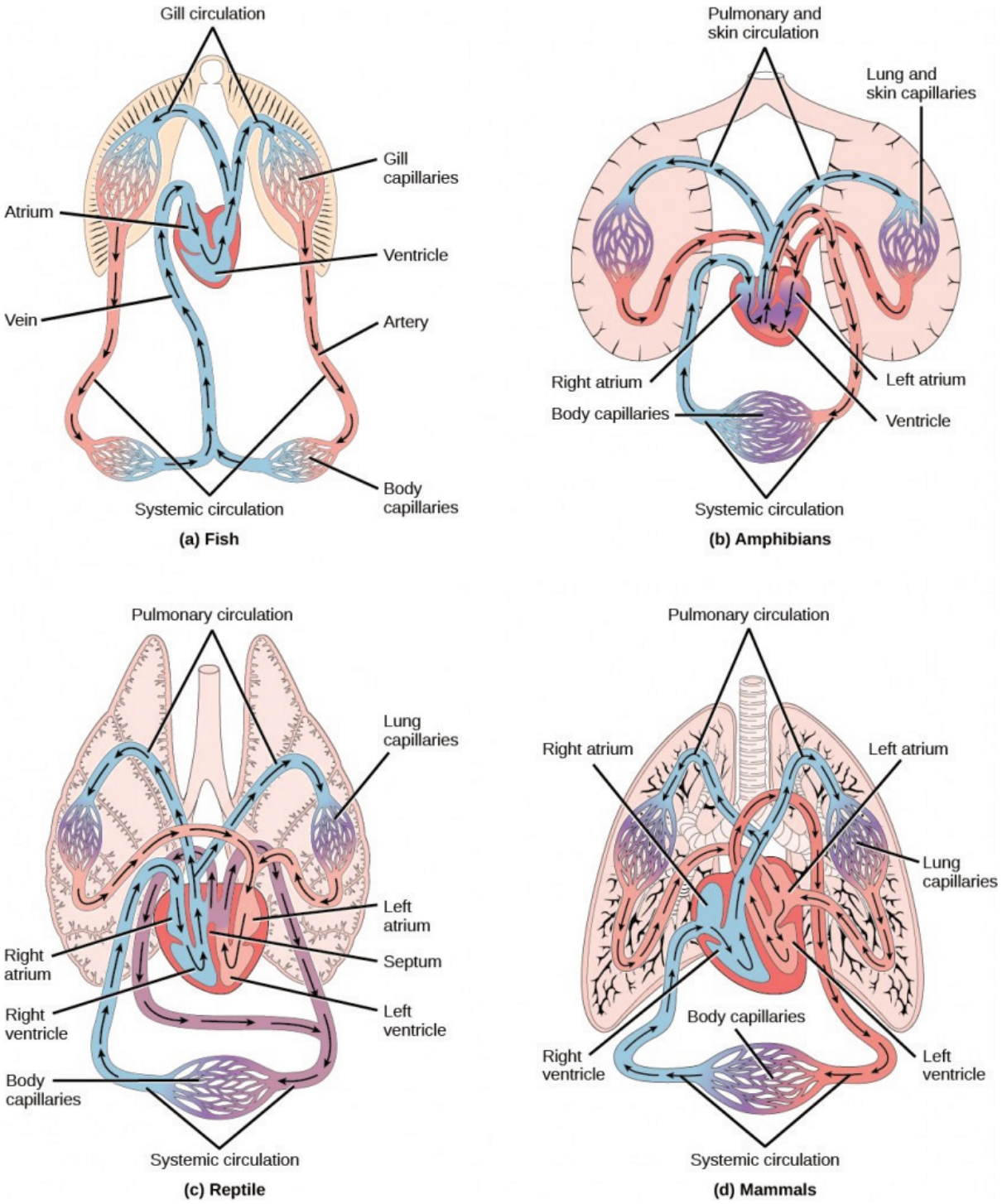


Figure 21.4. *(a) Fish have the simplest circulatory systems of the vertebrates: blood flows unidirectionally from the two-chambered heart through the gills and then the rest of the body. (b) Amphibians have two circulatory routes: one for oxygenation of the blood through the lungs and skin, and the other to take oxygen to the rest of the body. The blood is pumped from a three-chambered heart with two atria and a single ventricle. (c) Reptiles also have two circulatory routes; however, blood is only oxygenated through the lungs. The heart is three chambered, but the ventricles are partially separated so some mixing of oxygenated and deoxygenated blood occurs except in crocodilians and birds. (d) Mammals and birds have the most efficient heart with four chambers that completely*

separate the oxygenated and deoxygenated blood; it pumps only oxygenated blood through the body and deoxygenated blood to the lungs.

As illustrated in Figure 21.4a Fish have a single circuit for blood flow and a two-chambered heart that has only a single atrium and a single ventricle. The atrium collects blood that has returned from the body and the ventricle pumps the blood to the gills where gas exchange occurs and the blood is re-oxygenated; this is called **gill circulation**. The blood then continues through the rest of the body before arriving back at the atrium; this is called **systemic circulation**. This unidirectional flow of blood produces a gradient of oxygenated to deoxygenated blood around the fish's systemic circuit. The result is a limit in the amount of oxygen that can reach some of the organs and tissues of the body, reducing the overall metabolic capacity of fish.

In amphibians, reptiles, birds, and mammals, blood flow is directed in two circuits: one through the lungs and back to the heart, which is called **pulmonary circulation**, and the other throughout the rest of the body and its organs including the brain (systemic circulation). In amphibians, gas exchange also occurs through the skin during pulmonary circulation and is referred to as **pulmocutaneous circulation**.

As shown in Figure 21.4b, amphibians have a three-chambered heart that has two atria and one ventricle rather than the two-chambered heart of fish. The two **atria** (superior heart chambers) receive blood from the two different circuits (the lungs and the systems), and then there is some mixing of the blood in the heart's **ventricle** (inferior heart chamber), which reduces the efficiency of oxygenation. The advantage to this arrangement is that high pressure in the vessels pushes blood to the lungs and body. The mixing is mitigated by a ridge within the ventricle that diverts oxygen-rich blood through the systemic circulatory system and deoxygenated blood to the pulmocutaneous circuit. For this reason, amphibians are often described as having **double circulation**.

Most reptiles also have a three-chambered heart similar to the amphibian heart that directs blood to the pulmonary and systemic circuits, as shown in Figure 21.4c. The ventricle is divided more effectively by a partial septum, which results in less mixing of oxygenated and deoxygenated blood. Some reptiles (alligators and crocodiles) are the most primitive animals to exhibit a four-chambered heart. Crocodilians have a unique circulatory mechanism where the heart shunts blood from the lungs toward the stomach and other organs during long periods of submergence, for instance, while the animal waits for prey or stays underwater waiting for prey to rot. One adaptation includes two main arteries that leave the same part of the heart: one takes blood to the lungs and the other provides an alternate route to the stomach and other parts of the body. Two other adaptations include a hole in the heart between the two ventricles, called the foramen of Panizza, which allows blood to move from one side of the heart to the other, and specialized connective tissue that slows the blood flow to the lungs. Together these adaptations have made crocodiles and alligators one of the most evolutionarily successful animal groups on earth.

In mammals and birds, the heart is also divided into four chambers: two atria and two ventricles, as illustrated in Figure 21.4d. The oxygenated blood is separated from the deoxygenated blood, which improves the efficiency of double circulation and is probably required for the warm-blooded lifestyle of mammals and birds. The four-chambered heart of birds and mammals evolved independently from a three-chambered heart. The independent evolution of the same or a similar biological trait is referred to as convergent evolution.

Summary

In most animals, the circulatory system is used to transport blood through the body. Some primitive animals use diffusion for the exchange of water, nutrients, and gases. However, complex organisms use the circulatory

system to carry gases, nutrients, and waste through the body. Circulatory systems may be open (mixed with the interstitial fluid) or closed (separated from the interstitial fluid). Closed circulatory systems are a characteristic of vertebrates; however, there are significant differences in the structure of the heart and the circulation of blood between the different vertebrate groups due to adaptions during evolution and associated differences in anatomy. Fish have a two-chambered heart with unidirectional circulation. Amphibians have a three-chambered heart, which has some mixing of the blood, and they have double circulation. Most non-avian reptiles have a three-chambered heart, but have little mixing of the blood; they have double circulation. Mammals and birds have a four-chambered heart with no mixing of the blood and double circulation.

Components of the Blood

By the end of this section, you will be able to:

- List the basic components of the blood
- Compare red and white blood cells
- Describe blood plasma and serum

Hemoglobin is responsible for distributing oxygen, and to a lesser extent, carbon dioxide, throughout the circulatory systems of humans, vertebrates, and many invertebrates. The blood is more than the proteins, though. Blood is actually a term used to describe the liquid that moves through the vessels and includes **plasma** (the liquid portion, which contains water, proteins, salts, lipids, and glucose) and the cells (red and white cells) and cell fragments called **platelets**. Blood plasma is actually the dominant component of blood and contains the water, proteins, electrolytes, lipids, and glucose. The cells are responsible for carrying the gases (red cells) and immune the response (white). The platelets are responsible for blood clotting. Interstitial fluid that surrounds cells is separate from the blood, but in hemolymph, they are combined. In humans, cellular components make up approximately 45 percent of the blood and the liquid plasma 55 percent. Blood is 20 percent of a person's extracellular fluid and eight percent of weight.

The Role of Blood in the Body

Blood, like the human blood illustrated in Figure 21.5 is important for regulation of the body's systems and homeostasis. Blood helps maintain homeostasis by stabilizing pH, temperature, osmotic pressure, and by eliminating excess heat. Blood supports growth by distributing nutrients and hormones, and by removing waste. Blood plays a protective role by transporting clotting factors and platelets to prevent blood loss and transporting the disease-fighting agents or **white blood cells** to sites of infection.

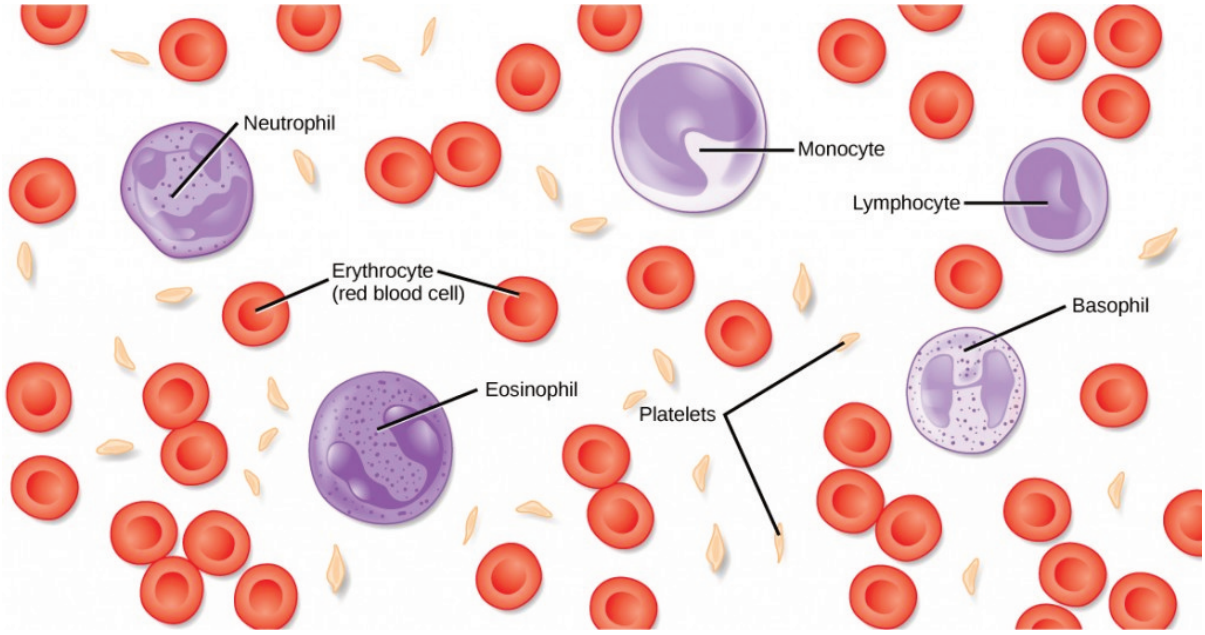


Figure 21.5. *The cells and cellular components of human blood are shown. Red blood cells deliver oxygen to the cells and remove carbon dioxide. White blood cells—including neutrophils, monocytes, lymphocytes, eosinophils, and basophils—are involved in the immune response. Platelets form clots that prevent blood loss after injury.*

Red Blood Cells

Red blood cells, or erythrocytes (erythro- = "red"; -cyte = "cell"), are specialized cells that circulate through the body delivering oxygen to cells; they are formed from stem cells in the bone marrow. In mammals, red blood cells are small biconcave cells that at maturity do not contain a nucleus or mitochondria and are only 7–8 μm in size. In birds and non-avian reptiles, a nucleus is still maintained in red blood cells.

The red coloring of blood comes from the iron-containing protein hemoglobin, illustrated in Figure 21.6a. The principal job of this protein is to carry oxygen, but it also transports carbon dioxide as well. Hemoglobin is packed into red blood cells at a rate of about 250 million molecules of hemoglobin per cell. Each hemoglobin molecule binds four oxygen molecules so that each red blood cell carries one billion molecules of oxygen. There are approximately 25 trillion red blood cells in the five liters of blood in the human body, which could carry up to 25 sextillion (25×10^{21}) molecules of oxygen in the body at any time. In mammals, the lack of organelles in erythrocytes leaves more room for the hemoglobin molecules, and the lack of mitochondria also prevents use of the oxygen for metabolic respiration. Only mammals have anucleated red blood cells, and some mammals (camels, for instance) even have nucleated red blood cells. The advantage of nucleated red blood cells is that these cells can undergo mitosis. Anucleated red blood cells metabolize anaerobically (without oxygen), making use of a primitive metabolic pathway to produce ATP and increase the efficiency of oxygen transport.

Not all organisms use hemoglobin as the method of oxygen transport. Invertebrates that utilize hemolymph rather than blood use different pigments to bind to the oxygen. These pigments use copper or iron to the oxygen. Invertebrates have a variety of other respiratory pigments. Hemocyanin, a blue-green, copper-containing protein, illustrated in Figure 21.6b is found in mollusks, crustaceans, and some of the arthropods. Chlorocruorin, a green-colored, iron-containing pigment is found in four families of polychaete tubeworms. Hemerythrin, a red, iron-containing protein is found in some polychaete worms and annelids and is illustrated in Figure

21.6c. Despite the name, hemerythrin does not contain a heme group and its oxygen-carrying capacity is poor compared to hemoglobin.

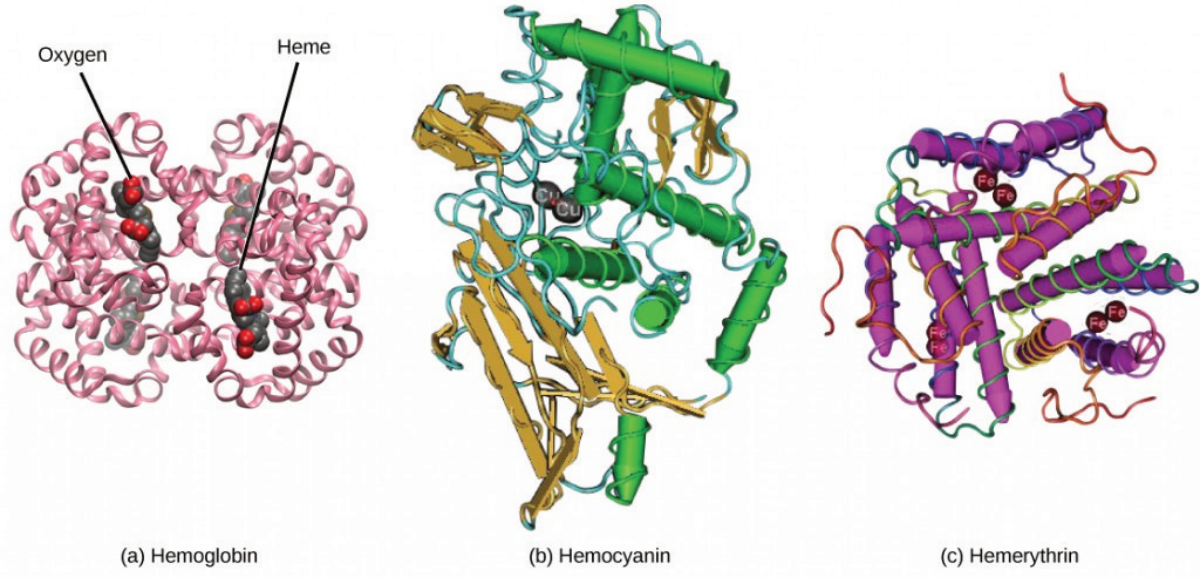


Figure 21.6. *In most vertebrates, (a) hemoglobin delivers oxygen to the body and removes some carbon dioxide. Hemoglobin is composed of four protein subunits, two alpha chains and two beta chains, and a heme group that has iron associated with it. The iron reversibly associates with oxygen, and in so doing is oxidized from* Fe^{2+} *to* Fe^{3+}*. In most mollusks and some arthropods, (b) hemocyanin delivers oxygen. Unlike hemoglobin, hemolymph is not carried in blood cells, but floats free in the hemolymph. Copper instead of iron binds the oxygen, giving the hemolymph a blue-green color. In annelids, such as the earthworm, and some other invertebrates, (c) hemerythrin carries oxygen. Like hemoglobin, hemerythrin is carried in blood cells and has iron associated with it, but despite its name, hemerythrin does not contain heme.*

The small size and large surface area of red blood cells allows for rapid diffusion of oxygen and carbon dioxide across the plasma membrane. In the lungs, carbon dioxide is released and oxygen is taken in by the blood. In the tissues, oxygen is released from the blood and carbon dioxide is bound for transport back to the lungs. Studies have found that hemoglobin also binds nitrous oxide (NO). NO is a vasodilator that relaxes the blood vessels and capillaries and may help with gas exchange and the passage of red blood cells through narrow vessels. Nitroglycerin, a heart medication for angina and heart attacks, is converted to NO to help relax the blood vessels and increase oxygen flow through the body.

A characteristic of red blood cells is their glycolipid and glycoprotein coating; these are lipids and proteins that have carbohydrate molecules attached. In humans, the surface glycoproteins and glycolipids on red blood cells vary between individuals, producing the different blood types, such as A, B, and O. Red blood cells have an average life span of 120 days, at which time they are broken down and recycled in the liver and spleen by phagocytic macrophages, a type of white blood cell.

White Blood Cells

White blood cells, also called leukocytes (leuko = white), make up approximately one percent by volume of the cells in blood. The role of white blood cells is very different than that of red blood cells: they are primarily

involved in the immune response to identify and target pathogens, such as invading bacteria, viruses, and other foreign organisms. White blood cells are formed continually; some only live for hours or days, but some live for years.

The morphology of white blood cells differs significantly from red blood cells. They have nuclei and do not contain hemoglobin. The different types of white blood cells are identified by their microscopic appearance after histologic staining, and each has a different specialized function. The two main groups, both illustrated in Figure 21.7 are the granulocytes, which include the neutrophils, eosinophils, and basophils, and the agranulocytes, which include the monocytes and lymphocytes.

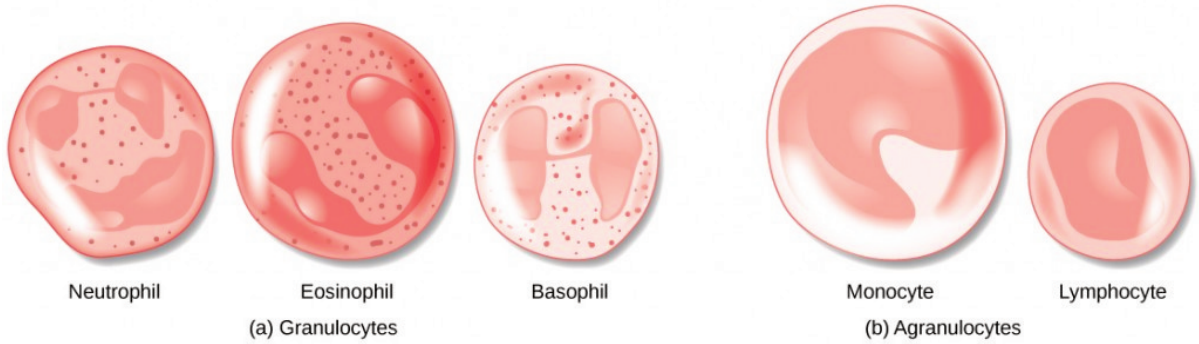


Figure 21.7. *(a) Granulocytes—including neutrophils, eosinophils and basophils—are characterized by a lobed nucleus and granular inclusions in the cytoplasm. Granulocytes are typically first-responders during injury or infection. (b) Agranulocytes include lymphocytes and monocytes. Lymphocytes, including B and T cells, are responsible for adaptive immune response. Monocytes differentiate into macrophages and dendritic cells, which in turn respond to infection or injury.*

Granulocytes contain granules in their cytoplasm; the agranulocytes are so named because of the lack of granules in their cytoplasm. Some leukocytes become macrophages that either stay at the same site or move through the blood stream and gather at sites of infection or inflammation where they are attracted by chemical signals from foreign particles and damaged cells. Lymphocytes are the primary cells of the immune system and include B cells, T cells, and natural killer cells. B cells destroy bacteria and inactivate their toxins. They also produce antibodies. T cells attack viruses, fungi, some bacteria, transplanted cells, and cancer cells. T cells attack viruses by releasing toxins that kill the viruses. Natural killer cells attack a variety of infectious microbes and certain tumor cells.

One reason that HIV poses significant management challenges is because the virus directly targets T cells by gaining entry through a receptor. Once inside the cell, HIV then multiplies using the T cell's own genetic machinery. After the HIV virus replicates, it is transmitted directly from the infected T cell to macrophages. The presence of HIV can remain unrecognized for an extensive period of time before full disease symptoms develop.

Platelets and Coagulation Factors

Blood must clot to heal wounds and prevent excess blood loss. Small cell fragments called platelets (thrombocytes) are attracted to the wound site where they adhere by extending many projections and releasing their contents. These contents activate other platelets and also interact with other coagulation factors, which convert fibrinogen, a water-soluble protein present in blood serum into fibrin (a non-water soluble protein), causing the blood to clot. Many of the clotting factors require vitamin K to work, and vitamin K deficiency can lead to problems with blood clotting. Many platelets converge and stick together at the wound site forming a

platelet plug (also called a fibrin clot), as illustrated in Figure 21.8b. The plug or clot lasts for a number of days and stops the loss of blood. Platelets are formed from the disintegration of larger cells called megakaryocytes, like that shown in Figure 21.8a. For each megakaryocyte, 2000–3000 platelets are formed with 150,000 to 400,000 platelets present in each cubic millimeter of blood. Each platelet is disc shaped and 2–4 μm in diameter. They contain many small vesicles but do not contain a nucleus.

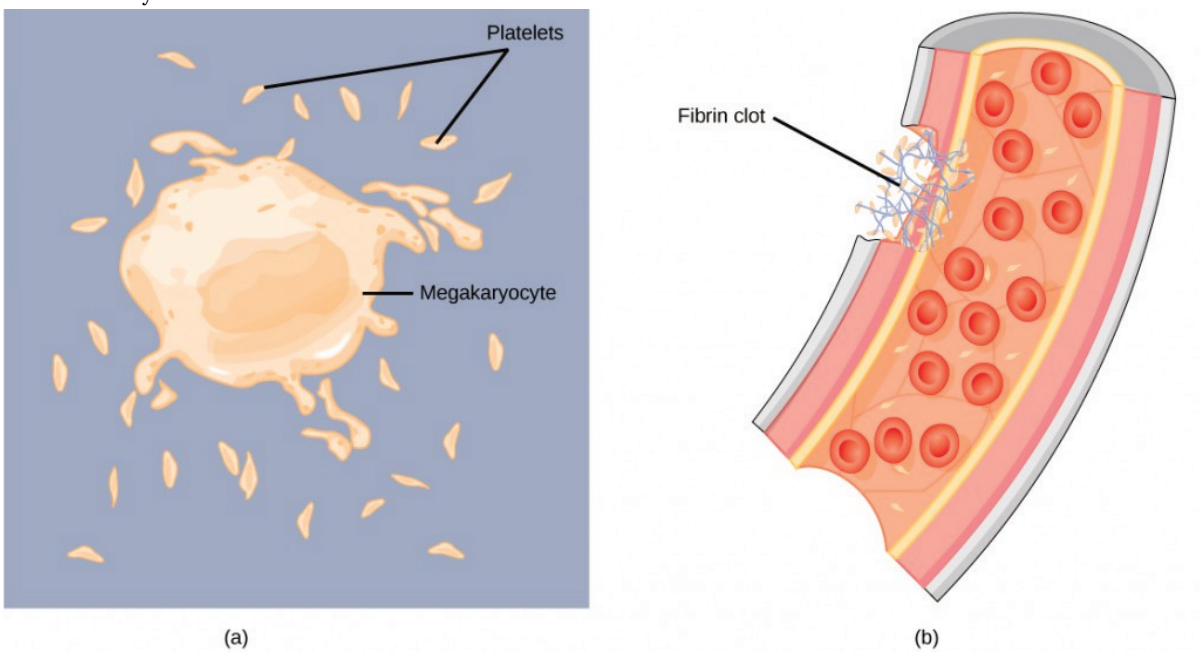


Figure 21.8. *(a) Platelets are formed from large cells called megakaryocytes. The megakaryocyte breaks up into thousands of fragments that become platelets. (b) Platelets are required for clotting of the blood. The platelets collect at a wound site in conjunction with other clotting factors, such as fibrinogen, to form a fibrin clot that prevents blood loss and allows the wound to heal.*

Plasma and Serum

The liquid component of blood is called plasma, and it is separated by spinning or centrifuging the blood at high rotations (3000 rpm or higher). The blood cells and platelets are separated by centrifugal forces to the bottom of a specimen tube. The upper liquid layer, the plasma, consists of 90 percent water along with various substances required for maintaining the body's pH, osmotic load, and for protecting the body. The plasma also contains the coagulation factors and antibodies.

The plasma component of blood without the coagulation factors is called the **serum**. Serum is similar to interstitial fluid in which the correct composition of key ions acting as electrolytes is essential for normal functioning of muscles and nerves. Other components in the serum include proteins that assist with maintaining pH and osmotic balance while giving viscosity to the blood. The serum also contains antibodies, specialized proteins that are important for defense against viruses and bacteria. Lipids, including cholesterol, are also transported in the serum, along with various other substances including nutrients, hormones, metabolic waste, plus external substances, such as, drugs, viruses, and bacteria.

Human serum albumin is the most abundant protein in human blood plasma and is synthesized in the liver. Albumin, which constitutes about half of the blood serum protein, transports hormones and fatty acids, buffers

pH, and maintains osmotic pressures. Immunoglobin is a protein antibody produced in the mucosal lining and plays an important role in antibody mediated immunity.

Blood Types Related to Proteins on the Surface of the Red Blood Cells

Red blood cells are coated in antigens made of glycolipids and glycoproteins. The composition of these molecules is determined by genetics, which have evolved over time. In humans, the different surface antigens are grouped into 24 different blood groups with more than 100 different antigens on each red blood cell. The two most well known blood groups are the ABO, shown in Figure 21.9, and Rh systems. The surface antigens in the ABO blood group are glycolipids, called antigen A and antigen B. People with blood type A have antigen A, those with blood type B have antigen B, those with blood type AB have both antigens, and people with blood type O have neither antigen. Antibodies called agglutinougens are found in the blood plasma and react with the A or B antigens, if the two are mixed. When type A and type B blood are combined, agglutination (clumping) of the blood occurs because of antibodies in the plasma that bind with the opposing antigen; this causes clots that coagulate in the kidney causing kidney failure. Type O blood has neither A or B antigens, and therefore, type O blood can be given to all blood types. Type O negative blood is the universal donor. Type AB positive blood is the universal acceptor because it has both A and B antigen. The ABO blood groups were discovered in 1900 and 1901 by Karl Landsteiner at the University of Vienna.

The Rh blood group was first discovered in Rhesus monkeys. Most people have the Rh antigen (Rh+) and do not have anti-Rh antibodies in their blood. The few people who do not have the Rh antigen and are Rh− can develop anti-Rh antibodies if exposed to Rh+ blood. This can happen after a blood transfusion or after an Rh− woman has an Rh+ baby. The first exposure does not usually cause a reaction; however, at the second exposure, enough antibodies have built up in the blood to produce a reaction that causes agglutination and breakdown of red blood cells. An injection can prevent this reaction.

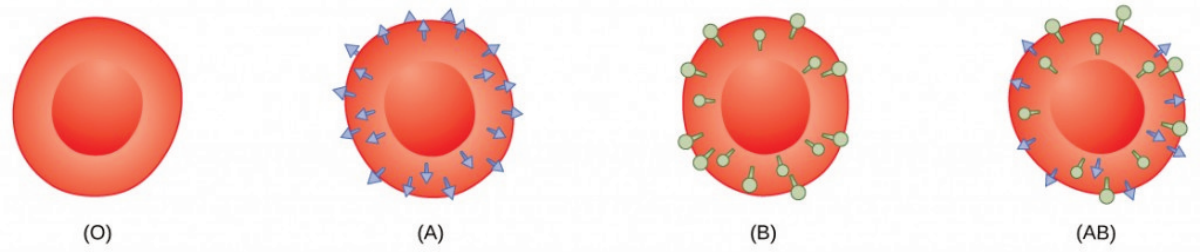


Figure 21.9. *Human red blood cells may have either type A or B glycoproteins on their surface, both glycoproteins combined (AB), or neither (O). The glycoproteins serve as antigens and can elicit an immune response in a person who receives a transfusion containing unfamiliar antigens. Type O blood, which has no A or B antigens, does not elicit an immune response when injected into a person of any blood type. Thus, O is considered the universal donor. Persons with type AB blood can accept blood from any blood type, and type AB is considered the universal acceptor.*

Play a blood typing game on the Nobel Prize website to solidify your understanding of blood types.

Summary

Specific components of the blood include red blood cells, white blood cells, platelets, and the plasma, which contains coagulation factors and serum. Blood is important for regulation of the body's pH, temperature, osmotic pressure, the circulation of nutrients and removal of waste, the distribution of hormones from endocrine glands, and the elimination of excess heat; it also contains components for blood clotting. Red blood cells are specialized cells that contain hemoglobin and circulate through the body delivering oxygen to cells. White blood cells are involved in the immune response to identify and target invading bacteria, viruses, and other foreign organisms; they also recycle waste components, such as old red blood cells. Platelets and blood clotting factors cause the change of the soluble protein fibrinogen to the insoluble protein fibrin at a wound site forming a plug. Plasma consists of 90 percent water along with various substances, such as coagulation factors and antibodies. The serum is the plasma component of the blood without the coagulation factors.

Mammalian Heart and Blood Vessels

By the end of this section, you will be able to:

- Describe the structure of the heart and explain how cardiac muscle is different from other muscles
- Describe the cardiac cycle
- Explain the structure of arteries, veins, and capillaries, and how blood flows through the body

The heart is a complex muscle that pumps blood through the three divisions of the circulatory system: the coronary (vessels that serve the heart), pulmonary (heart and lungs), and systemic (systems of the body), as shown in Figure 21.10. Coronary circulation intrinsic to the heart takes blood directly from the main artery (aorta) coming from the heart. For pulmonary and systemic circulation, the heart has to pump blood to the lungs or the rest of the body, respectively. In vertebrates, the lungs are relatively close to the heart in the thoracic cavity. The shorter distance to pump means that the muscle wall on the right side of the heart is not as thick as the left side which must have enough pressure to pump blood all the way to your big toe.

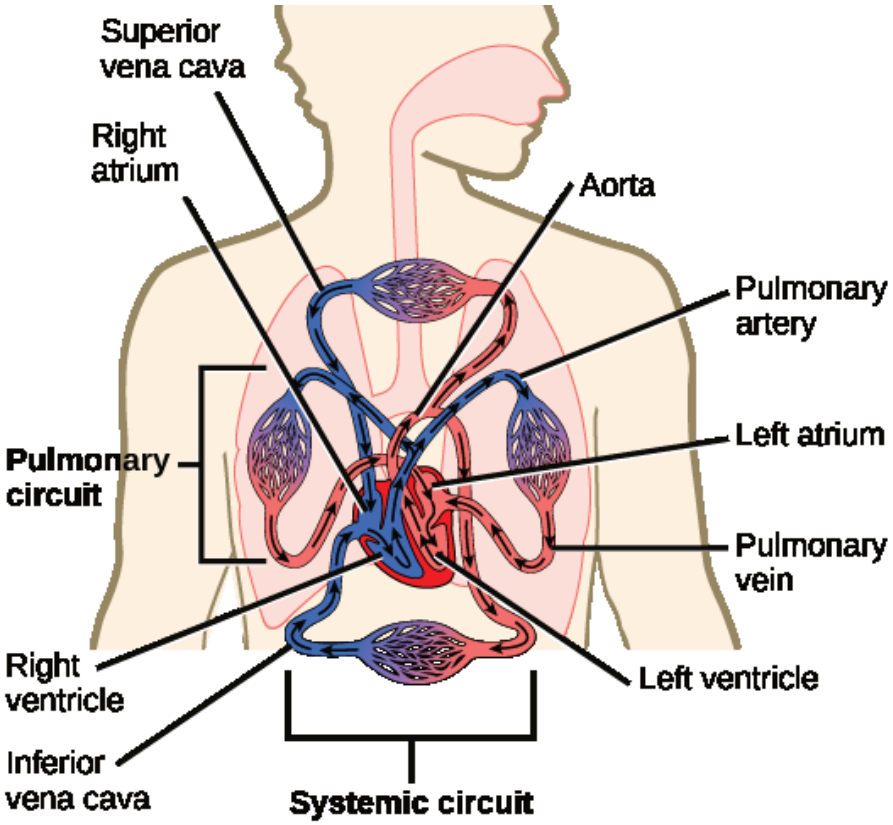


Figure 21.10. *The mammalian circulatory system is divided into three circuits: the systemic circuit, the pulmonary circuit, and the coronary circuit. Blood is pumped from veins of the systemic circuit into the right atrium of the heart, then into the right ventricle. Blood then enters the pulmonary circuit, and is oxygenated by the lungs. From the pulmonary circuit, blood re-enters the heart through the left atrium. From the left ventricle, blood re-enters the systemic circuit through the aorta and is distributed to the rest of the body. The coronary circuit, which provides blood to the heart, is not shown.*

Which of the following statements about the circulatory system is false?

1. Blood in the pulmonary vein is deoxygenated.
2. Blood in the inferior vena cava is deoxygenated.
3. Blood in the pulmonary artery is deoxygenated.
4. Blood in the aorta is oxygenated.

Structure of the Heart

The heart muscle is asymmetrical as a result of the distance blood must travel in the pulmonary and systemic circuits. Since the right side of the heart sends blood to the pulmonary circuit it is smaller than the left side which must send blood out to the whole body in the systemic circuit, as shown in Figure 21.11. In humans, the heart is about the size of a clenched fist; it is divided into four chambers: two atria and two ventricles. There is one atrium and one ventricle on the right side and one atrium and one ventricle on the left side. The atria

are the chambers that receive blood, and the ventricles are the chambers that pump blood. The right atrium receives deoxygenated blood from the **superior vena cava**, which drains blood from the jugular vein that comes from the brain and from the veins that come from the arms, as well as from the **inferior vena cava** which drains blood from the veins that come from the lower organs and the legs. In addition, the right atrium receives blood from the coronary sinus which drains deoxygenated blood from the heart itself. This deoxygenated blood then passes to the right ventricle through the **atrioventricular valve** or the **tricuspid valve**, a flap of connective tissue that opens in only one direction to prevent the backflow of blood. The valve separating the chambers on the left side of the heart valve is called the biscuspid or mitral valve. After it is filled, the right ventricle pumps the blood through the pulmonary arteries, by-passing the **semilunar valve** (or pulmonic valve) to the lungs for re-oxygenation. After blood passes through the pulmonary arteries, the right semilunar valves close preventing the blood from flowing backwards into the right ventricle. The left atrium then receives the oxygen-rich blood from the lungs via the pulmonary veins. This blood passes through the **bicuspid valve** or mitral valve (the atrioventricular valve on the left side of the heart) to the left ventricle where the blood is pumped out through **aorta**, the major artery of the body, taking oxygenated blood to the organs and muscles of the body. Once blood is pumped out of the left ventricle and into the aorta, the aortic semilunar valve (or aortic valve) closes preventing blood from flowing backward into the left ventricle. This pattern of pumping is referred to as double circulation and is found in all mammals.

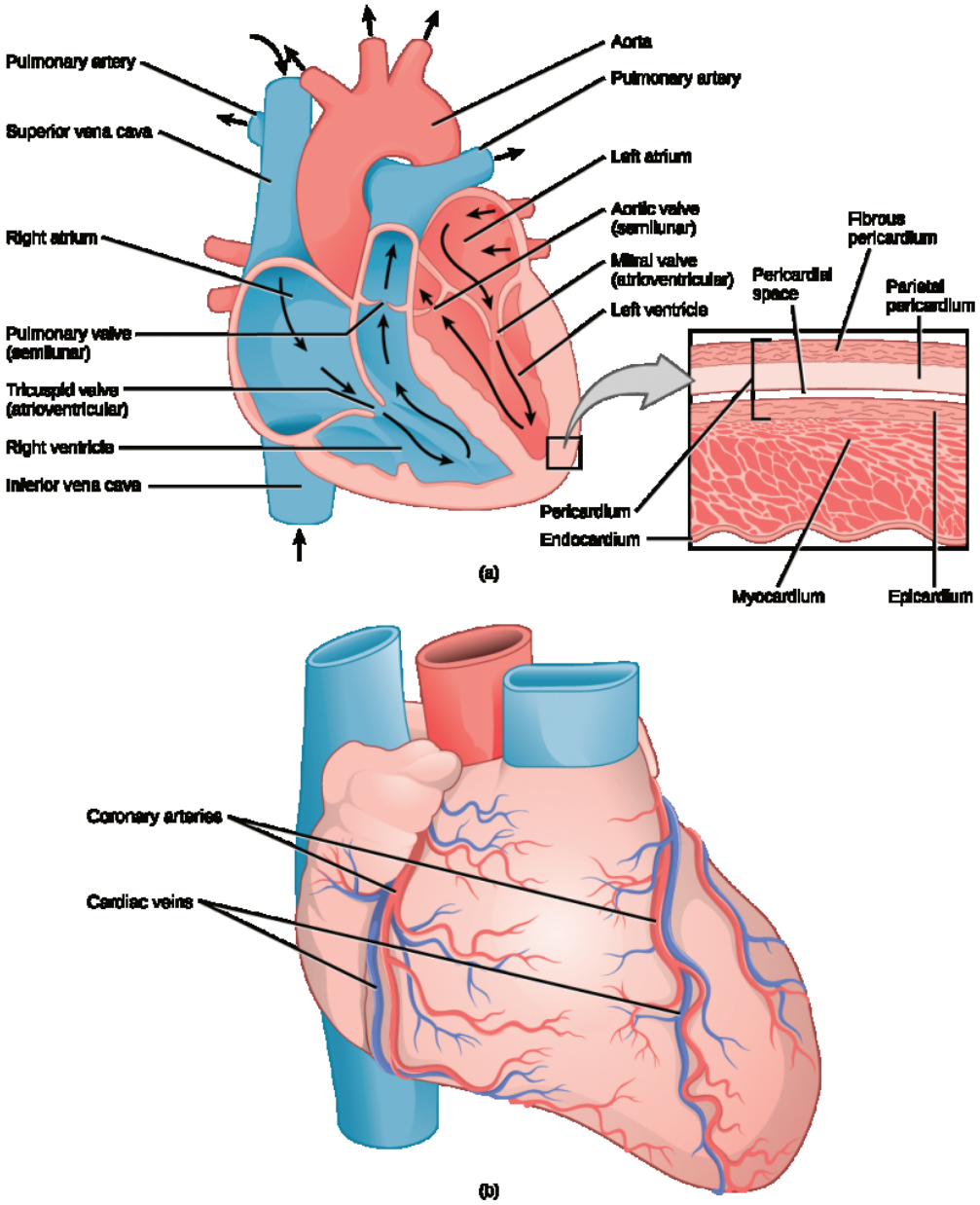


Figure 21.11. *(a) The heart is primarily made of a thick muscle layer, called the myocardium, surrounded by membranes. One-way valves separate the four chambers. (b) Blood vessels of the coronary system, including the coronary arteries and veins, keep the heart musculature oxygenated.*

Which of the following statements about the heart is false?

1. The mitral valve separates the left ventricle from the left atrium.
2. Blood travels through the bicuspid valve to the left atrium.
3. Both the aortic and the pulmonary valves are semilunar valves.
4. The mitral valve is an atrioventricular valve.

The heart is composed of three layers; the epicardium, the myocardium, and the endocardium, illustrated in Figure 21.11. The inner wall of the heart has a lining called the **endocardium**. The **myocardium** consists of

the heart muscle cells that make up the middle layer and the bulk of the heart wall. The outer layer of cells is called the **epicardium**, of which the second layer is a membranous layered structure called the **pericardium** that surrounds and protects the heart; it allows enough room for vigorous pumping but also keeps the heart in place to reduce friction between the heart and other structures.

The heart has its own blood vessels that supply the heart muscle with blood. The **coronary arteries**branch from the aorta and surround the outer surface of the heart like a crown. They diverge into capillaries where the heart muscle is supplied with oxygen before converging again into the **coronary veins** to take the deoxygenated blood back to the right atrium where the blood will be re-oxygenated through the pulmonary circuit. The heart muscle will die without a steady supply of blood. **Atherosclerosis** is the blockage of an artery by the buildup of fatty plaques. Because of the size (narrow) of the coronary arteries and their function in serving the heart itself, atherosclerosis can be deadly in these arteries. The slowdown of blood flow and subsequent oxygen deprivation that results from atherosclerosis causes severe pain, known as **angina**, and complete blockage of the arteries will cause **myocardial infarction**: the death of cardiac muscle tissue, commonly known as a heart attack.

The Cardiac Cycle

The main purpose of the heart is to pump blood through the body; it does so in a repeating sequence called the cardiac cycle. The **cardiac cycle** is the coordination of the filling and emptying of the heart of blood by electrical signals that cause the heart muscles to contract and relax. The human heart beats over 100,000 times per day. In each cardiac cycle, the heart contracts (**systole**), pushing out the blood and pumping it through the body; this is followed by a relaxation phase (**diastole**), where the heart fills with blood, as illustrated in Figure 21.12. The atria contract at the same time, forcing blood through the atrioventricular valves into the ventricles. Closing of the atrioventricular valves produces a monosyllabic "lup" sound. Following a brief delay, the ventricles contract at the same time forcing blood through the semilunar valves into the aorta and the artery transporting blood to the lungs (via the pulmonary artery). Closing of the semilunar valves produces a monosyllabic "dup" sound.

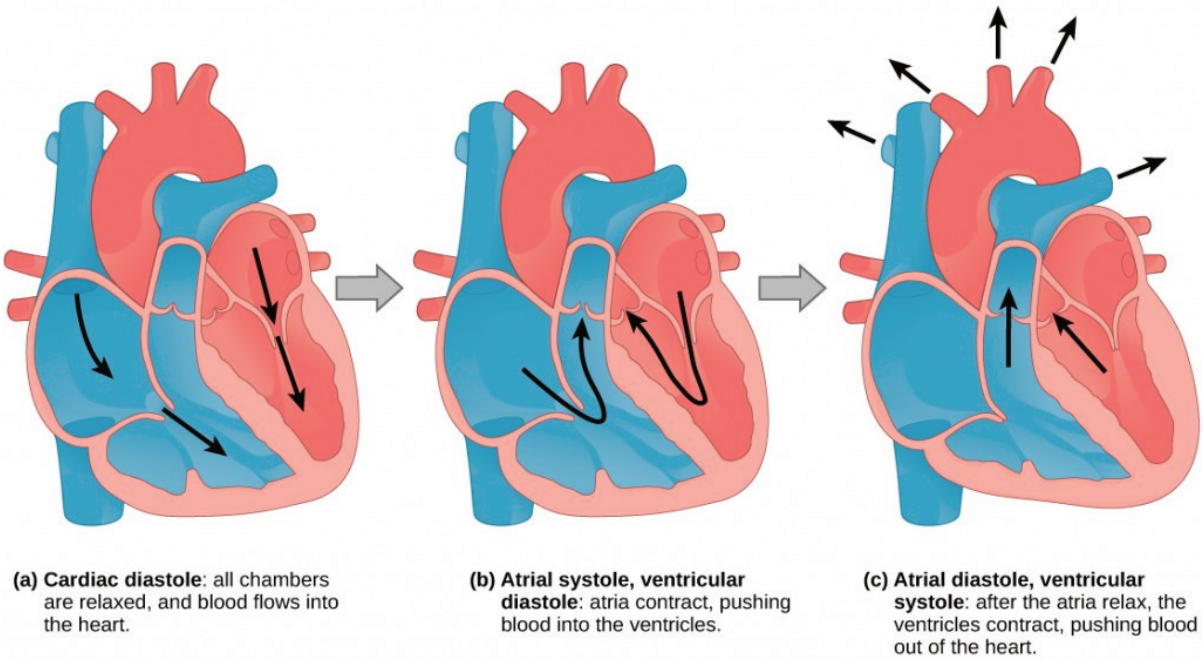


Figure 21.12. *During (a) cardiac diastole, the heart muscle is relaxed and blood flows into the heart. During (b)*

atrial systole, the atria contract, pushing blood into the ventricles. During (c) atrial diastole, the ventricles contract, forcing blood out of the heart.

The pumping of the heart is a function of the cardiac muscle cells, or cardiomyocytes, that make up the heart muscle. **Cardiomyocytes**, shown in Figure 21.13, are distinctive muscle cells that are striated like skeletal muscle but pump rhythmically and involuntarily like smooth muscle; they are connected by intercalated disks exclusive to cardiac muscle. They are self-stimulated for a period of time and isolated cardiomyocytes will beat if given the correct balance of nutrients and electrolytes.

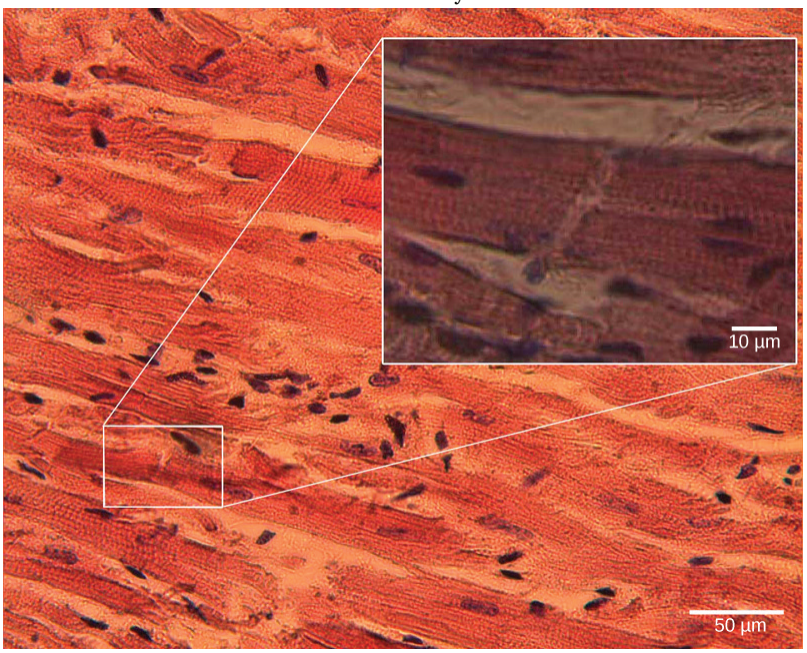


Figure 21.13. *Cardiomyocytes are striated muscle cells found in cardiac tissue. (credit: modification of work by Dr. S. Girod, Anton Becker; scale-bar data from Matt Russell)*

The autonomous beating of cardiac muscle cells is regulated by the heart's internal pacemaker that uses electrical signals to time the beating of the heart. The electrical signals and mechanical actions, illustrated in Figure 21.14, are intimately intertwined. The internal pacemaker starts at the **sinoatrial (SA) node**, which is located near the wall of the right atrium. Electrical charges spontaneously pulse from the SA node causing the two atria to contract in unison. The pulse reaches a second node, called the atrioventricular (AV) node, between the right atrium and right ventricle where it pauses for approximately 0.1 second before spreading to the walls of the ventricles. From the AV node, the electrical impulse enters the bundle of His, then to the left and right bundle branches extending through the interventricular septum. Finally, the Purkinje fibers conduct the impulse from the apex of the heart up the ventricular myocardium, and then the ventricles contract. This pause allows the atria to empty completely into the ventricles before the ventricles pump out the blood. The electrical impulses in the heart produce electrical currents that flow through the body and can be measured on the skin using electrodes. This information can be observed as an **electrocardiogram (ECG)**—a recording of the electrical impulses of the cardiac muscle.

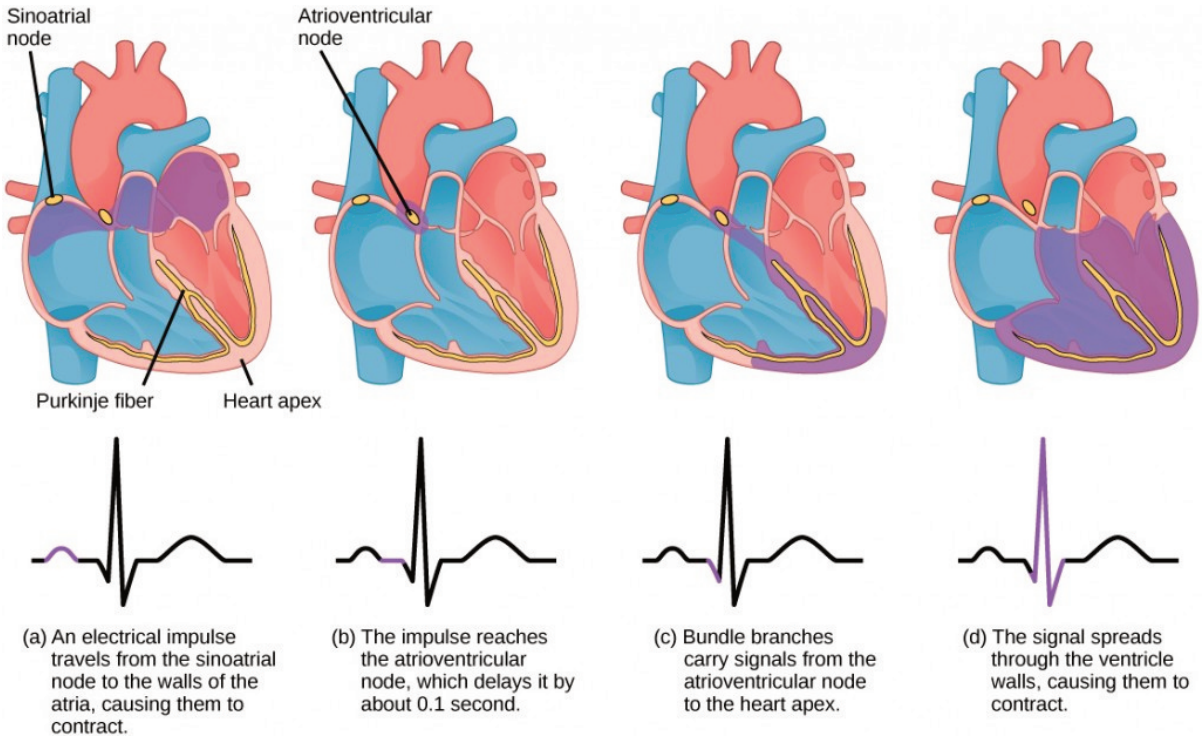


Figure 21.14. *The beating of the heart is regulated by an electrical impulse that causes the characteristic reading of an ECG. The signal is initiated at the sinoatrial valve. The signal then (a) spreads to the atria, causing them to contract. The signal is (b) delayed at the atrioventricular node before it is passed on to the (c) heart apex. The delay allows the atria to relax before the (d) ventricles contract. The final part of the ECG cycle prepares the heart for the next beat.*

Visit this site to see the heart's "pacemaker" in action.

Arteries, Veins, and Capillaries

The blood from the heart is carried through the body by a complex network of blood vessels (Figure 21.15). **Arteries** take blood away from the heart. The main artery is the aorta that branches into major arteries that take blood to different limbs and organs. These major arteries include the carotid artery that takes blood to the brain, the brachial arteries that take blood to the arms, and the thoracic artery that takes blood to the thorax and then into the hepatic, renal, and gastric arteries for the liver, kidney, and stomach, respectively. The iliac artery takes blood to the lower limbs. The major arteries diverge into minor arteries, and then smaller vessels called **arterioles**, to reach more deeply into the muscles and organs of the body.

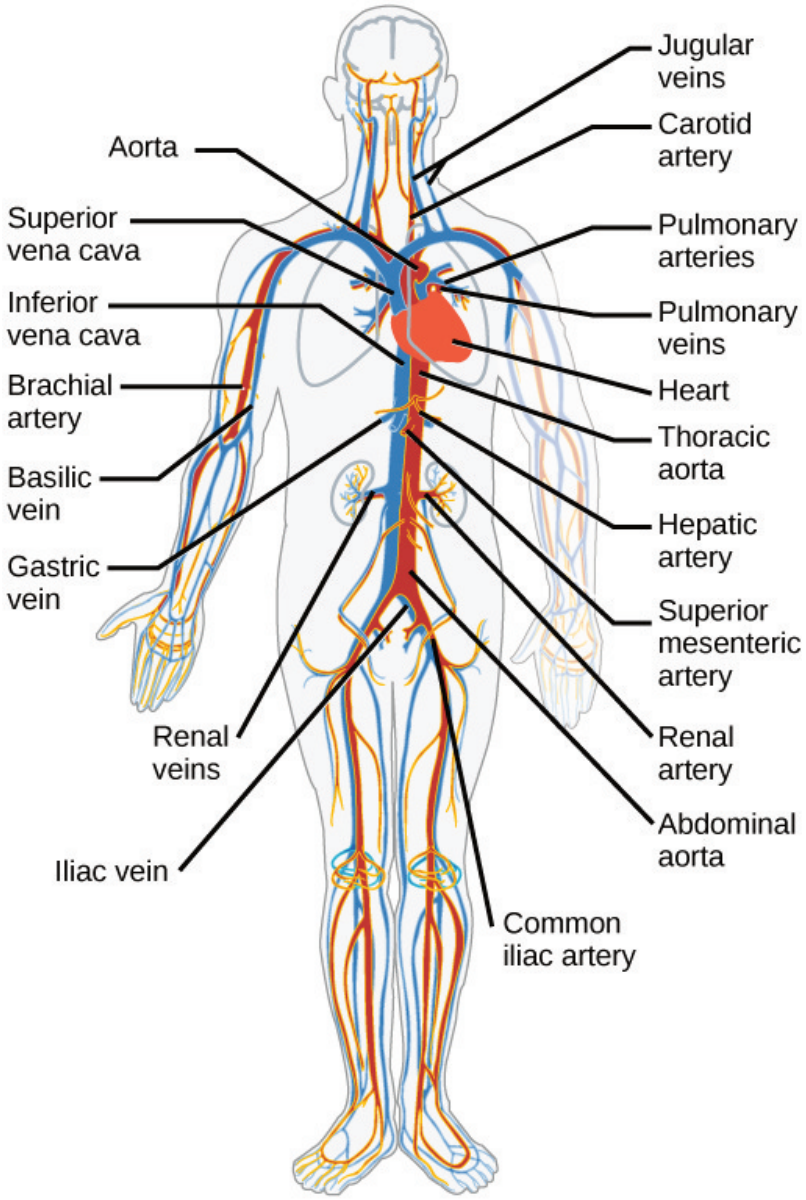


Figure 21.15. *The major human arteries and veins are shown. (credit: modification of work by Mariana Ruiz Villareal)*

Arterioles diverge into capillary beds. **Capillary beds** contain a large number (10 to 100) of **capillaries** that branch among the cells and tissues of the body. Capillaries are narrow-diameter tubes that can fit red blood cells through in single file and are the sites for the exchange of nutrients, waste, and oxygen with tissues at the cellular level. Fluid also crosses into the interstitial space from the capillaries. The capillaries converge again into **venules** that connect to minor veins that finally connect to major veins that take blood high in carbon dioxide back to the heart. **Veins** are blood vessels that bring blood back to the heart. The major veins drain blood from the same organs and limbs that the major arteries supply. Fluid is also brought back to the heart via the lymphatic system.

The structure of the different types of blood vessels reflects their function or layers. There are three distinct layers, or tunics, that form the walls of blood vessels (Figure 21.16). The first tunic is a smooth, inner lining

of endothelial cells that are in contact with the red blood cells. The endothelial tunic is continuous with the endocardium of the heart. In capillaries, this single layer of cells is the location of diffusion of oxygen and carbon dioxide between the endothelial cells and red blood cells, as well as the exchange site via endocytosis and exocytosis. The movement of materials at the site of capillaries is regulated by **vasoconstriction**, narrowing of the blood vessels, and **vasodilation,** widening of the blood vessels; this is important in the overall regulation of blood pressure.

Veins and arteries both have two further tunics that surround the endothelium: the middle tunic is composed of smooth muscle and the outermost layer is connective tissue (collagen and elastic fibers). The elastic connective tissue stretches and supports the blood vessels, and the smooth muscle layer helps regulate blood flow by altering vascular resistance through vasoconstriction and vasodilation. The arteries have thicker smooth muscle and connective tissue than the veins to accommodate the higher pressure and speed of freshly pumped blood. The veins are thinner walled as the pressure and rate of flow are much lower. In addition, veins are structurally different than arteries in that veins have valves to prevent the backflow of blood. Because veins have to work against gravity to get blood back to the heart, contraction of skeletal muscle assists with the flow of blood back to the heart.

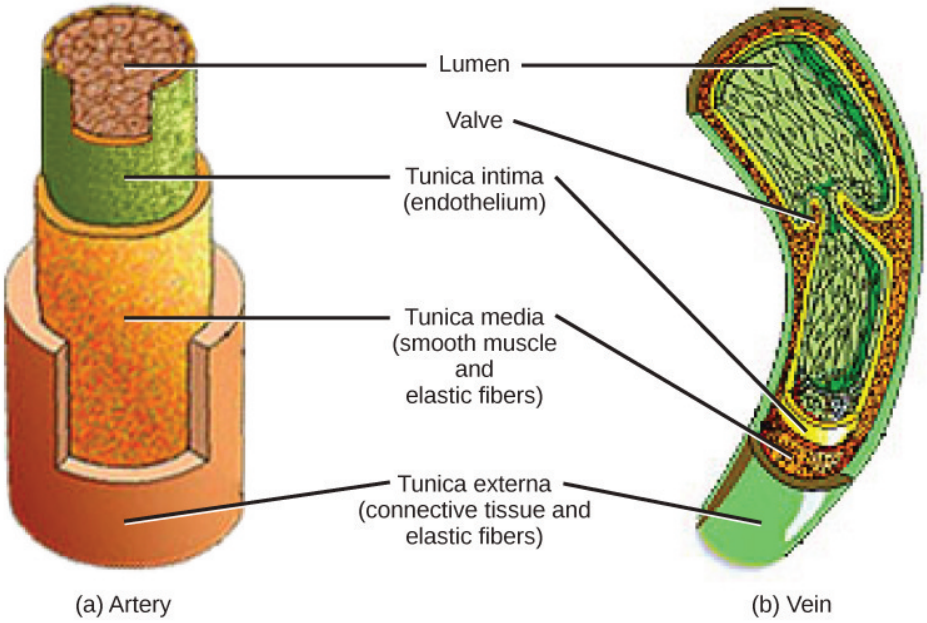


Figure 21.16. *Arteries and veins consist of three layers: an outer tunica externa, a middle tunica media, and an inner tunica intima. Capillaries consist of a single layer of epithelial cells, the tunica intima. (credit: modification of work by* NCI, NIH)

Summary

The heart muscle pumps blood through three divisions of the circulatory system: coronary, pulmonary, and systemic. There is one atrium and one ventricle on the right side and one atrium and one ventricle on the left side. The pumping of the heart is a function of cardiomyocytes, distinctive muscle cells that are striated like skeletal muscle but pump rhythmically and involuntarily like smooth muscle. The internal pacemaker starts at the sinoatrial node, which is located near the wall of the right atrium. Electrical charges pulse from the SA node causing the two atria to contract in unison; then the pulse reaches the atrioventricular node between the right

atrium and right ventricle. A pause in the electric signal allows the atria to empty completely into the ventricles before the ventricles pump out the blood. The blood from the heart is carried through the body by a complex network of blood vessels; arteries take blood away from the heart, and veins bring blood back to the heart.

Blood Flow and Blood Pressure Regulation

By the end of this section, you will be able to:

- Describe the system of blood flow through the body
- Describe how blood pressure is regulated

Blood pressure (BP) is the pressure exerted by blood on the walls of a blood vessel that helps to push blood through the body. Systolic blood pressure measures the amount of pressure that blood exerts on vessels while the heart is beating. The optimal systolic blood pressure is 120 mmHg. Diastolic blood pressure measures the pressure in the vessels between heartbeats. The optimal diastolic blood pressure is 80 mmHg. Many factors can affect blood pressure, such as hormones, stress, exercise, eating, sitting, and standing. Blood flow through the body is regulated by the size of blood vessels, by the action of smooth muscle, by one-way valves, and by the fluid pressure of the blood itself.

How Blood Flows Through the Body

Blood is pushed through the body by the action of the pumping heart. With each rhythmic pump, blood is pushed under high pressure and velocity away from the heart, initially along the main artery, the aorta. In the aorta, the blood travels at 30 cm/sec. As blood moves into the arteries, arterioles, and ultimately to the capillary beds, the rate of movement slows dramatically to about 0.026 cm/sec, one-thousand times slower than the rate of movement in the aorta. While the diameter of each individual arteriole and capillary is far narrower than the diameter of the aorta, and according to the law of continuity, fluid should travel faster through a narrower diameter tube, the rate is actually slower due to the overall diameter of all the combined capillaries being far greater than the diameter of the individual aorta.

The slow rate of travel through the capillary beds, which reach almost every cell in the body, assists with gas and nutrient exchange and also promotes the diffusion of fluid into the interstitial space. After the blood has passed through the capillary beds to the venules, veins, and finally to the main venae cavae, the rate of flow increases again but is still much slower than the initial rate in the aorta. Blood primarily moves in the veins by the rhythmic movement of smooth muscle in the vessel wall and by the action of the skeletal muscle as the body moves. Because most veins must move blood against the pull of gravity, blood is prevented from flowing backward in the veins by one-way valves. Because skeletal muscle contraction aids in venous blood flow,

it is important to get up and move frequently after long periods of sitting so that blood will not pool in the extremities.

Blood flow through the capillary beds is regulated depending on the body's needs and is directed by nerve and hormone signals. For example, after a large meal, most of the blood is diverted to the stomach by vasodilation of vessels of the digestive system and vasoconstriction of other vessels. During exercise, blood is diverted to the skeletal muscles through vasodilation while blood to the digestive system would be lessened through vasoconstriction. The blood entering some capillary beds is controlled by small muscles, called precapillary sphincters, illustrated in Figure 21.17. If the sphincters are open, the blood will flow into the associated branches of the capillary blood. If all of the sphincters are closed, then the blood will flow directly from the arteriole to the venule through the thoroughfare channel (see Figure 21.17). These muscles allow the body to precisely control when capillary beds receive blood flow. At any given moment only about 5-10% of our capillary beds actually have blood flowing through them.

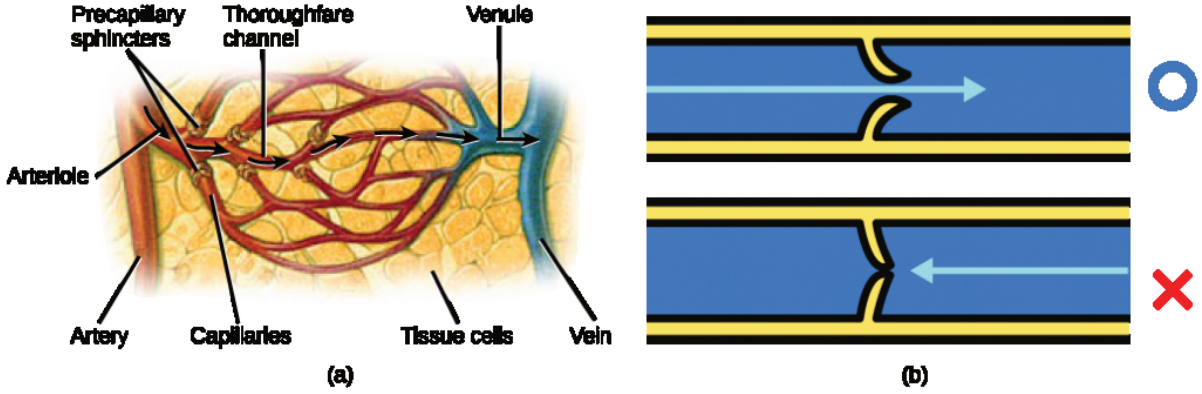


Figure 21.17. *(a) Precapillary sphincters are rings of smooth muscle that regulate the flow of blood through capillaries; they help control the location of blood flow to where it is needed. (b) Valves in the veins prevent blood from moving backward. (credit a: modification of work by NCI)*

Varicose veins are veins that become enlarged because the valves no longer close properly, allowing blood to flow backward. Varicose veins are often most prominent on the legs. Why do you think this is the case?

Visit this site to see the circulatory system's blood flow.

Proteins and other large solutes cannot leave the capillaries. The loss of the watery plasma creates a hyperosmotic solution within the capillaries, especially near the venules. This causes about 85% of the plasma that leaves the capillaries to eventually diffuses back into the capillaries near the venules. The remaining 15% of blood plasma drains out from the interstitial fluid into nearby lymphatic vessels (Figure 21.18). The fluid in the lymph is similar in composition to the interstitial fluid. The lymph fluid passes through lymph nodes before it returns to the heart via the vena cava. **Lymph nodes** are specialized organs that filter the lymph by percolation through a maze of connective tissue filled with white blood cells. The white blood cells remove infectious agents, such as bacteria and viruses, to clean the lymph before it returns to the bloodstream. After it is cleaned, the lymph returns to the heart by the action of smooth muscle pumping, skeletal muscle action, and one-way valves joining the returning blood near the junction of the venae cavae entering the right atrium of the heart.

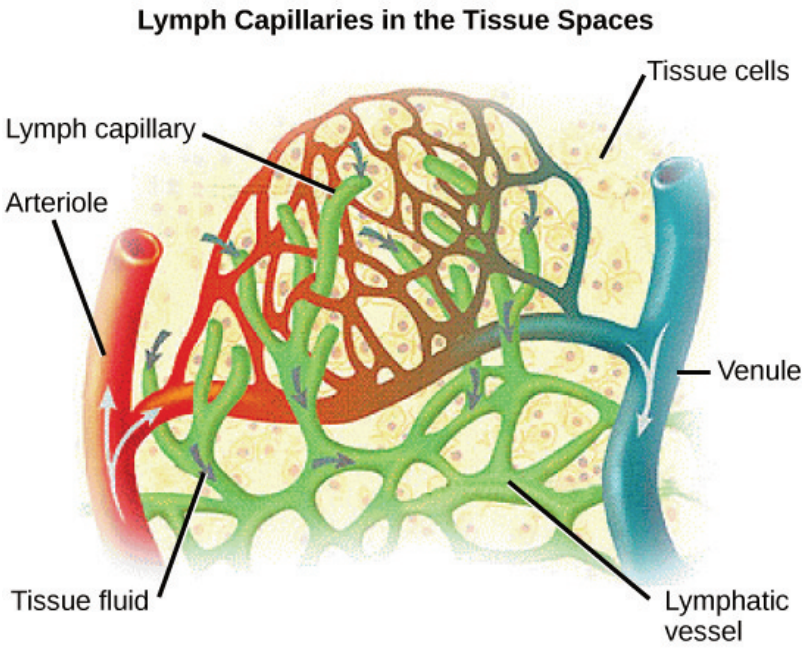


Figure 21.18. *Fluid from the capillaries moves into the interstitial space and lymph capillaries by diffusion down a pressure gradient and also by osmosis. Out of 7,200 liters of fluid pumped by the average heart in a day, over 1,500 liters is filtered. (credit: modification of work by NCI, NIH)*

Vertebrate Diversity in Blood Circulation

Blood circulation has evolved differently in vertebrates and may show variation in different animals for the required amount of pressure, organ and vessel location, and organ size. Animals with longs necks and those that live in cold environments have distinct blood pressure adaptations.

Long necked animals, such as giraffes, need to pump blood upward from the heart against gravity. The blood pressure required from the pumping of the left ventricle would be equivalent to 250 mm Hg (mm Hg = millimeters of mercury, a unit of pressure) to reach the height of a giraffe's head, which is 2.5 meters higher than the heart. However, if checks and balances were not in place, this blood pressure would damage the giraffe's brain, particularly if it was bending down to drink. These checks and balances include valves and feedback mechanisms that reduce the rate of cardiac output. Long-necked dinosaurs such as the sauropods had to pump blood even higher, up to ten meters above the heart. This would have required a blood pressure of more than 600 mm Hg, which could only have been achieved by an enormous heart. Evidence for such an enormous heart does not exist and mechanisms to reduce the blood pressure required include the slowing of metabolism as these animals grew larger. It is likely that they did not routinely feed on tree tops but grazed on the ground.

Living in cold water, whales need to maintain the temperature in their blood. This is achieved by the veins and arteries being close together so that heat exchange can occur. This mechanism is called a countercurrent heat exchanger. The blood vessels and the whole body are also protected by thick layers of blubber to prevent heat loss. In land animals that live in cold environments, thick fur and hibernation are used to retain heat and slow metabolism.

Blood Pressure

The pressure of the blood flow in the body is produced by the hydrostatic pressure of the fluid (blood) against the walls of the blood vessels. Fluid will move from areas of high to low hydrostatic pressures. In the arteries, the hydrostatic pressure near the heart is very high and blood flows to the arterioles where the rate of flow is slowed by the narrow openings of the arterioles. During systole, when new blood is entering the arteries, the artery walls stretch to accommodate the increase of pressure of the extra blood; during diastole, the walls return to normal because of their elastic properties. The blood pressure of the systole phase and the diastole phase, graphed in Figure 21.19, gives the two pressure readings for blood pressure. For example, 120/80 indicates a reading of 120 mm Hg during the systole and 80 mm Hg during diastole. Throughout the cardiac cycle, the blood continues to empty into the arterioles at a relatively even rate. This resistance to blood flow is called **peripheral resistance.**

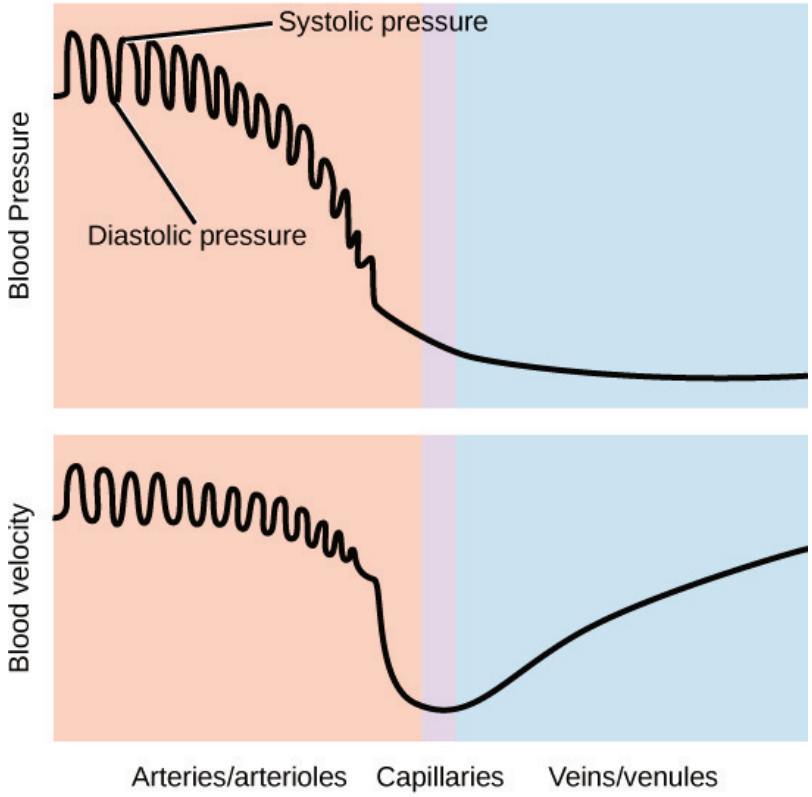


Figure 21.19. *Blood pressure is related to the blood velocity in the arteries and arterioles. In the capillaries and veins, the blood pressure continues to decease but velocity increases.*

Blood Pressure Regulation

Cardiac output is the volume of blood pumped by the heart in one minute. It is calculated by multiplying the number of heart contractions that occur per minute (heart rate) times the **stroke volume** (the volume of blood pumped into the aorta per contraction of the left ventricle). Therefore, cardiac output can be increased by increasing heart rate, as when exercising. However, cardiac output can also be increased by increasing stroke

volume, such as if the heart contracts with greater strength. Stroke volume can also be increased by speeding blood circulation through the body so that more blood enters the heart between contractions. During heavy exertion, the blood vessels relax and increase in diameter, offsetting the increased heart rate and ensuring adequate oxygenated blood gets to the muscles. Stress triggers a decrease in the diameter of the blood vessels, consequently increasing blood pressure. These changes can also be caused by nerve signals or hormones, and even standing up or lying down can have a great effect on blood pressure.

Summary

Blood primarily moves through the body by the rhythmic movement of smooth muscle in the vessel wall and by the action of the skeletal muscle as the body moves. Blood is prevented from flowing backward in the veins by one-way valves. Blood flow through the capillary beds is controlled by precapillary sphincters to increase and decrease flow depending on the body's needs and is directed by nerve and hormone signals. Lymph vessels take fluid that has leaked out of the blood to the lymph nodes where it is cleaned before returning to the heart. During systole, blood enters the arteries, and the artery walls stretch to accommodate the extra blood. During diastole, the artery walls return to normal. The blood pressure of the systole phase and the diastole phase gives the two pressure readings for blood pressure.

License

1.9 Nervous System Infections

Bacterial Diseases of the Nervous System

By the end of this section, you will be able to:

- Identify the most common bacteria that can cause infections of the nervous system
- Compare the major characteristics of specific bacterial diseases affecting the nervous system

Bacterial infections that affect the nervous system are serious and can be life-threatening. Fortunately, there are only a few bacterial species commonly associated with neurological infections.

Bacterial Meningitis

Bacterial meningitis is one of the most serious forms of meningitis. Bacteria that cause meningitis often gain access to the CNS through the bloodstream after trauma or as a result of the action of bacterial toxins. Bacteria may also spread from structures in the upper respiratory tract, such as the oropharynx, nasopharynx, sinuses, and middle ear. Patients with head wounds or cochlear implants (an electronic device placed in the inner ear) are also at risk for developing meningitis.

Many of the bacteria that can cause **meningitis** are commonly found in healthy people. The most common causes of non-neonatal bacterial meningitis are ***Neisseria meningitidis***, ***Streptococcus pneumoniae***, and ***Haemophilus influenzae***. All three of these bacterial pathogens are spread from person to person by respiratory secretions. Each can colonize and cross through the mucous membranes of the oropharynx and nasopharynx, and enter the blood. Once in the blood, these pathogens can disseminate throughout the body and are capable of both establishing an infection and triggering inflammation in any body site, including the meninges (Figure 1.). Without appropriate systemic antibacterial therapy, the case-fatality rate can be as high as 70%, and 20% of those survivors may be left with irreversible nerve damage or tissue destruction, resulting in hearing loss, neurologic disability, or loss of a limb. Mortality rates are much lower (as low as 15%) in populations where appropriate therapeutic drugs and preventive vaccines are available.

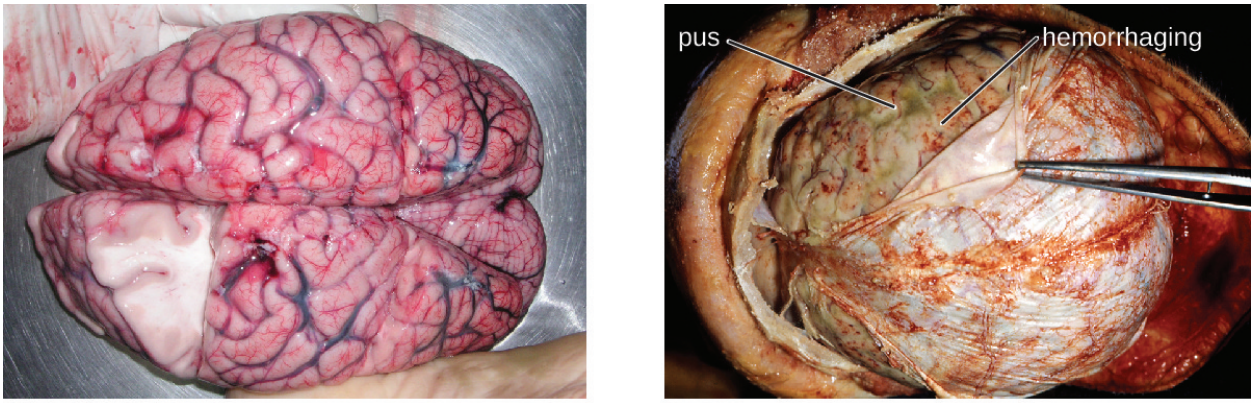


Figure 1. *(a) A normal human brain removed during an autopsy. (b) The brain of a patient who died from bacterial meningitis. Note the pus under the dura mater (being retracted by the forceps) and the red hemorrhagic foci on the meninges. (credit b: modification of work by the Centers for Disease Control and Prevention)*

A variety of other bacteria, including ***Listeria monocytogenes*** and ***Escherichia coli***, are also capable of causing meningitis. These bacteria cause infections of the arachnoid mater and CSF after spreading through the circulation in blood or by spreading from an infection of the sinuses or nasopharynx. ***Streptococcus agalactiae***, commonly found in the microbiota of the vagina and gastrointestinal tract, can also cause bacterial meningitis in newborns after transmission from the mother either before or during birth.

The profound inflammation caused by these microbes can result in early symptoms that include severe headache, fever, confusion, nausea, vomiting, photophobia, and stiff neck. Systemic inflammatory responses associated with some types of bacterial meningitis can lead to hemorrhaging and purpuric lesions on skin, followed by even more severe conditions that include shock, convulsions, coma, and death—in some cases, in the span of just a few hours.

Diagnosis of bacterial meningitis is best confirmed by analysis of CSF obtained by a **lumbar puncture**. Abnormal levels of **polymorphonuclear neutrophils (PMNs)** (> 10 PMNs/mm^3), glucose (< 45 mg/dL), and protein (> 45 mg/dL) in the CSF are suggestive of bacterial meningitis. Characteristics of specific forms of bacterial meningitis are detailed in the subsections that follow.

Meningococcal Meningitis

Meningococcal meningitis is a serious infection caused by the gram-negative coccus *N. meningitidis*. In some cases, death can occur within a few hours of the onset of symptoms. Nonfatal cases can result in irreversible nerve damage, resulting in hearing loss and brain damage, or amputation of extremities because of tissue necrosis.

Meningococcal meningitis can infect people of any age, but its prevalence is highest among infants, adolescents, and young adults. Meningococcal meningitis was once the most common cause of meningitis epidemics in human populations. This is still the case in a swath of sub-Saharan Africa known as the **meningitis belt**, but meningococcal meningitis epidemics have become rare in most other regions, thanks to meningococcal vaccines. However, outbreaks can still occur in communities, schools, colleges, prisons, and other populations where people are in close direct contact.

N. meningitidis has a high affinity for mucosal membranes in the oropharynx and nasopharynx. Contact with

respiratory secretions containing N. *meningitidis* is an effective mode of transmission. The pathogenicity of N. *meningitidis* is enhanced by **virulence factors** that contribute to the rapid progression of the disease. These include **lipooligosaccharide (LOS) endotoxin**, **type IV pili** for attachment to host tissues, and **polysaccharide capsules** that help the cells avoid phagocytosis and complement-mediated killing. Additional virulence factors include **IgA protease** (which breaks down IgA antibodies), the **invasion factors** Opa, Opc, and porin (which facilitate transcellular entry through the **blood-brain barrier**), **iron-uptake factors** (which strip heme units from hemoglobin in host cells and use them for growth), and **stress proteins** that protect bacteria from reactive oxygen molecules.

A unique sign of meningococcal meningitis is the formation of a **petechial rash** on the skin or mucous membranes, characterized by tiny, red, flat, hemorrhagic lesions. This rash, which appears soon after disease onset, is a response to LOS endotoxin and adherence virulence factors that disrupt the endothelial cells of capillaries and small veins in the skin. The blood vessel disruption triggers the formation of tiny blood clots, causing blood to leak into the surrounding tissue. As the infection progresses, the levels of virulence factors increase, and the hemorrhagic lesions can increase in size as blood continues to leak into tissues. Lesions larger than 1.0 cm usually occur in patients developing shock, as virulence factors cause increased hemorrhage and clot formation. Sepsis, as a result of systemic damage from meningococcal virulence factors, can lead to rapid multiple organ failure, shock, disseminated intravascular coagulation, and death.

Because meningococcoal meningitis progresses so rapidly, a greater variety of clinical specimens are required for the timely detection of N. *meningitidis*. Required specimens can include blood, CSF, naso- and oropharyngeal swabs, urethral and endocervical swabs, petechial aspirates, and biopsies. Safety protocols for handling and transport of specimens suspected of containing N. *meningitidis* should always be followed, since cases of fatal meningococcal disease have occurred in healthcare workers exposed to droplets or aerosols from patient specimens. Prompt presumptive diagnosis of meningococcal meningitis can occur when CSF is directly evaluated by Gram stain, revealing extra- and intracellular gram-negative diplococci with a distinctive coffee-bean microscopic morphology associated with **PMNs** (Figure 2.). Identification can also be made directly from CSF using latex agglutination and immunochromatographic rapid diagnostic tests specific for N. *meningitidis*. Species identification can also be performed using DNA sequence-based typing schemes for hypervariable outer membrane proteins of N. *meningitidis*, which has replaced sero(sub)typing.

Meningococcal infections can be treated with antibiotic therapy, and third-generation **cephalosporins** are most often employed. However, because outcomes can be negative even with treatment, preventive vaccination is the best form of treatment. In 2010, countries in Africa's **meningitis belt** began using a new serogroup A meningococcal conjugate vaccine. This program has dramatically reduced the number of cases of meningococcal meningitis by conferring individual and herd immunity.

Twelve different **capsular serotypes** of N. *meningitidis* are known to exist. Serotypes A, B, C, W, X, and Y are the most prevalent worldwide. The CDC recommends that children between 11–12 years of age be vaccinated with a single dose of a quadrivalent vaccine that protects against serotypes A, C, W, and Y, with a booster at age 16. An additional booster or injections of serogroup B meningococcal vaccine may be given to individuals in high-risk settings (such as epidemic outbreaks on college campuses).

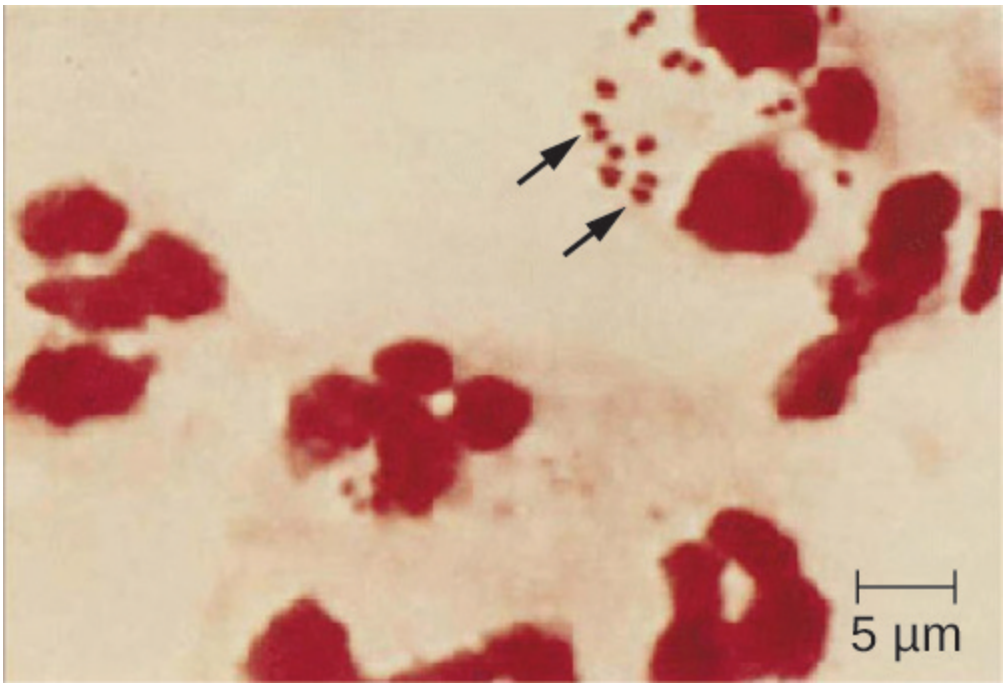


Figure 2. *N. meningitidis (arrows) associated with neutrophils (the larger stained cells) in a gram-stained CSF sample. (credit: modification of work by the Centers for Disease Control and Prevention)*

MENINGITIS ON CAMPUS

College students living in dorms or communal housing are at increased risk for contracting epidemic meningitis. From 2011 to 2015, there have been at least nine meningococcal outbreaks on college campuses in the United States. These incidents involved a total of 43 students (of whom four died). In spite of rapid diagnosis and aggressive antimicrobial treatment, several of the survivors suffered from amputations or serious neurological problems.

Prophylactic vaccination of first-year college students living in dorms is recommended by the CDC, and insurance companies now cover meningococcal vaccination for students in college dorms. Some colleges have mandated vaccination with meningococcal conjugate vaccine for certain students entering college (Figure 3.).

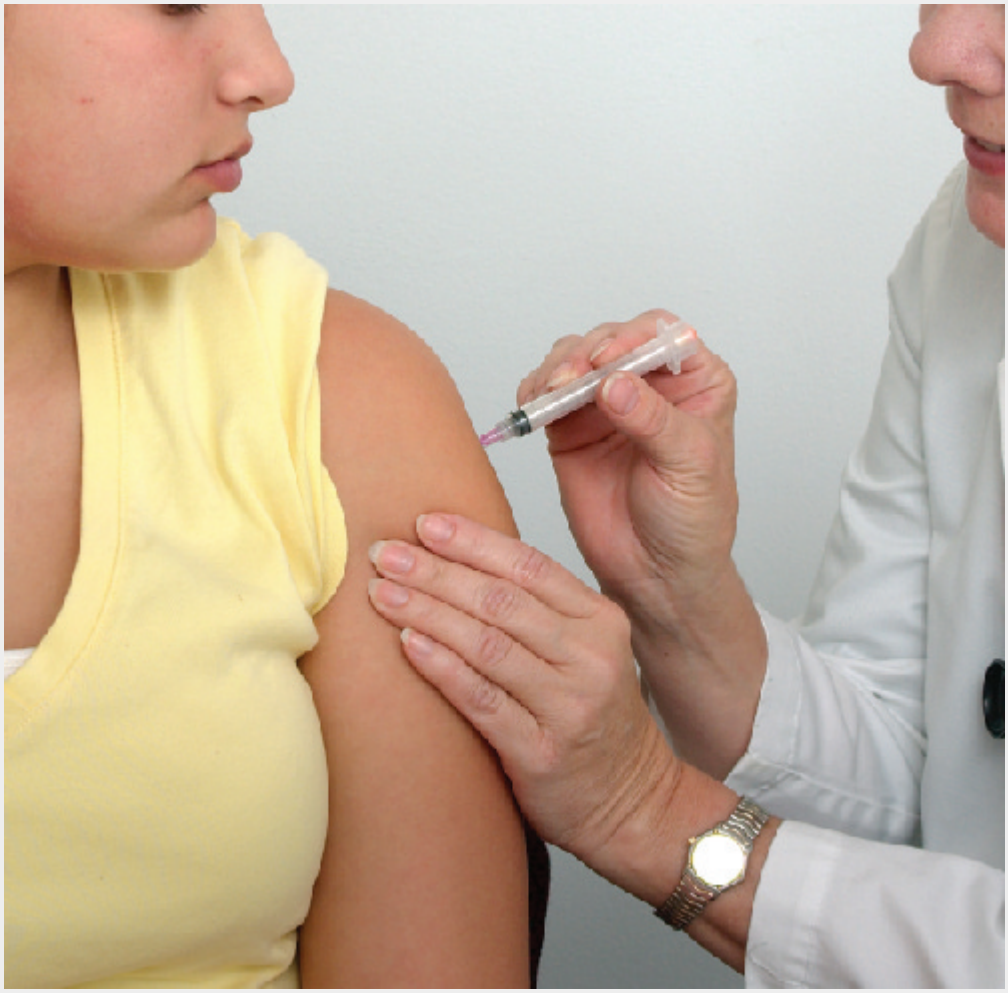


Figure 3. *To prevent campus outbreaks, some colleges now require students to be vaccinated against meningogoccal meningitis. (credit: modification of work by James Gathany, Centers for Disease Control and Prevention)*

Pneumococcal Meningitis

Pneumococcal meningitis is caused by the encapsulated gram-positive bacterium *S. pneumoniae*(pneumococcus, also called strep pneumo). This organism is commonly found in the **microbiota** of the pharynx of 30–70% of young children, depending on the sampling method, while *S. pneumoniae* can be found in fewer than 5% of healthy adults. Although it is often present without disease symptoms, this microbe can cross the **blood-brain barrier** in susceptible individuals. In some cases, it may also result in septicemia. Since the introduction of the **Hib vaccine**, *S. pneumoniae* has become the leading cause of meningitis in humans aged 2 months through adulthood.

S. pneumoniae can be identified in **CSF** samples using gram-stained specimens, latex agglutination,

and **immunochromatographic RDT** specific for *S. pneumoniae*. In gram-stained samples, *S. pneumoniae* appears as gram-positive, **lancet-shaped diplococci** (Figure 4.). Identification of *S. pneumoniae* can also be achieved using cultures of CSF and blood, and at least 93 distinct serotypes can be identified based on the **quellung reaction** to unique capsular polysaccharides. PCR and RT-PCR assays are also available to confirm identification.

Major **virulence factors** produced by *S. pneumoniae* include **PI-1 pilin** for adherence to host cells (pneumococcal adherence) and **virulence factor B** (PavB) for attachment to cells of the respiratory tract; **choline-binding proteins** (cbpA) that bind to epithelial cells and interfere with immune factors IgA and C3; and the cytoplasmic bacterial toxin **pneumolysin** that triggers an inflammatory response.

With the emergence of drug-resistant strains of *S. pneumoniae*, pneumococcal meningitis is typically treated with broad-spectrum antibiotics, such as **levofloxacin**, **cefotaxime**, **penicillin**, or other **β-lactam** antibiotics.

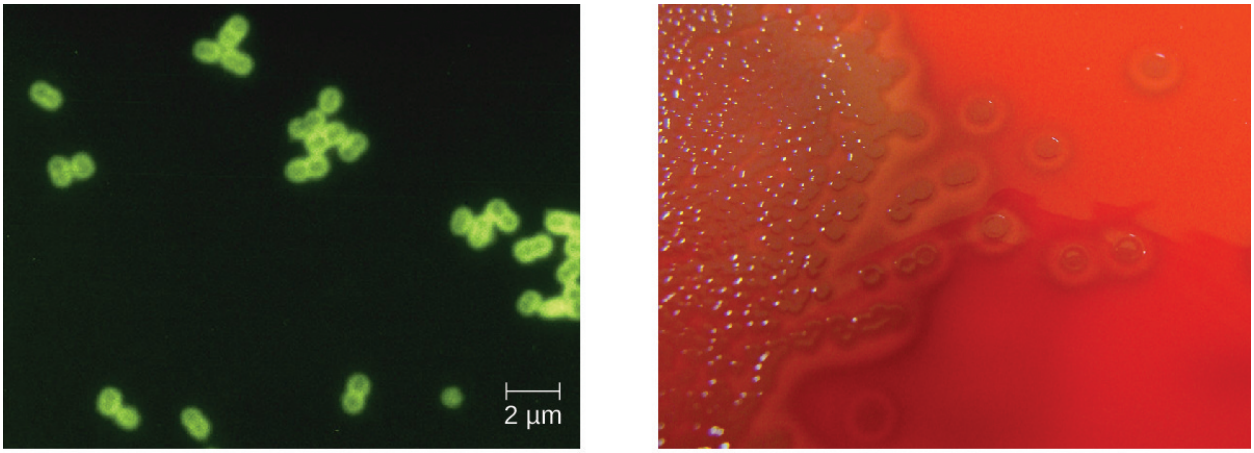


Figure 4. *(a) Digitally colorized fluorescent antibody stained micrograph of Streptococcus pneumoniae in CSF. (b) S. pneumoniae growing on blood agar. (credit a: modification of work by the Centers for Disease Control and Prevention; credit b: modification of work by Nathan Reading)*

Haemophilus influenzae Type b

Meningitis due to *H. influenzae* serotype b (Hib), an encapsulated pleomorphic gram-negative coccobacilli, is now uncommon in most countries, because of the use of the effective **Hib vaccine**. Without the use of the Hib vaccine, *H. influenzae* can be the primary cause of meningitis in children 2 months thru 5 years of age. *H. influenzae* can be found in the throats of healthy individuals, including infants and young children. By five years of age, most children have developed immunity to this microbe. Infants older than 2 months of age, however, do not produce a sufficient protective antibody response and are susceptible to serious disease. The intracranial pressure caused by this infection leads to a 5% mortality rate and 20% incidence of deafness or brain damage in survivors.

H. influenzae produces at least 16 different virulence factors, including **LOS**, which triggers inflammation, and *Haemophilus* adhesion and penetration factor (Hap), which aids in attachment and invasion into respiratory epithelial cells. The bacterium also has a polysaccharide capsule that helps it avoid phagocytosis, as well as factors such as **IgA1 protease** and **P2 protein** that allow it to evade antibodies secreted from mucous membranes. In addition, factors such as **hemoglobin-binding protein (Hgp)** and **transferrin-binding protein (Tbp)** acquire iron from hemoglobin and transferrin, respectively, for bacterial growth.

Preliminary diagnosis of *H. influenzae* infections can be made by direct PCR and a smear of **CSF**. Stained smears will reveal intracellular and extracellular PMNs with small, pleomorphic, gram-negative coccobacilli or filamentous forms that are characteristic of *H. influenzae*. Initial confirmation of this genus can be based on its fastidious growth on chocolate agar. Identification is confirmed with requirements for exogenous biochemical growth cofactors NAD and heme (by MALDI-TOF), latex agglutination, and RT-PCR.

Meningitis caused by *H. influenzae* is usually treated with **doxycycline**, **fluoroquinolones**, second- and third-generation **cephalosporins**, and **carbapenems**. The best means of preventing *H. influenza* infection is with the use of the **Hib polysaccharide conjugate vaccine**. It is recommended that all children receive this vaccine at 2, 4, and 6 months of age, with a final booster dose at 12 to 15 months of age.

Neonatal Meningitis

S. agalactiae, **Group B streptococcus (GBS)**, is an encapsulated gram-positive bacterium that is the most common cause of **neonatal meningitis**, a term that refers to meningitis occurring in babies up to 3 months of age. *S. agalactiae* can also cause meningitis in people of all ages and can be found in the urogenital and gastrointestinal **microbiota** of about 10–30% of humans.

Neonatal infection occurs as either early onset or late-onset disease. Early onset disease is defined as occurring in infants up to 7 days old. The infant initially becomes infected by *S. agalactiae* during childbirth, when the bacteria may be transferred from the mother's vagina. Incidence of early onset neonatal meningitis can be greatly reduced by giving intravenous antibiotics to the mother during labor.

Late-onset neonatal meningitis occurs in infants between 1 week and 3 months of age. Infants born to mothers with *S. agalactiae* in the urogenital tract have a higher risk of late-onset menigitis, but late-onset infections can be transmitted from sources other than the mother; often, the source of infection is unknown. Infants who are born prematurely (before 37 weeks of pregnancy) or to mothers who develop a fever also have a greater risk of contracting late-onset neonatal meningitis.

Signs and symptoms of early onset disease include temperature instability, **apnea** (cessation of breathing), **bradycardia** (slow heart rate), **hypotension**, difficulty feeding, irritability, and limpness. When asleep, the baby may be difficult to wake up. Symptoms of late-onset disease are more likely to include seizures, bulging fontanel (soft spot), stiff neck, **hemiparesis** (weakness on one side of the body), and **opisthotonos** (rigid body with arched back and head thrown backward).

S. agalactiae produces at least 12 virulence factors that include FbsA that attaches to host cell surface proteins, **PI-1 pili** that promotes the invasion of human endothelial cells, a polysaccharide capsule that prevents the activation of the alternative complement pathway and inhibits phagocytosis, and the toxin **CAMP factor**, which forms pores in host cell membranes and binds to IgG and IgM antibodies.

Diagnosis of neonatal meningitis is often, but not uniformly, confirmed by positive results from cultures of **CSF** or blood. Tests include routine culture, antigen detection by enzyme immunoassay, serotyping of different capsule types, PCR, and RT-PCR. It is typically treated with β-lactam antibiotics such as intravenous **penicillin** or **ampicillin** plus **gentamicin**. Even with treatment, roughly 10% mortality is seen in infected neonates.

- Which groups are most vulnerable to each of the bacterial meningitis diseases?
- For which of the bacterial meningitis diseases are there vaccines presently available?
- Which organism can cause epidemic meningitis?

Clostridium-Associated Diseases

Species in the genus ***Clostridium*** are gram-positive, endospore-forming rods that are obligate anaerobes. Endospores of *Clostridium* spp. are widespread in nature, commonly found in soil, water, feces, sewage, and marine sediments. *Clostridium* spp. produce more types of protein exotoxins than any other bacterial genus, including two exotoxins with protease activity that are the most potent known biological toxins: **botulinum neurotoxin** (BoNT) and **tetanus neurotoxin** (TeNT). These two toxins have lethal doses of 0.2–10 ng per kg body weight.

BoNT can be produced by unique strains of *C. butyricum*, and *C. baratii*; however, it is primarily associated with *C. botulinum* and the condition of botulism. TeNT, which causes tetanus, is only produced by *C. tetani*. These powerful neural exotoxins are the primary virulence factors for these pathogens.

Diagnosis of tetanus or botulism typically involves bioassays that detect the presence of BoNT and TeNT in fecal specimens, blood (serum), or suspect foods. In addition, both *C. botulinum* and *C. tetani* can be isolated and cultured using commercially available media for anaerobes. ELISA and RT-PCR tests are also available.

Tetanus

Tetanus is a noncommunicable disease characterized by uncontrollable muscle spasms (contractions) caused by the action of TeNT. It generally occurs when *C. tetani* infects a wound and produces TeNT, which rapidly binds to neural tissue, resulting in an intoxication (poisoning) of neurons. Depending on the site and extent of infection, cases of tetanus can be described as localized, cephalic, or generalized. Generalized tetanus that occurs in a newborn is called neonatal tetanus.

Localized tetanus occurs when TeNT only affects the muscle groups close to the injury site. There is no CNS involvement, and the symptoms are usually mild, with localized muscle spasms caused by a dysfunction in the surrounding neurons. Individuals with partial immunity—especially previously vaccinated individuals who neglect to get the recommended booster shots—are most likely to develop localized tetanus as a result of *C. tetani* infecting a puncture wound.

Cephalic tetanus is a rare, localized form of tetanus generally associated with wounds on the head or face. In rare cases, it has occurred in cases of otitis media (middle ear infection). Cephalic tetanus often results in patients seeing double images, because of the spasms affecting the muscles that control eye movement.

Both localized and cephalic tetanus may progress to generalized tetanus—a much more serious condition—if TeNT is able to spread further into body tissues. In generalized tetanus, TeNT enters neurons of the PNS. From there, TeNT travels from the site of the wound, usually on an extremity of the body, retrograde (back up) to inhibitory neurons in the CNS. There, it prevents the release of **gamma aminobutyric acid** (GABA), the neurotransmitter responsible for muscle relaxation. The resulting muscle spasms often first occur in the jaw muscles, leading to the characteristic symptom of **lockjaw** (inability to open the mouth). As the toxin progressively continues to block neurotransmitter release, other muscles become involved, resulting in uncontrollable, sudden muscle spasms that are powerful enough to cause tendons to rupture and bones to fracture. Spasms in the muscles in the neck, back, and legs may cause the body to form a rigid, stiff arch, a posture called **opisthotonos** (Figure 5.). Spasms in the larynx, diaphragm, and muscles of the chest restrict the patient's ability to swallow and breathe, eventually leading to death by asphyxiation (insufficient supply of oxygen).

Neonatal tetanus typically occurs when the stump of the umbilical cord is contaminated with spores of *C.*

tetani after delivery. Although this condition is rare in the United States, neonatal tetanus is a major cause of infant mortality in countries that lack maternal immunization for tetanus and where birth often occurs in unsanitary conditions. At the end of the first week of life, infected infants become irritable, feed poorly, and develop rigidity with spasms. Neonatal tetanus has a very poor prognosis with a mortality rate of 70%–100%.

Treatment for patients with tetanus includes assisted breathing through the use of a ventilator, wound debridement, fluid balance, and antibiotic therapy with metronidazole or penicillin to halt the growth of *C. tetani*. In addition, patients are treated with **TeNT antitoxin**, preferably in the form of human immunoglobulin to neutralize nonfixed toxin and benzodiazepines to enhance the effect of GABA for muscle relaxation and anxiety.

A **tetanus toxoid (TT) vaccine** is available for protection and prevention of tetanus. It is the T component of vaccines such as DTaP, Tdap, and Td. The CDC recommends children receive doses of the DTaP vaccine at 2, 4, 6, and 15–18 months of age and another at 4–6 years of age. One dose of Td is recommended for adolescents and adults as a TT booster every 10 years.

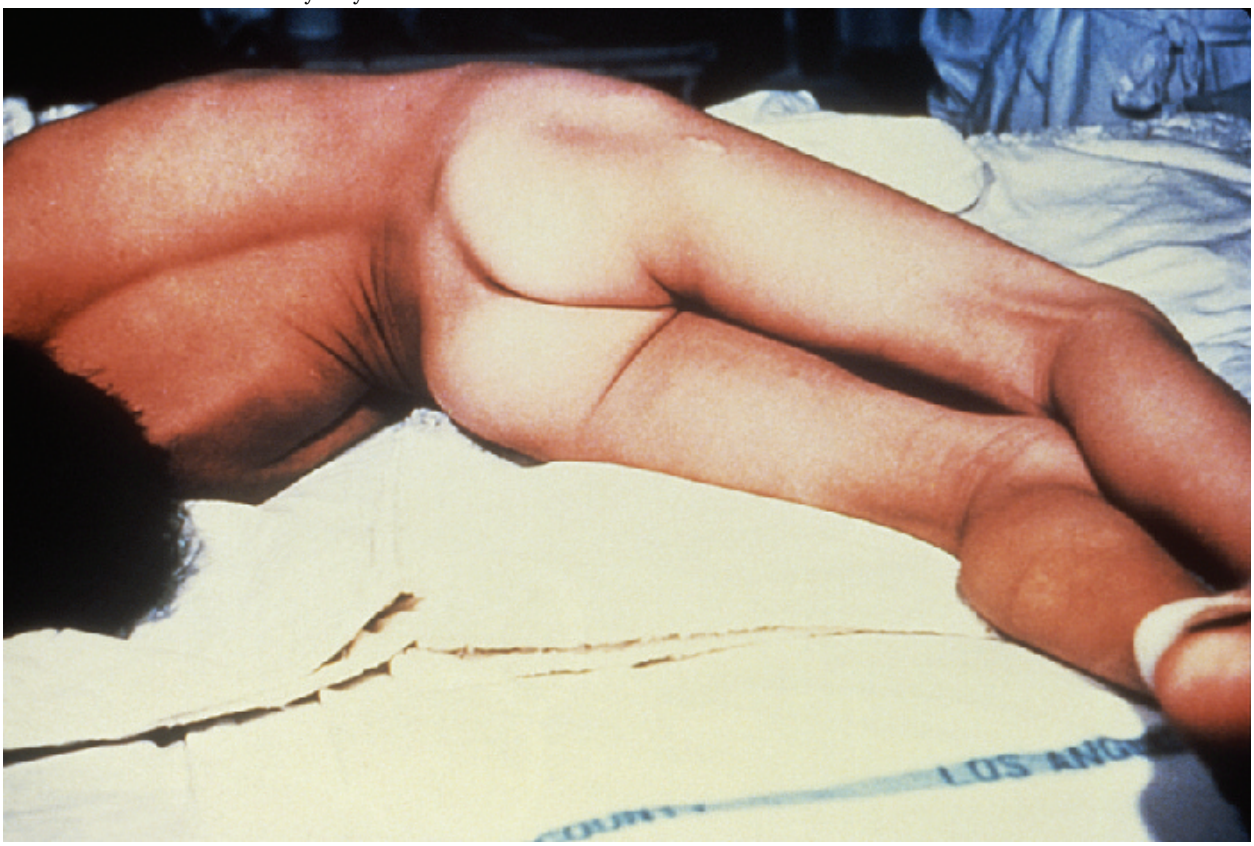


Figure 5. *A tetanus patient exhibiting the rigid body posture known as opisthotonos. (credit: Centers for Disease Control and Prevention)*

Botulism

Botulism is a rare but frequently fatal illness caused by intoxication by **BoNT**. It can occur either as the result of an infection by *C. botulinum*, in which case the bacteria produce BoNT *in vivo*, or as the result of a direct introduction of BoNT into tissues.

Infection and production of BoNT *in vivo* can result in **wound botulism**, infant botulism, and adult intestinal

toxemia. Wound botulism typically occurs when *C. botulinum* is introduced directly into a wound after a traumatic injury, deep puncture wound, or injection site. Infant botulism, which occurs in infants younger than 1 year of age, and adult intestinal toxemia, which occurs in immunocompromised adults, results from ingesting *C. botulinum* endospores in food. The endospores germinate in the body, resulting in the production of BoNT in the intestinal tract.

Intoxications occur when BoNT is produced outside the body and then introduced directly into the body through food (**foodborne botulism**), air (**inhalation botulism**), or a clinical procedure (**iatrogenic botulism**). Foodborne botulism, the most common of these forms, occurs when BoNT is produced in contaminated food and then ingested along with the food. Inhalation botulism is rare because BoNT is unstable as an aerosol and does not occur in nature; however, it can be produced in the laboratory and was used (unsuccessfully) as a bioweapon by terrorists in Japan in the 1990s. A few cases of accidental inhalation botulism have also occurred. Iatrogenic botulism is also rare; it is associated with injections of BoNT used for cosmetic purposes.

When BoNT enters the bloodstream in the gastrointestinal tract, wound, or lungs, it is transferred to the neuromuscular junctions of motor neurons where it binds irreversibly to presynaptic membranes and prevents the release of **acetylcholine** from the presynaptic terminal of motor neurons into the neuromuscular junction. The consequence of preventing acetylcholine release is the loss of muscle activity, leading to muscle relaxation and eventually paralysis.

If BoNT is absorbed through the gastrointestinal tract, early symptoms of botulism include blurred vision, drooping eyelids, difficulty swallowing, abdominal cramps, nausea, vomiting, constipation, or possibly diarrhea. This is followed by progressive **flaccid paralysis**, a gradual weakening and loss of control over the muscles. A patient's experience can be particularly terrifying, because hearing remains normal, consciousness is not lost, and he or she is fully aware of the progression of his or her condition. In infants, notable signs of botulism include weak cry, decreased ability to suckle, and hypotonia (limpness of head or body). Eventually, botulism ends in death from respiratory failure caused by the progressive paralysis of the muscles of the upper airway, diaphragm, and chest.

Botulism is treated with an **antitoxin** specific for BoNT. If administered in time, the antitoxin stops the progression of paralysis but does not reverse it. Once the antitoxin has been administered, the patient will slowly regain neurological function, but this may take several weeks or months, depending on the severity of the case. During recovery, patients generally must remain hospitalized and receive breathing assistance through a ventilator.

- How frequently should the tetanus vaccination be updated in adults?
- What are the most common causes of botulism?
- Why is botulism not treated with an antibiotic?

MEDICINAL USES OF BOTULINUM TOXIN

Although it is the most toxic biological material known to man, botulinum toxin is often intentionally injected into people to treat other conditions. Type A botulinum toxin is used cosmetically to reduce wrinkles. The injection of minute quantities of this toxin into the face causes the relaxation of facial muscles, thereby giving the skin a smoother appearance. Eyelid twitching and crossed eyes can also be treated with botulinum toxin injections. Other uses of this toxin include the treatment of hyperhidrosis (excessive sweating). In fact, botulinum toxin can be used

to moderate the effects of several other apparently nonmicrobial diseases involving inappropriate nerve function. Such diseases include cerebral palsy, multiple sclerosis, and Parkinson's disease. Each of these diseases is characterized by a loss of control over muscle contractions; treatment with botulinum toxin serves to relax contracted muscles.

Listeriosis

Listeria monocytogenes is a nonencapsulated, nonsporulating, gram-positive rod and a foodborne pathogen that causes **listeriosis**. At-risk groups include pregnant women, neonates, the elderly, and the immunocompromised. Listeriosis leads to meningitis in about 20% of cases, particularly neonates and patients over the age of 60. The CDC identifies listeriosis as the third leading cause of death due to foodborne illness, with overall mortality rates reaching 16%. In pregnant women, listeriosis can cause also cause spontaneous abortion in pregnant women because of the pathogen's unique ability to cross the placenta.

L. monocytogenes is generally introduced into food items by contamination with soil or animal manure used as fertilizer. Foods commonly associated with listeriosis include fresh fruits and vegetables, frozen vegetables, processed meats, soft cheeses, and raw milk. Unlike most other foodborne pathogens, *Listeria* is able to grow at temperatures between 0 °C and 50 °C, and can therefore continue to grow, even in refrigerated foods.

Ingestion of contaminated food leads initially to infection of the gastrointestinal tract. However, *L. monocytogenes* produces several unique virulence factors that allow it to cross the intestinal barrier and spread to other body systems. Surface proteins called **internalins** (InlA and InlB) help *L. monocytogenes* invade nonphagocytic cells and tissues, penetrating the intestinal wall and becoming disseminating through the circulatory and lymphatic systems. Internalins also enable *L. monocytogenes* to breach other important barriers, including the **blood-brain barrier** and the placenta. Within tissues, *L. monocytogenes* uses other proteins called **listeriolysin O** and **ActA** to facilitate intercellular movement, allowing the infection to spread from cell to cell (Figure 6.).

L. monocytogenes is usually identified by cultivation of samples from a normally sterile site (e.g., blood or **CSF**). Recovery of viable organisms can be enhanced using cold enrichment by incubating samples in a broth at 4 °C for a week or more. Distinguishing types and subtypes of *L. monocytogenes*—an important step for diagnosis and epidemiology—is typically done using pulsed-field gel electrophoresis. Identification can also be achieved using chemiluminescence DNA probe assays and MALDI-TOF.

Treatment for listeriosis involves antibiotic therapy, most commonly with **ampicillin** and **gentamicin**. There is no vaccine available.

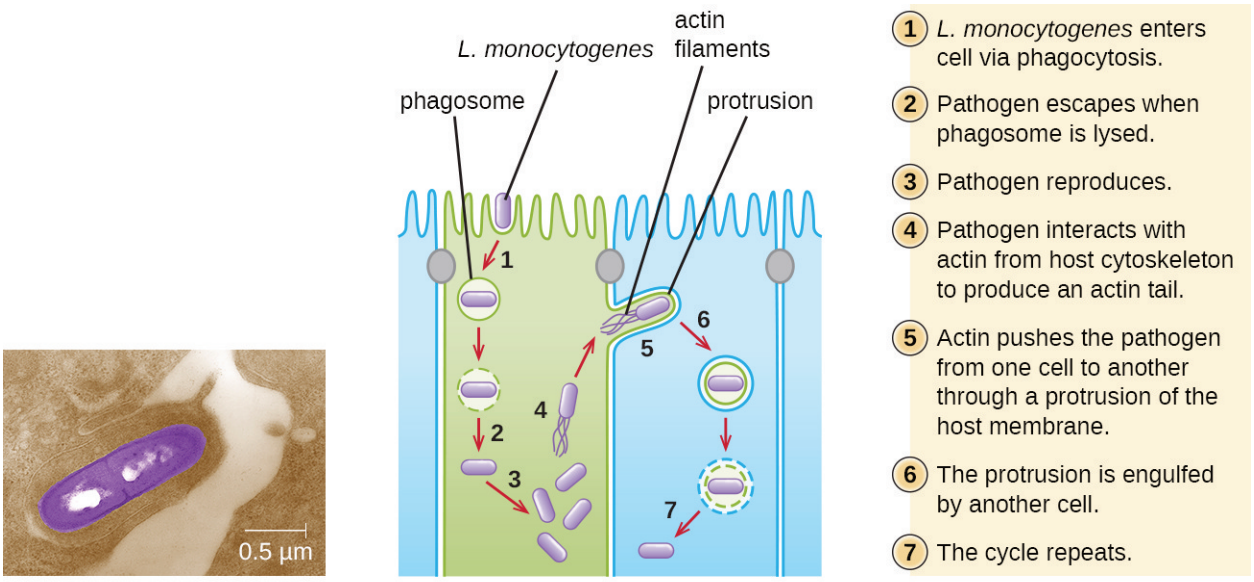


Figure 6. (a) An electron micrograph of Listeria monocytogenes infecting a host cell. (b) Listeria is able to use host cell components to cause infection. For example, phagocytosis allows it to enter host cells, and the host's cytoskeleton provides the materials to help the pathogen move to other cells. (credit a: modification of work by the Centers for Disease Control and Prevention; credit b: modification of work by Keith Ireton)

- How does *Listeria* enter the nervous system?

Hansen's Disease (Leprosy)

Hansen's disease (also known as **leprosy**) is caused by a long, thin, filamentous rod-shaped bacterium ***Mycobacterium leprae***, an obligate intracellular pathogen. *M. leprae* is classified as gram-positive bacteria, but it is best visualized microscopically with an acid-fast stain and is generally referred to as an **acid-fast bacterium**. Hansen's disease affects the PNS, leading to permanent damage and loss of appendages or other body parts.

Hansen's disease is communicable but not highly contagious; approximately 95% of the human population cannot be easily infected because they have a natural immunity to *M. leprae*. Person-to-person transmission occurs by inhalation into nasal mucosa or prolonged and repeated contact with infected skin. Armadillos, one of only five mammals susceptible to Hansen's disease, have also been implicated in transmission of some cases.

In the human body, *M. leprae* grows best at the cooler temperatures found in peripheral tissues like the nose, toes, fingers, and ears. Some of the **virulence factors** that contribute to *M. leprae*'s pathogenicity are located on the capsule and cell wall of the bacterium. These virulence factors enable it to bind to and invade **Schwann cells**, resulting in progressive demyelination that gradually destroys neurons of the PNS. The loss of neuronal function leads to hypoesthesia (numbness) in infected lesions. *M. leprae* is readily phagocytized by macrophages but is able to survive within macrophages in part by neutralizing reactive oxygen species produced in the oxidative burst of the phagolysosome. Like *L. monocytogenes*, *M. leprae* also can move directly between macrophages to avoid clearance by immune factors.

The extent of the disease is related to the immune response of the patient. Initial symptoms may not appear

for as long as 2 to 5 years after infection. These often begin with small, blanched, numb areas of the skin. In most individuals, these will resolve spontaneously, but some cases may progress to a more serious form of the disease. **Tuberculoid (paucibacillary) Hansen's disease** is marked by the presence of relatively few (three or less) flat, blanched skin lesions with small nodules at the edges and few bacteria present in the lesion. Although these lesions can persist for years or decades, the bacteria are held in check by an effective immune response including **cell-mediated cytotoxicity**. Individuals who are unable to contain the infection may later develop **lepromatous (multibacillary) Hansen's disease**. This is a progressive form of the disease characterized by nodules filled with acid-fast bacilli and macrophages. Impaired function of infected Schwann cells leads to peripheral nerve damage, resulting in sensory loss that leads to ulcers, deformities, and fractures. Damage to the ulnar nerve (in the wrist) by *M. leprae* is one of the most common causes of crippling of the hand. In some cases, chronic tissue damage can ultimately lead to loss of fingers or toes. When mucosal tissues are also involved, disfiguring lesions of the nose and face can also occur (Figure 7.).

Hansen's disease is diagnosed on the basis of clinical signs and symptoms of the disease, and confirmed by the presence of acid-fast bacilli on skin smears or in skin biopsy specimens (Figure 7.). *M. leprae* does not grow *in vitro* on any known laboratory media, but it can be identified by culturing *in vivo* in the footpads of laboratory mice or armadillos. Where needed, PCR and genotyping of *M. leprae* DNA in infected human tissue may be performed for diagnosis and epidemiology.

Hansen's disease responds well to treatment and, if diagnosed and treated early, does not cause disability. In the United States, most patients with Hansen's disease are treated in ambulatory care clinics in major cities by the National Hansen's Disease program, the only institution in the United States exclusively devoted to Hansen's disease. Since 1995, WHO has made multidrug therapy for Hansen's disease available free of charge to all patients worldwide. As a result, global prevalence of Hansen's disease has declined from about 5.2 million cases in 1985 to roughly 176,000 in 2014. Multidrug therapy consists of **dapsone** and **rifampicin** for all patients and a third drug, **clofazimin**, for patients with multibacillary disease.

Currently, there is no universally accepted vaccine for Hansen's disease. India and Brazil use a **tuberculosis vaccine** against Hansen's disease because both diseases are caused by species of *Mycobacterium*. The effectiveness of this method is questionable, however, since it appears that the vaccine works in some populations but not in others.

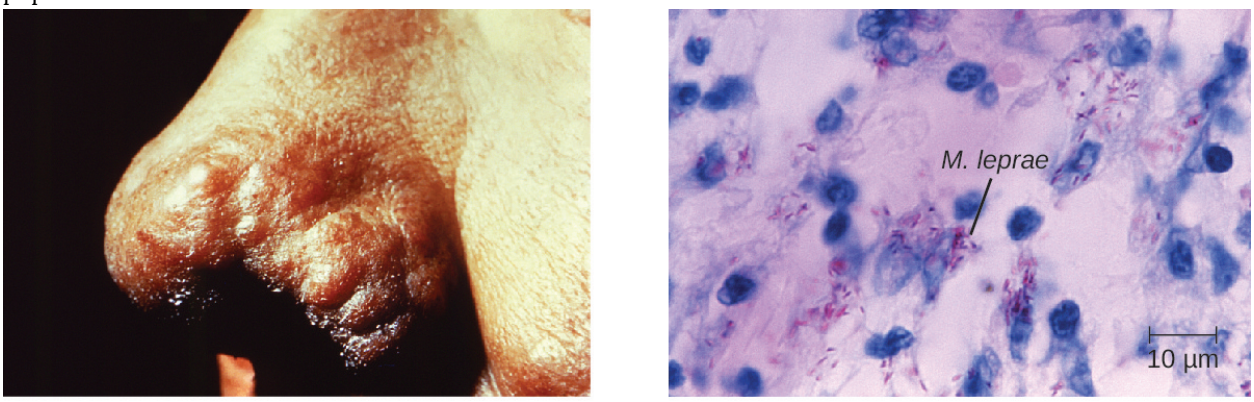


Figure 7. *(a) The nose of a patient with Hansen's disease. Note the lepromatous/multibacillary lesions around the nostril. (b) Hansen's disease is caused by Mycobacterium leprae, a gram-positive bacillus. (credit a, b: modifications of work by the Centers for Disease Control and Prevention)*

- What prevents the progression from tuberculoid to lepromatus leprosy?
- Why does Hansen's disease typically affect the nerves of the extremities?

LEPER COLONIES

Disfiguring, deadly diseases like leprosy have historically been stigmatized in many cultures. Before leprosy was understood, victims were often isolated in leper colonies, a practice mentioned frequently in ancient texts, including the Bible. But leper colonies are not just an artifact of the ancient world. In Hawaii, a leper colony established in the late nineteenth century persisted until the mid-twentieth century, its residents forced to live in deplorable conditions. Although leprosy is a communicable disease, it is not considered contagious (easily communicable), and it certainly does not pose enough of a threat to justify the permanent isolation of its victims. Today, we reserve the practices of isolation and quarantine to patients with more dangerous diseases, such as Ebola or multiple-drug-resistant bacteria like *Mycobacterium tuberculosis* and *Staphylococcus aureus*. The ethical argument for this practice is that isolating infected patients is necessary to prevent the transmission and spread of highly contagious diseases—even when it goes against the wishes of the patient.

Of course, it is much easier to justify the practice of temporary, clinical quarantining than permanent social segregation, as occurred in leper colonies. In the 1980s, there were calls by some groups to establish camps for people infected with AIDS. Although this idea was never actually implemented, it begs the question—where do we draw the line? Are permanent isolation camps or colonies ever medically or socially justifiable? Suppose there were an outbreak of a fatal, contagious disease for which there is no treatment. Would it be justifiable to impose social isolation on those afflicted with the disease? How would we balance the rights of the infected with the risk they pose to others? To what extent should society expect individuals to put their own health at risk for the sake of treating others humanely?

BACTERIAL INFECTIONS OF THE NERVOUS SYSTEM

Despite the formidable defenses protecting the nervous system, a number of bacterial pathogens are known to cause serious infections of the CNS or PNS. Unfortunately, these infections are often serious and life threatening. Figure 8. summarizes some important infections of the nervous system.

Bacterial Infections of the Nervous System					
Disease	**Pathogen**	**Signs and Symptoms**	**Transmission**	**Antimicrobial Drugs**	**Vaccine**
Botulism	*Clostridium botulinum*	Blurred vision, drooping eyelids, difficulty swallowing and breathing, nausea, vomiting, often fatal	Ingestion of preformed toxin in food, ingestion of endospores in food by infants or immuno-compromised adults, bacterium introduced via wound or injection	Antitoxin; penicillin (for wound botulism)	None
Hansen's disease (leprosy)	*Mycobacterium leprae*	Hypopigmented skin, skin lesions, and nodules, loss of peripheral nerve function, loss of fingers, toes, and extremities	Inhalation, possible transmissible from armadillos to humans	Dapsone, rifampin, clofazimin	None
Haemophilus influenzae type b meningitis	*Haemophilus influenzae*	Nausea, vomiting, photophobia, stiff neck, confusion	Direct contact, inhalation of aerosols	Doxycycline, fluoroquinolones, second- and third-generation cephalosporins, and carbapenems	Hib vaccine
Listeriosis	*Listeria monocytogenes*	Initial flu-like symptoms, sepsis and potentially fatal meningitis in susceptible individu-als, miscarriage in pregnant women	Bacterium ingested with contaminated food or water	Ampicillin, gentamicin	None
Meningococcal meningitis	*Neisseria meningitidis*	Nausea, vomiting, photophobia, stiff neck, confusion; often fatal	Direct contact	Cephalosporins or penicillins	Meningococcal conjugate
Neonatal meningitis	*Streptococcus agalactiae*	Temperature instability, apnea, bradycardia, hypotension, feeding difficulty, irritability, limpness, seizures, bulging fontanel, stiff neck, opisthotonos, hemiparesis, often fatal	Direct contact in birth canal	Ampicillin plus gentamicin, cefotaxime, or both	None
Pneumococcal meningitis	*Streptococcus pneumoniae*	Nausea, vomiting, photophobia, stiff neck, confusion, often fatal	Direct contact, aerosols	Cephalosporins, penicillin	Pneumococcal vaccines
Tetanus	*Clostridium tetani*	Progressive spasmatic paralysis starting with the jaw, often fatal	Bacterium introduced in puncture wound	Penicillin, antitoxin	DTaP, Tdap

Figure 8.

Key Concepts and Summary

- **Bacterial meningitis** can be caused by several species of encapsulated bacteria, including *Haemophilus influenzae*, *Neisseria meningitidis*, *Streptococcus pneumoniae*, and *Streptococcus agalactiae* (group B streptococci). *H. influenzae* affects primarily young children and neonates, *N. meningitidis* is the only communicable pathogen and mostly affects children and young adults, *S. pneumoniae* affects mostly young children, and *S. agalactiae* affects newborns during or shortly after birth.
- Symptoms of bacterial meningitis include fever, neck stiffness, headache, confusion, convulsions, coma, and death.
- Diagnosis of bacterial meningitis is made through observations and culture of organisms in CSF. Bacterial meningitis is treated with antibiotics. *H. influenzae* and *N. meningitidis* have vaccines available.
- *Clostridium* species cause neurological diseases, including **botulism** and **tetanus**, by producing potent neurotoxins that interfere with neurotransmitter release. The PNS is typically affected. Treatment of *Clostridium* infection is effective only through early diagnosis with administration of antibiotics to control the infection and antitoxins to neutralize the endotoxin before they enter cells.
- *Listeria monocytogenes* is a foodborne pathogen that can infect the CNS, causing meningitis. The infection can be spread through the placenta to a fetus. Diagnosis is through culture of blood or CSF. Treatment is with antibiotics and there is no vaccine.
- **Hansen's disease** (**leprosy**) is caused by the intracellular parasite *Mycobacterium leprae*. Infections cause demylenation of neurons, resulting in decreased sensation in peripheral appendages and body sites. Treatment is with multi-drug antibiotic therapy, and there is no universally recognized vaccine.

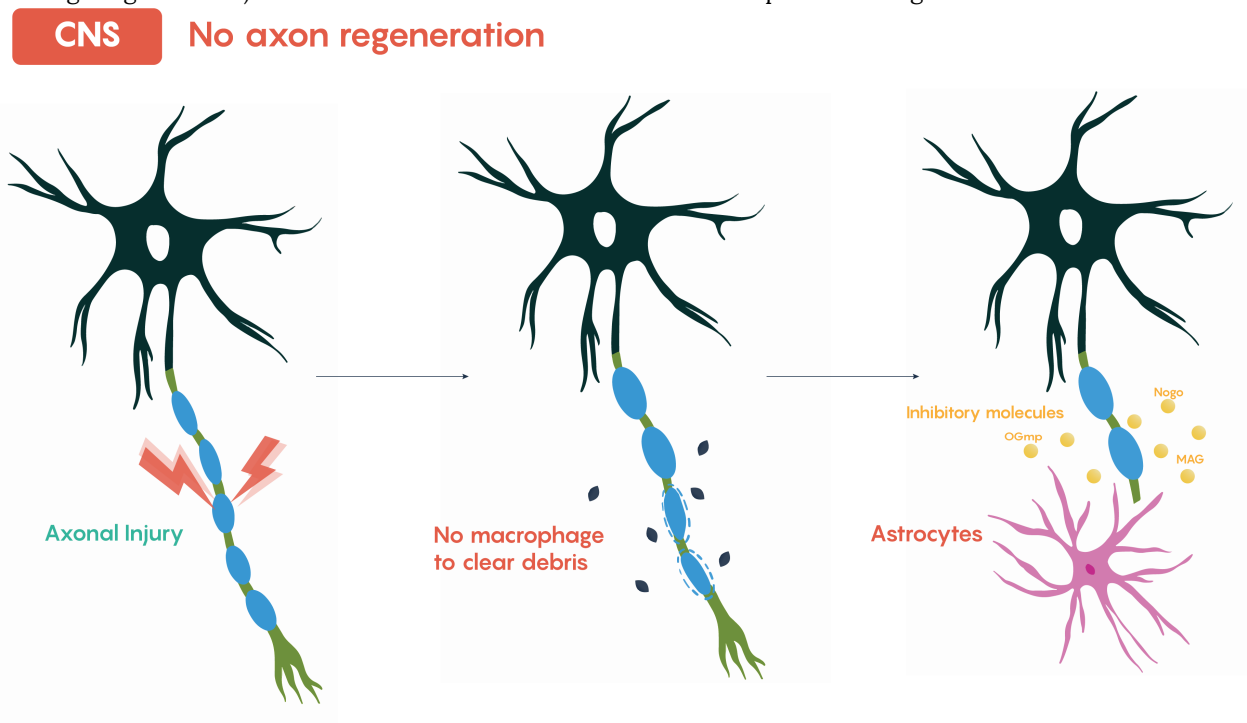
License

UNIT 2 – NEURODEGENERATION

2.1 Acute Physical Damage to the Nervous System

Axonal Injury in the PNS and the CNS

The previous chapter dealt with the impact that micro-organisms had on the health of neurons. This chapter outlines the differing roles of the PNS and CNS following injury and in recovery. It has long been known that following damage to axons, that the neurons within the PNS can undergo outgrowth and can recover (i.e. undergo regeneration) while neurons within the CNS do not seem capable of doing so.



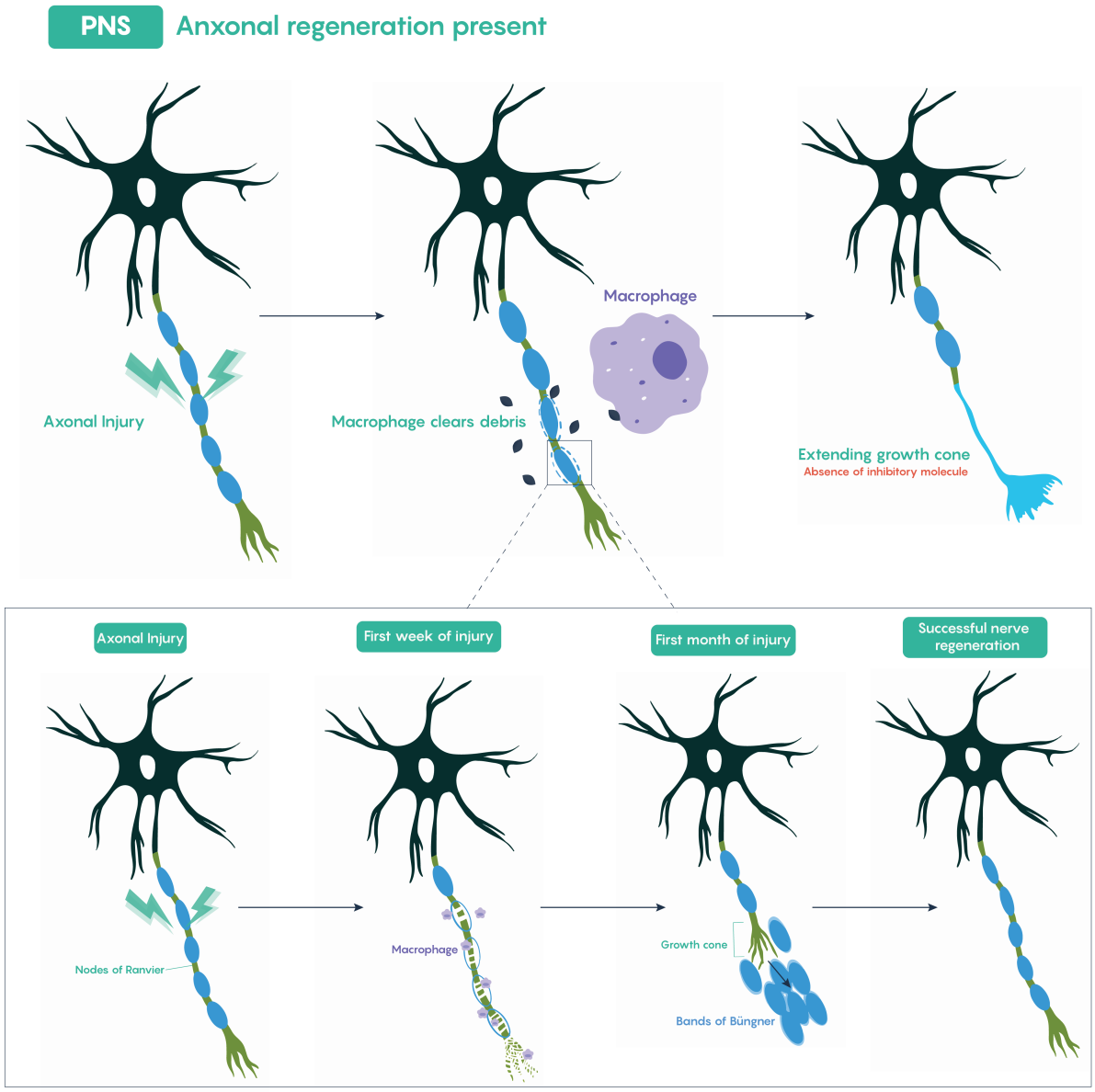


Figure 1. *Differences in neuronal regeneration and outgrowth in the CNS (top) and PNS (bottom panel) following damage to axons.*

What are the key differences?

Although it is possible that there are inherent properties that make neurons in the CNS somehow different from those in the PNS, it is more likely that external factors and cells account for the differences in their abilities to regenerate following damage. As shown in Figure 1. above, within the CNS, following axonal injury, the site of damage distal to injury (i.e. further away from damage) often undergoes degeneration and the distal axon degenerates and eventually disappears. Although there are several reasons that this is thought to occur, most

notably this is believed to involve a lack of macrophage clearing of damaged myelin as well as the formation of a glial scar via activated astrocytes that cause a physical barrier to their re-growth. Additionally, molecules that are unique to the CNS (see chapter in this Unit on Multiple Sclerosis) also are believed to be up-regulated within the CNS following damage that prevent regeneration. These molecules are associated with the CNS specific glial cells, oligodendrocytes that provide myelination, and these cells increase the production of Nogo, MAG (Myelin Associated Glycoprotein) and OGmp (Oligodendroctye myelin glycoprotein) among others.

In contrast, PNS neurons (bottom panel of figure 1) show significant clearing of damaged axons via macrophages (not observed in the CNS) and then axonal outgrowth and repair across the bridge of Schwann cells that occurs following a process known as Wallerian degeneration (the loss of the axon distal to the injury).

Pathophysiological implications – TBI (Traumatic Brain Injury)

You might be asking yourself, where do these types of axonal injuries occur with the brain and CNS? Increasingly researchers and clinicians are finding that there is specific axonal injury that could occur following traumatic brain injury (TBI) or concussion related injuries. One of the ways in which axons within the brain become damaged include the process of coup/contre-coup where the brain (and its neurons) are first compressed (coup) and then stretched (contre-coup). The mechanical forces on the neuron on the brain may result in varying degrees of damage to the neurons (Figure 2.).

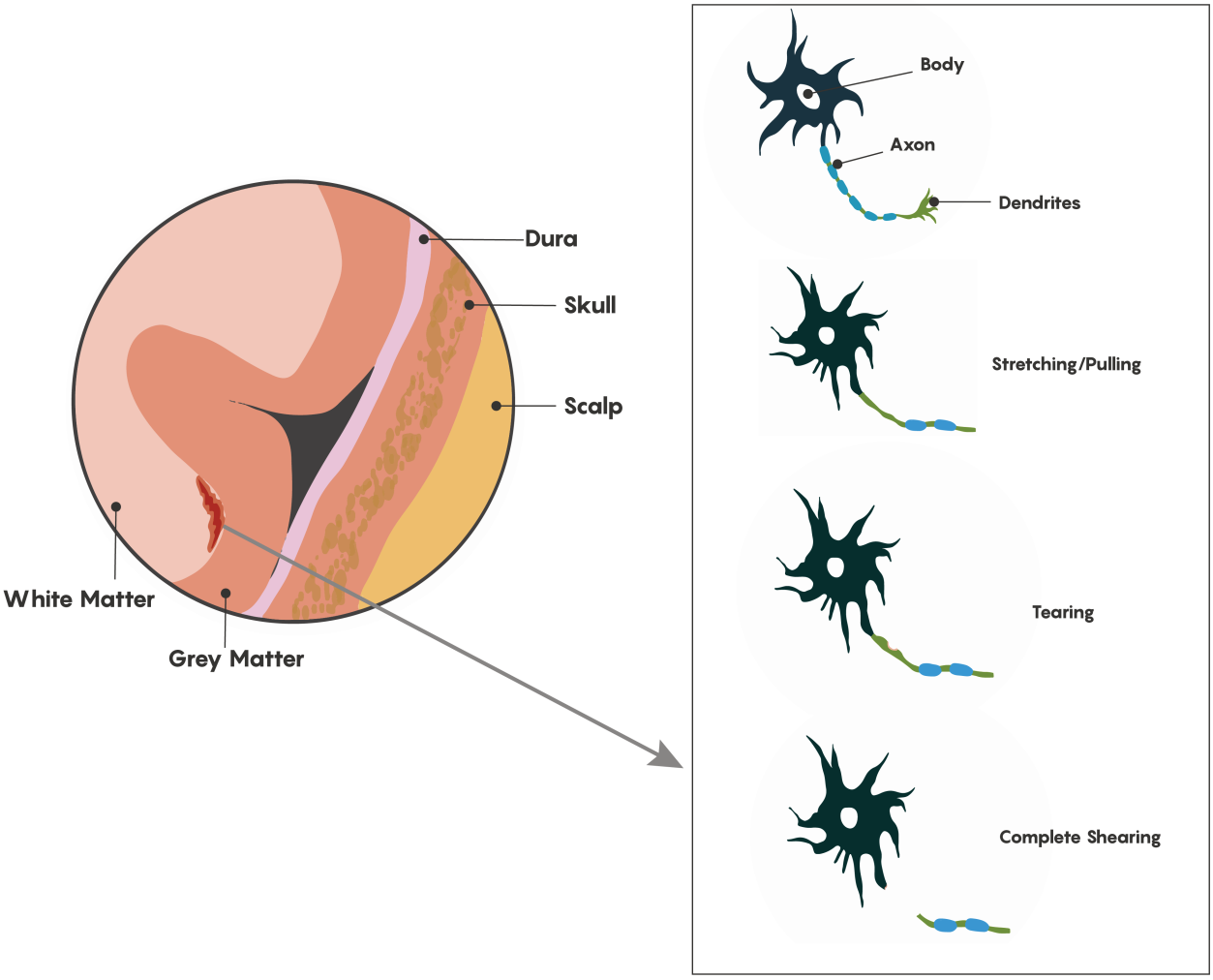


Figure 2. *Schematic diagram of diffuse axonal injury following TBI/concussion.*

As illustrated in Figure 2., depending on the area of the brain being impacted, a number of different types of damage can occur along the length of the axon including stretching/pulling of axons which may affect myelination and localization of axonal channel proteins, and both tearing and shearing which will cause loss of axonal integrity. This type of diffuse axonal injury will have effects on both the structure of the grey matter of the brain and the white matter axonal tracts. Ultimately these types of injuries often go undetected and the most common methods used are clinical assessments using variations of the Glasgow Coma Scale (GCS) that examine the severity of the loss of consciousness as these injuries, although structural are undetectable by either MRI or CT-scans.

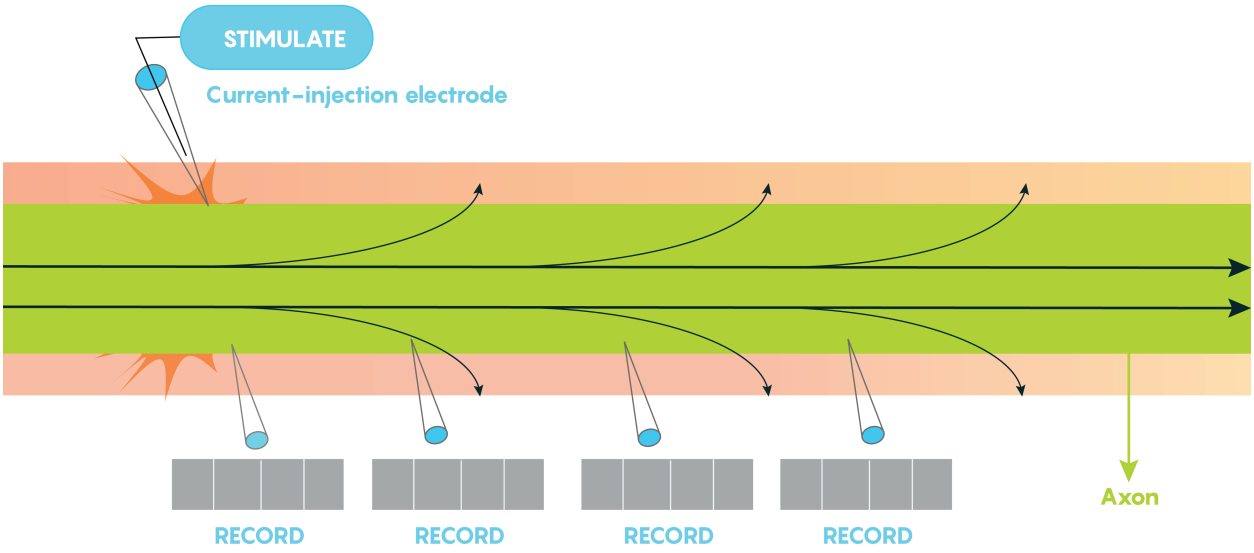


Figure 3.

Did you know?

Did you know that there is still controversy between TBI/concussions and the development of a neurodegenerative disorder known as Chronic Traumatic Encephalopahty (CTE) which is thought to cause behavioral changes in athletes in sports with contact/impact?

Although there are likely *structural* changes as indicated above, most often the diagnosis of post-concussion or TBI related disturbances occur because of *functional* changes in cognitive function and possible mood disorder changes (depression etc.). Although there are likely *structural* changes as indicated above, most often the diagnosis of post-concussion or TBI related disturbances occur because of *functional* changes in cognitive function and possible mood disorder changes (depression etc.).

Did you know that one of the chief complaints following TBI/concussions is the inability to concentrate and focus on computer/TV screens? Individuals with concussion injuries require not just physical rest but cognitive rest, and typical LCD screens refresh at a 60 Hz rate. Most individuals are capable of processing and fusing these high frequency images without a cognitive load, but following concussions, individuals will have higher critical flicker frequencies such that staring at a screen will increase cognitive fatigue and eyestrain. We don't understand why this happens yet but perhaps there is a Nobel Prize in it for an aspiring neurobiologist!

2.2 Stroke and Loss of Blood Flow as an Acute Injury to the Brain

The lack of blood flow to an area of the brain known as *Ischemia*. This is dangerous to the brain as a lack of circulating blood deprives the neurons of oxygen and nourishment. This ischemia that underlies stroke can occur in 2 different ways, *hemorrhage*: release of blood from blood vessels after the vessel rupture causes damage by cutting off connecting pathways, resulting in local or generalized pressure injury as well as impaired blood flow to the brain, and blocking a blood vessel causing a lack of blood flow to that region of the brain as shown in Figure 1.

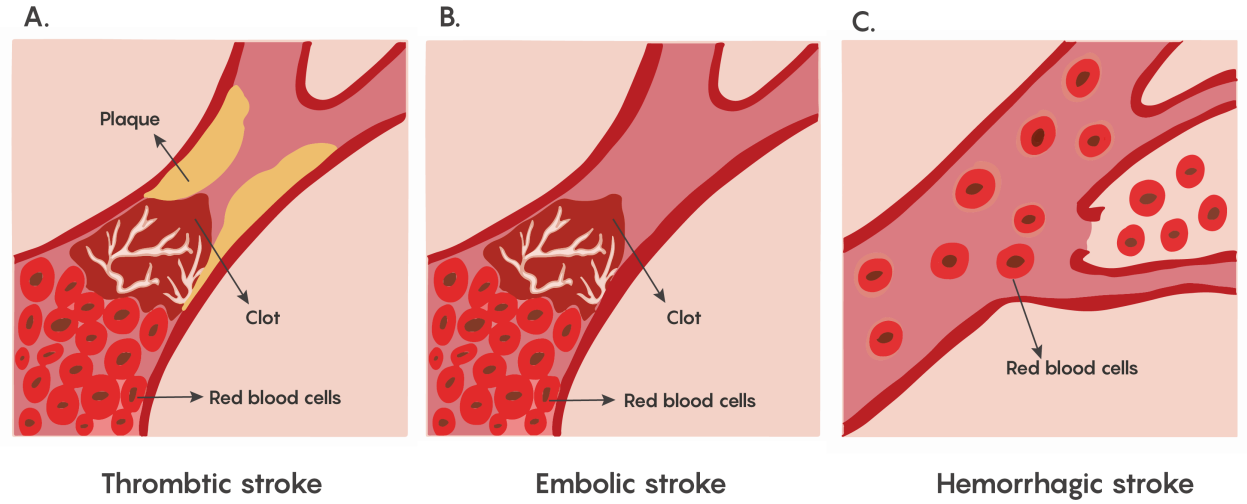


Figure 1. *Showing the major types of ischemia (lack of blood flow) in stroke*

Depending on the area of the brain where this lack of blood flow has occurred, functions that the specific area of the brain normally performs such as movement, sensation, or emotions, speech etc. may be affected and the loss of function varies with location and extent of damage.

Most forms of ischemia in stroke involve the thrombotic or embolic types of blockage, and a much smaller percentage involve hemorrhage. Although both are serious, all strokes have a therapeutic window that allows for neurons that are undergoing ischemia to be rescued.

Cellular Mechanisms underlying ischemia induced cell death

The brain requires a continuous supply of O2 and glucose for neurons to function. If the cerebral blood flow is interrupted, then individual neuronal metabolism can be affected within 30 seconds and will completely stop within 2 minutes of deprivation. If left unchecked, neuronal cell death occurs in 5 minutes. During this time period these neurons will no longer be able to maintain their resting membrane potentials and when they die, will release K+ ions causing other nearby cells to depolarize. In addition, as Na+/K+ATP dependent pumps will no longer have ATP production to drive their activity, the neurons will also start to depolarize and fire action potentials inappropriately. This leads to the glutamate excitotoxicity theory proposed by John Olney and may be

the basis of why pyramidal neurons that are found in the hippocampus and Purkinje cells in the cerebellum that rely on glutamate neurotransmission are particularly vulnerable and die following ischemia.

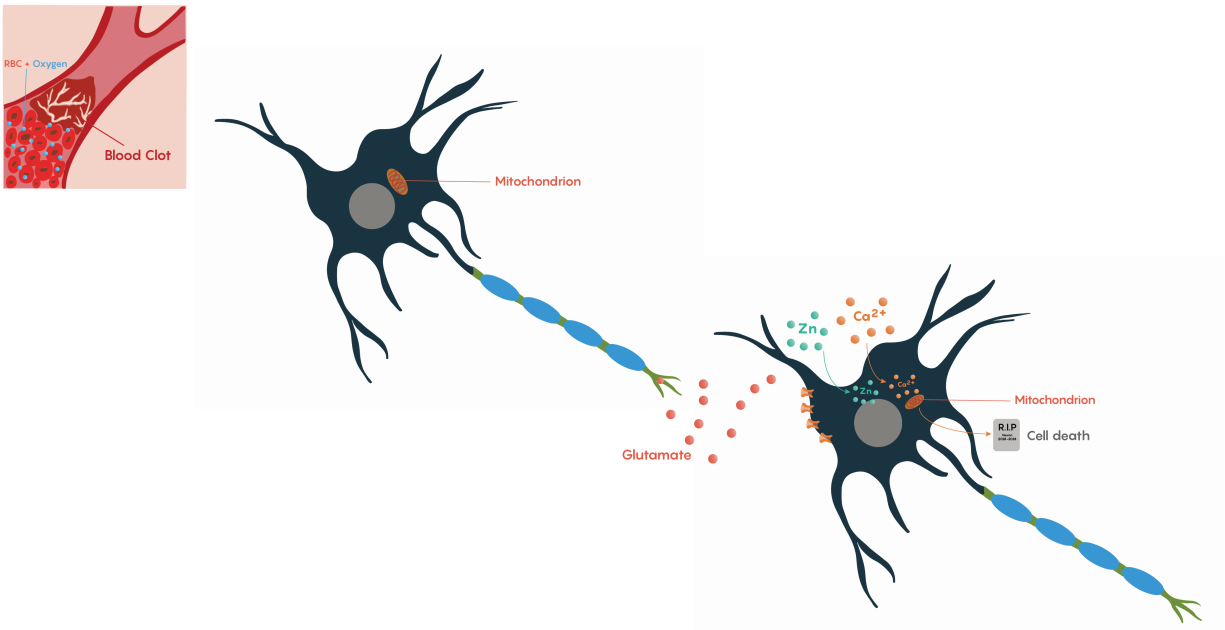


Figure 2.

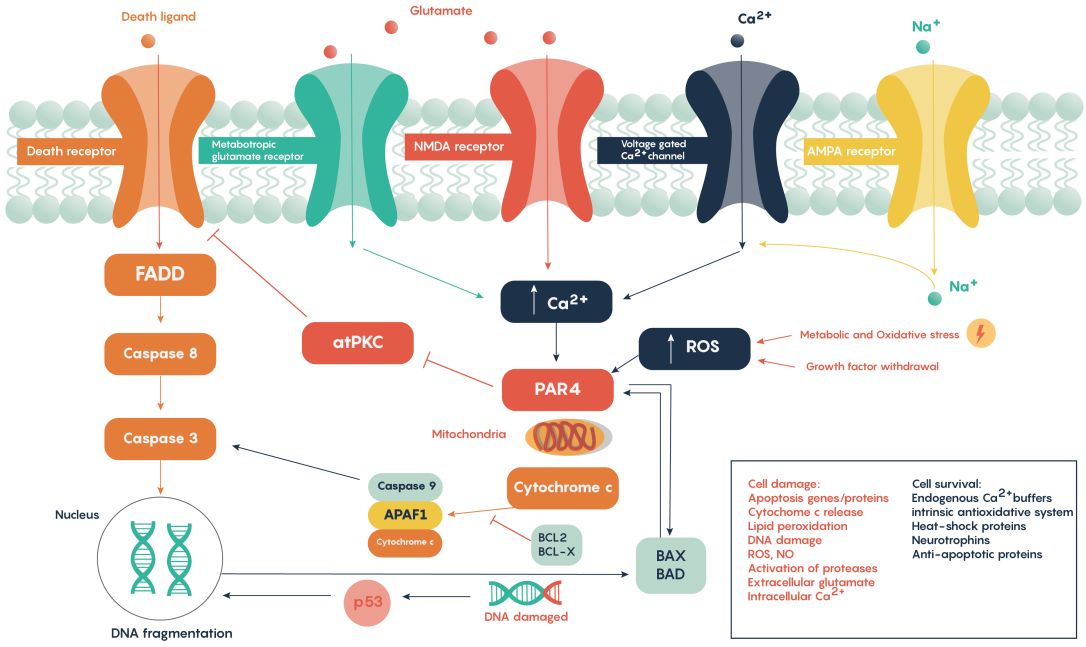


Figure 3. *Molecular pathways outlining the role of glutamate in excitoxicity following stroke.*

Following ischemia to a region of neurons, the increased release of glutamate and its decreased uptake without

ATP production (Figure 2.) produces an excess of glutamate which impacts downstream neurons. Glutamate will impact a number of glutamate specific receptors such as the AMPA, NMDA and metabotropic type receptors which in turn will cause activation of voltage gated Ca2+ channels, all of which result in the increase in intracellular Ca2+ levels. In turn, this will activate the protease activated receptor PAR4 which will activate the pro-apoptotic proteins BAX/BAD that will then form a complex with the mitochondrial factor cytochrome c which is released from the mitochondrial matrix as the intracellular ATP stores fail. This complex in turn will then activate Caspase 9 and the downstream and ultimate factor Caspase 3 which is involved in the apoptotic DNA fragmentation and eventual death of the neuron. As this is a programmable/apoptotic form of cell death, there are a number of therapeutic interventions that may prevent this stroke and ischemia induced form of cell death.

Animal models of stroke

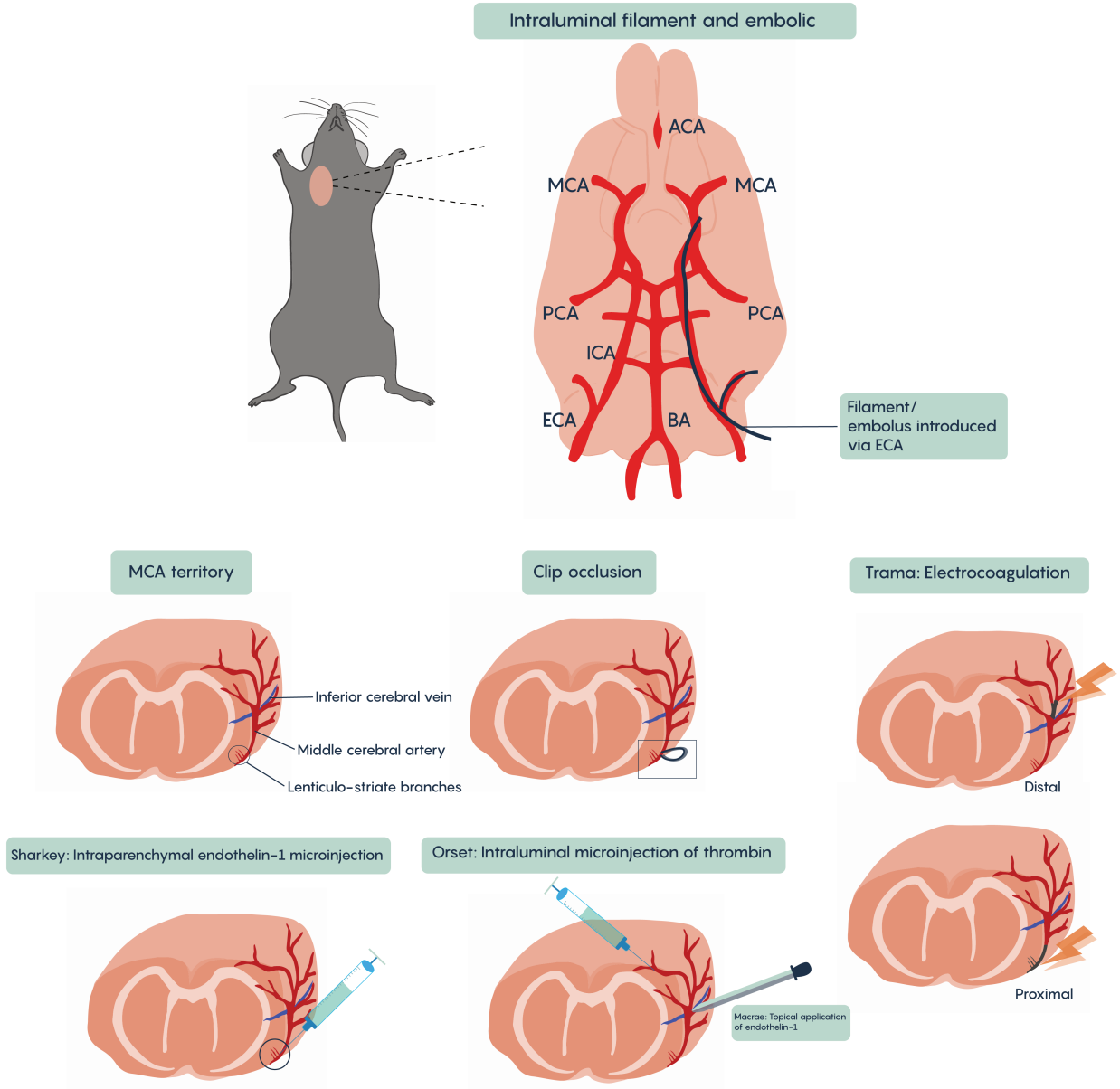


Figure 4. *Various animal models of ischemia and stroke.*

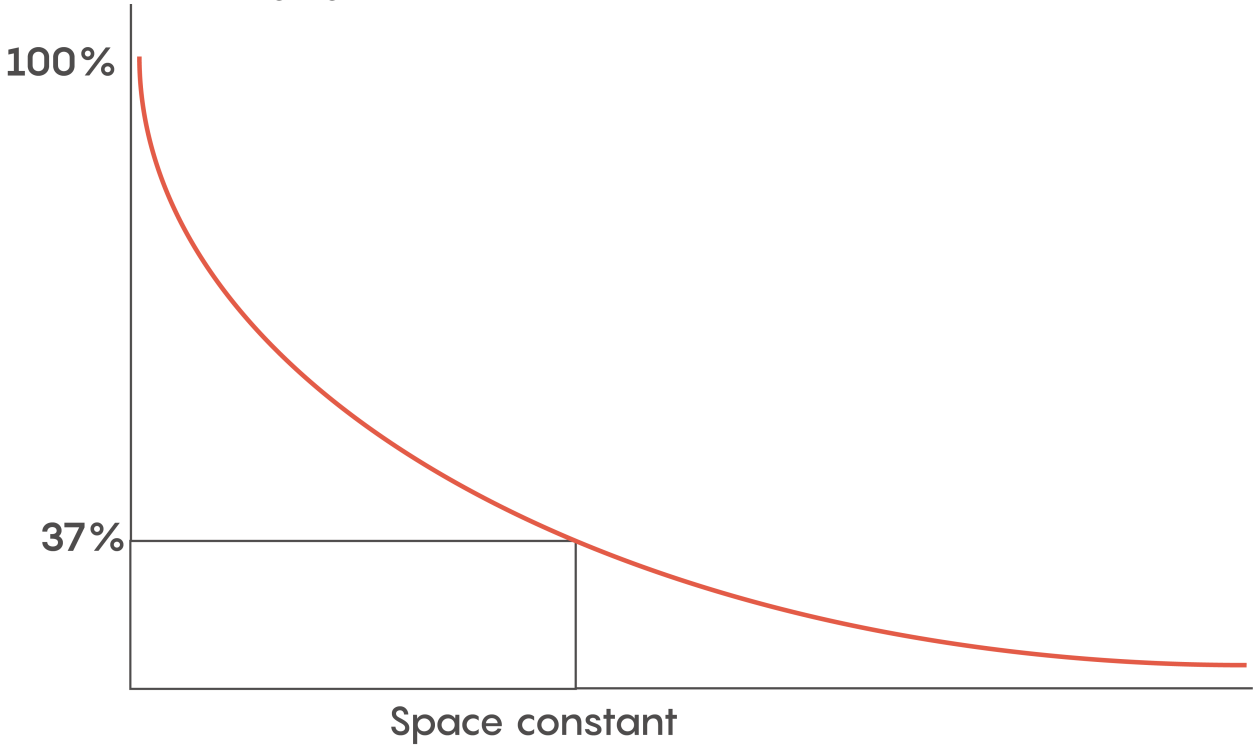
A number of different animal models of stroke have been developed. Most involve interruptions in blood flow such as the intraparenchymal (i.e. directly into the brain tissue) injection of drugs such as endothelin-1 (Et-1) which induces vasospasms of the blood vessels creating ischemia, of the introduction of coagulants such as thrombin injection that will block blood vessels (Figure 4. Animal models of stroken). Most methods will involve blockade of normal blood flow to an area of the brain to produce ischemia whether through occlusion of a blood vessel such as the middle cerebral artery (MCA) or the chemical methods described here. These animal models have proved invaluable in understanding the role of different factors such as cytochrome c or BAD/BAX in excitotoxicity and hold the promise of developing therapeutic interventions.

2.3 Demyelinating diseases with an emphasis on Multiple Sclerosis

Myelin is produced from the cell membranes of either Schwann cells (for neurons in the PNS) or oligodendroglia/ oligodendrocytes (for neurons in the CNS). As such, myelin is enriched with membrane lipids and proteins that are found within these cells. Normally myelin functions to increase nerve cell conduction by increasing the biophysical property of the membrane resistance (i.e. a neuron cell membrane's leakiness). Myelin reduces membrane leakiness by preventing open channels and as a result, increasing how far a single electrical impulse within the axon will travel. Importantly this also increases how quickly an action potential will travel down an axon – myelin greatly increases the conduction velocity of a neuron (Figure 1.).

Myelin helps neurons to cheat

Various factors help to determine how fast an action potential travels down an axon (called the conduction velocity). The biophysical features of a neuron including how big its axonal diameter is and the membrane leakiness, help scientists to determine what is known as the length or space constant (lambda or λ) for each neuron. Why is this λ value important? λ is directly proportional to the conduction velocity – so the factors that determine λ also determine a neuron's conduction velocity. Let's not forget –speed thrills within the CNS and brain, and the faster a signal gets there, the more the brain likes it.



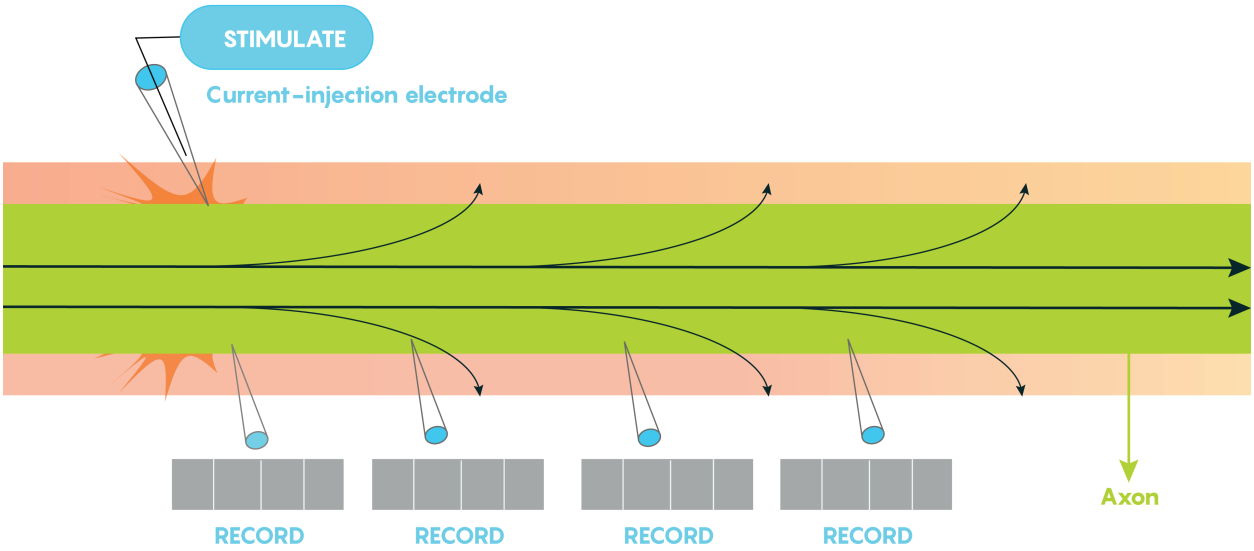


Figure 1. *Showing the biophysical variables that determine the length constant including membrane leakiness (Rm) and internal diameter (Raxial). Myelin increase Rm to increase both the length constant and therefore speed of conduction.*

Another reason for myelination includes having a lot of neurons so space is a premium. Although the length constant is inversely related to the axonal diameter (i.e. bigger diameter axons have bigger length constants), we need to pack as many neurons into a small space as possible. So within the brain, faster communication means myelination is key.

Large vertebrate nerve fibers are wrapped in myelin sheaths formed by central oligodendroglial cells or Schwann cells in the periphery but the myelin only wraps the axon at specific locations. Myelin is interrupted at regularly spaced intervals, or nodes. This helps the neuron, because during action potential propagation the excitatory signal jumps from one node to the next, and we call this *saltatory conduction which is much faster than passive electronic spread.* In addition, myelin also helps Rm (leakiness or membrane resistance) because it only directs voltage-sensitive Na^+ channels to highly concentrated areas known as the nodes of Ranvier (Figure 2.). So in many ways myelin helps the neuron "cheat' by limiting leakiness (i.e. open channels to specific areas). As shown in Figure 2., Before glial ensheathment, sodium channels are distributed uniformly, and at low density. At the time of glial ensheathment but before the formation of compact myelin, loose clusters of sodium channels develop at sites that will eventually become nodes. Following the formation of compact myelin and mature paranodal axon-glial cell junctions, well-defined nodal clusters of voltage gated sodium channels are established, and sodium channels are eliminated from the axon membrane beneath the myelin sheath.

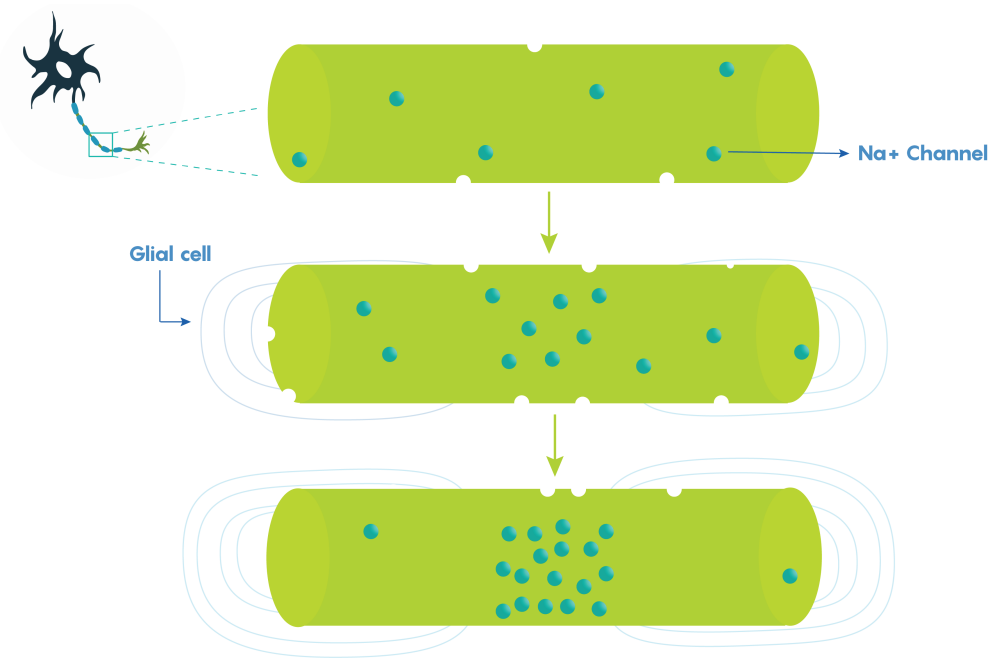


Figure 2. *Myelination directs leakiness to Nodes of Ranvier. During development voltage dependent Na+ channels are found along the entire length of the axon. As myelination occurs, these voltage gated channels (and hence leakiness) are localized to only the node (part c).*

Demyelinating diseases are prevalent – and in Canada Multiple Sclerosis affects many

Demyelinating diseases remain one of the most common disorders where 1:500 to 1:1000 adult individuals in North America are affected, but these diseases tend to affect women more frequently than males. As the name suggests, within these diseases, the myelin described above is lost and the axons which previously have been myelinated no longer have myelin, changing their conduction velocities.

Multiple Sclerosis: Overview

Within this disease, the myelin is destructively removed from around the axon which slows down nerve impulses. As axons are demyelinated, these result in inflammatory patches called lesions and it is thought that this disorder is an autoimmune disease. As the disease progresses, oligodendrocytes and, ultimately, the axons themselves are destroyed. There is very compelling evidence that the destruction is caused by selective activation of the cellular immune system and inflammatory molecules.

Potential causes and theories

Currently there is no known cause for multiple sclerosis although many different hypotheses have been put forward. Surprisingly, there are no known associative genes that have been implicated in causing multiple sclerosis and scientists believe there might be a complex interaction between genes and environmental factors to produce demyelination observed in multiple sclerosis. The most common theories about the cause(s) of multiple sclerosis include:

1. Viral infection and resulting autoimmune reaction where evidence from Experimental allergic encephalomyelitis mouse models suggest a strong link
2. Genetic factors: inherited predisposition possibly through the immune system, although a mutation in a gene has not been discovered
3. Environmental factor(s) which might work with genetics such as low vitamin D levels or smoking.

Although this is a well characterized disorder, we still don't know much about its causes.

Diagnosis, loss of function, and pathology

Typically an individual with demyelination in multiple sclerosis may have functional deficits that result from reduced speed of conduction which might include loss of vision, different atypical sensations in the periphery and findings on an MRI that include hyperintensities, bright patches on structural MRIs (Figure 3.), around sites like the lateral ventricle, optic nerve, brainstem, spinal cord, cerebellum and other areas.

Multiple sclerosis also presents itself differently including having acute phases where the condition has been associated with relapsing/remitting where symptoms may not appear for periods of time and a chronic phase which is associated with progressive forms of multiple sclerosis where the individual progressively becomes worse and the symptoms become more severe.

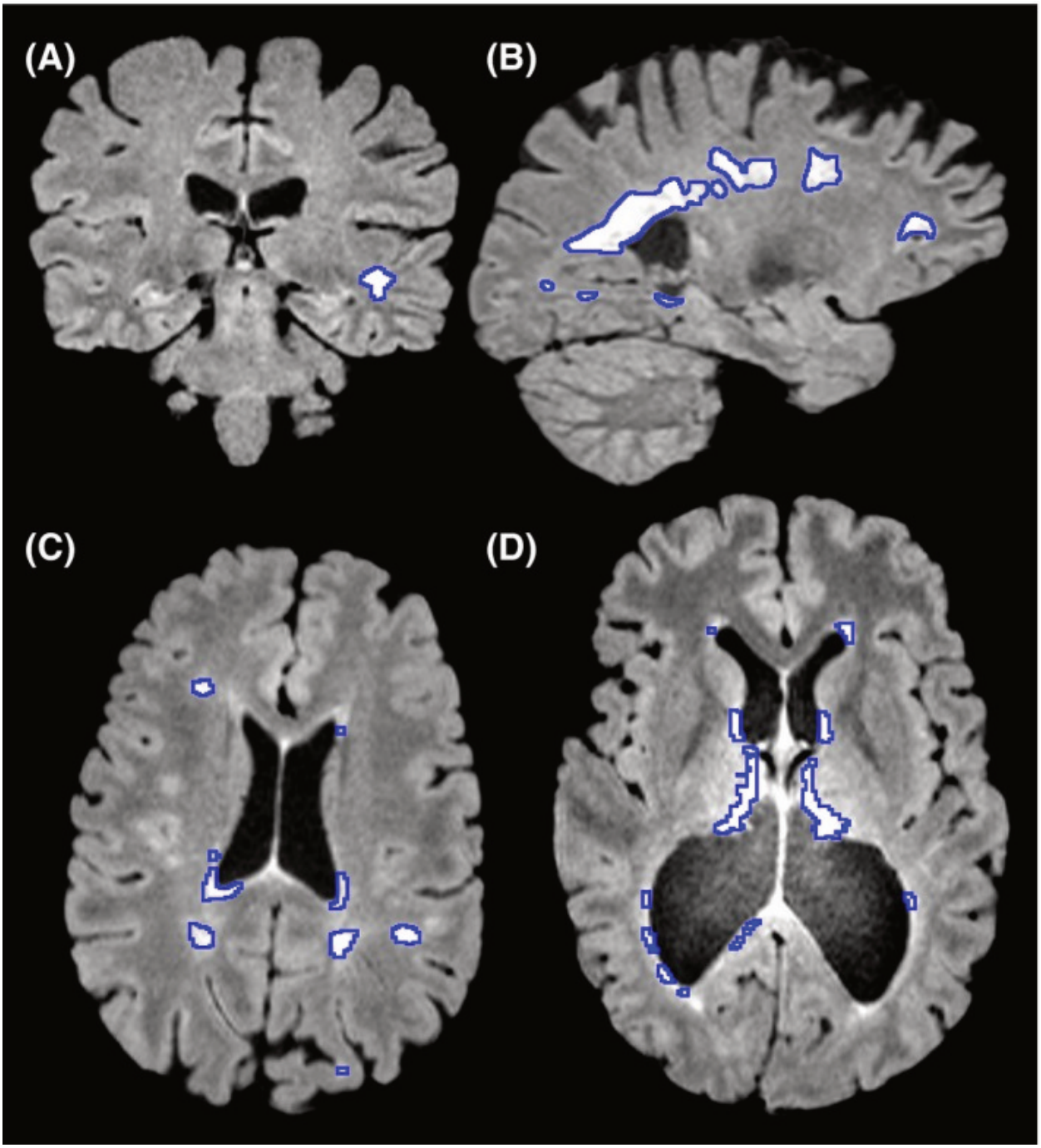


Figure 3. *MRI images showing white hyperintensities in different areas of the brain of an individual experiencing symptoms of multiple sclerosis. (A) A coronal slice showing a lesion in peripheral white matter. (B) A sagittal slice showing large periventricular lesions. (C) An axial slice showing both periventricular and peripheral white matter lesions. (D) A case where severe atrophy caused midline false positives to not be removed, as they were further from midline than expected. Image from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4731385/ Under CC by 4.0.*

Animal models of multiple sclerosis

Experimental autoimmune encephalomyelitis (EAE): one of the best studied models of autoimmune diseases. This model produces inflammation of both the brain and spinal cord. This is a good validity model for multiple sclerosis, as EAE is believed to be mediated by T cells and can be induced in many animal models following immunization with a myelin specific protein such as myelin basic protein (MBP) or protolipid protein (PLP) in complete Freund's adjuvant (or CFA which helps to produce a specific immune response). Within weeks animals develop cellular inflammatory cell infiltration of the myelin sheaths of the central nervous system which then result in demyelination or paralysis (Figure 4.).

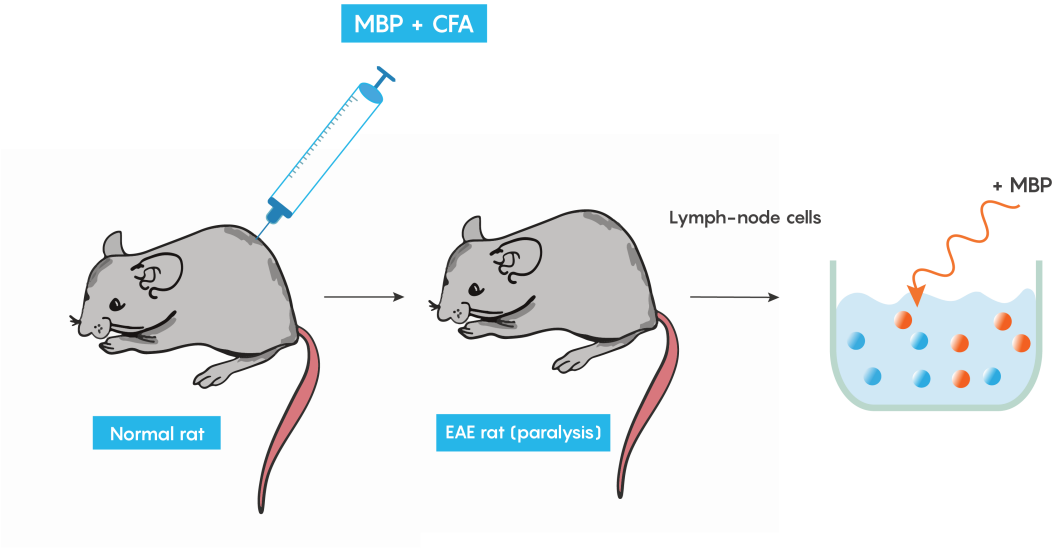


Figure 4. *Inducing an inflammatory response to produce EAE as a model of multiple sclerosis.*

The cuprizone model of multiple sclerosis

Cuprizone treatment is one of the most frequently used toxin-induced multiple sclerosis models. Other toxins such as lysolecithin or ethidium bromide require stereotaxic microinjections into brain areas and result in only localized focal demyelination but cuprizone models are advantageous in that oral administration of cuprizone produces a global damage. Following cuprizone ingestion, the mouse often exhibits impaired divalent ion (Cu^{2+}, Zn^{2+}) homeostasis and results in the loss of Cu-Zn superoxide dismutase activity within the brain's tanycytes resulting in the production of reactive oxygen species (ROS) which activate M1 macrophages in the brain to increase the production and release of pro-inflammatory molecules as highlighted in Figure 5.

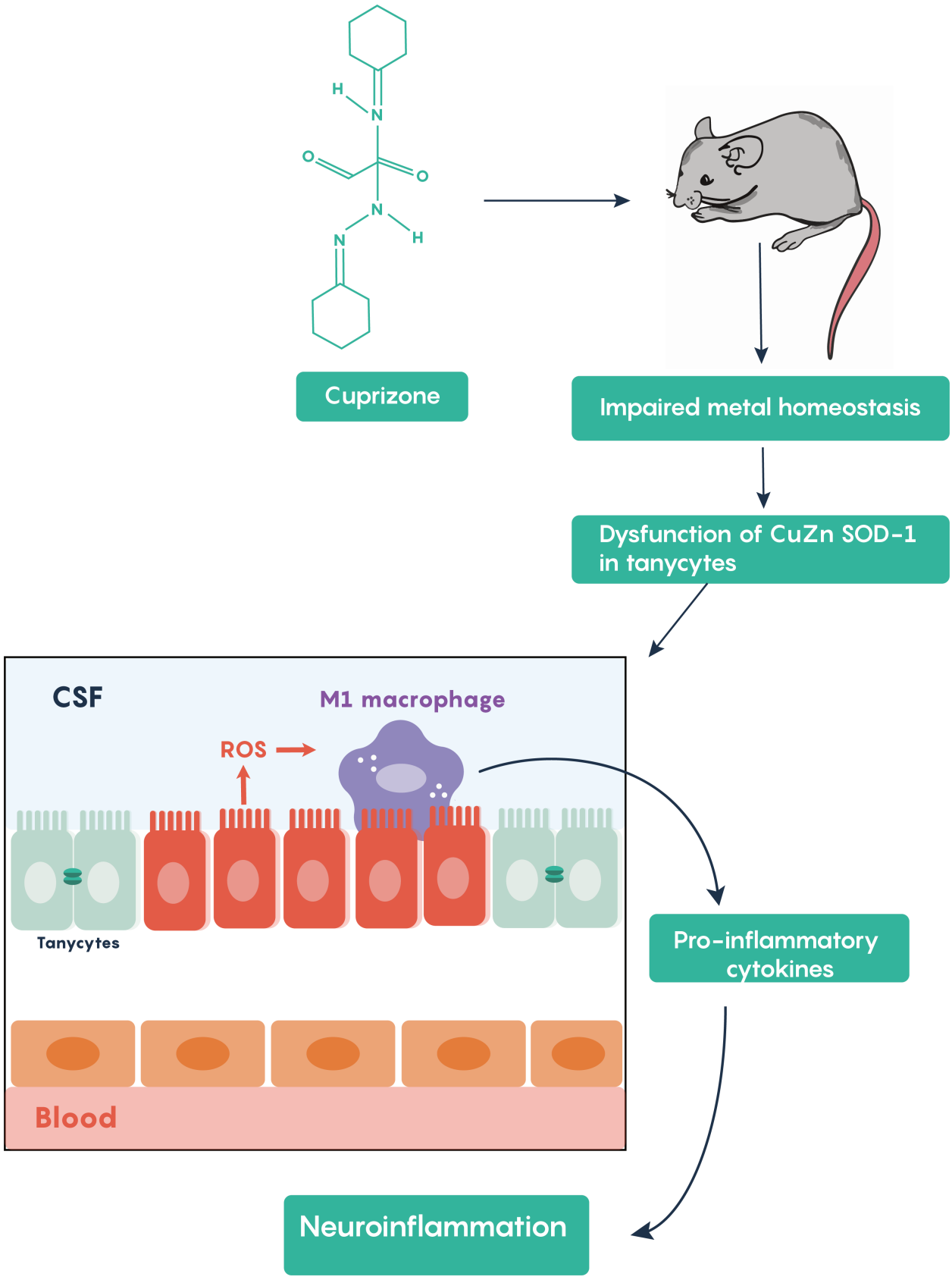


Figure 5. *Mouse model of demyelination in multiple sclerosis highlighting the activation of the inflammatory*

process.

2.4 Chronic Neurodegenerative Diseases

Alpha-Synucleinopathies and Parkinson's Disease

The current model for most neurodegenerative conditions is that neurons die via apoptosis or a programmed form of cell death. This has very important clinical implications as turning on or turning off specific genes/proteins is a method to stop or possibly reverse neurodegeneration. Neurodegenerative diseases such as Parkinson's Disease and Alzheimer's Disease and others are all believed to use apoptotic pathways and additionally suggest that there is a component protein that is aberrantly folded to produce apoptosis.

Parkinson's Disease: Overview

Most cases of this disorder appear to be sporadic (i.e. non-genetic in origin). A very few cases seem to have a genetic origin (for example the genes most often associated with *DJ-1*, *Parkin* (*Ubiquitin E3 ligase*) and *alpha synuclein* genes). Parkinson's Disease is most often associated with loss of "pigmented" nuclei in the brain and typically involve the loss of a group of neurons found in the Substantia Nigra (Figure 1.). The substantia nigra neurons are dopaminergic and are pigmented because they contain the protein *melanin*.

The typical onset for Parkinson's Disease is middle to later stages of life (i.e. 50 and beyond) although a small percentage of individuals who have known genetic mutations in *Parkin* or *alpha-synuclein* develop symptoms earlier.

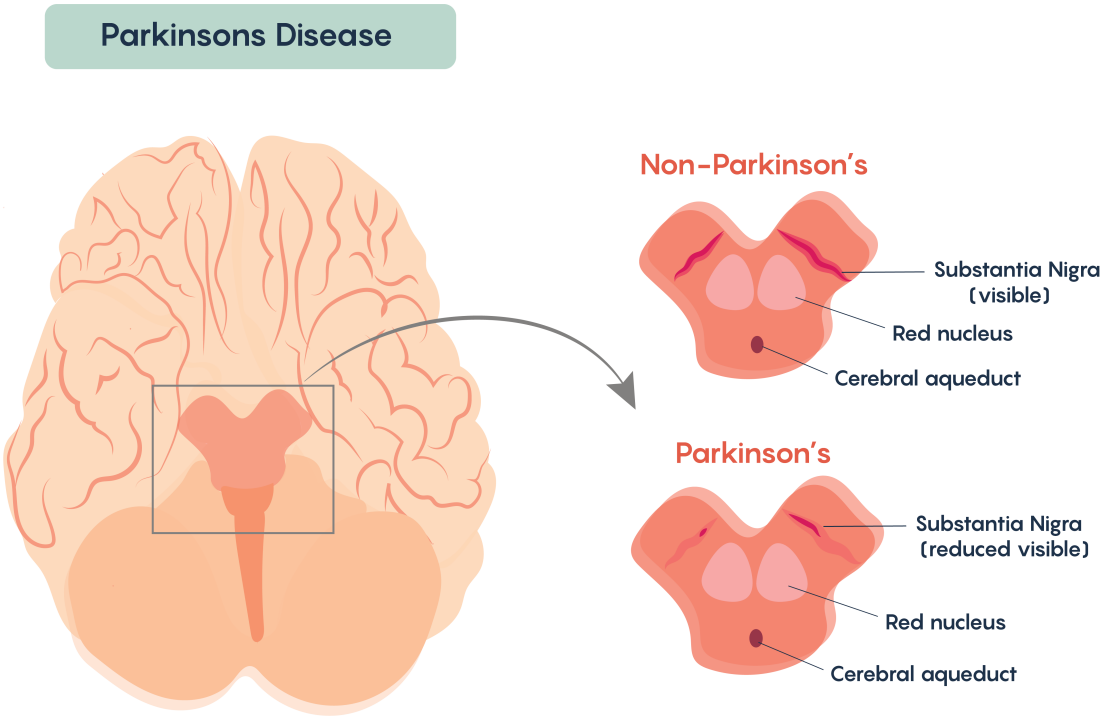


Figure 1. *Loss of the pigmented dopaminergic neurons within the Substantia Nigra of individuals with Parkinson's Disease.*

Loss of these cells affect the processing and execution of voluntary movement in individuals with Parkinson's Disease. Similar to Multiple Sclerosis, once diagnosed, the symptoms become continuous and progressive – i.e. the symptoms worsen over time. Again, there are many similarities with Multiple Sclerosis, and there is no known cure for Parkinson's Disease and the disease remains idiopathic although there are some known causes of Parkinson's Disease including loss of movement following cerebral atherosclerosis, viral encephalitis, and as the result of side effects from drugs such as phenothiazides and reserpine.

"Classic" symptoms associated with Parkinson's Disease

- **Bradykinesia:** Slowness in Initiation and Execution of Voluntary Movements
- **Rigidity:** Increase Muscle Tone and Increase Resistance to Movement (Arms and Legs Stiff) – as severity increases produce cogwheel rigidity
- **Tremor:** Usually Tremor at Rest; When person sits, arm shakes; Tremor Stops when person attempts to grab something (pill rolling tremor)
- **Postural Instability:** abnormal fixation of posture (stoop when standing), problems with equilibrium, and righting reflex
- **Gait Disturbance:** Shuffling feet
- **Orthostatic Hypotension**
- **Dementia** (in some instances)
- **Dystonia** (inappropriate and continuous muscle contraction)
- **Ophthalmoplegia** (weakness in eye muscles)
- **Affective Mood Disorders** (such as major depression)

Lewy bodies and alpha-synuclein – hallmark features of Parkinson's Disease

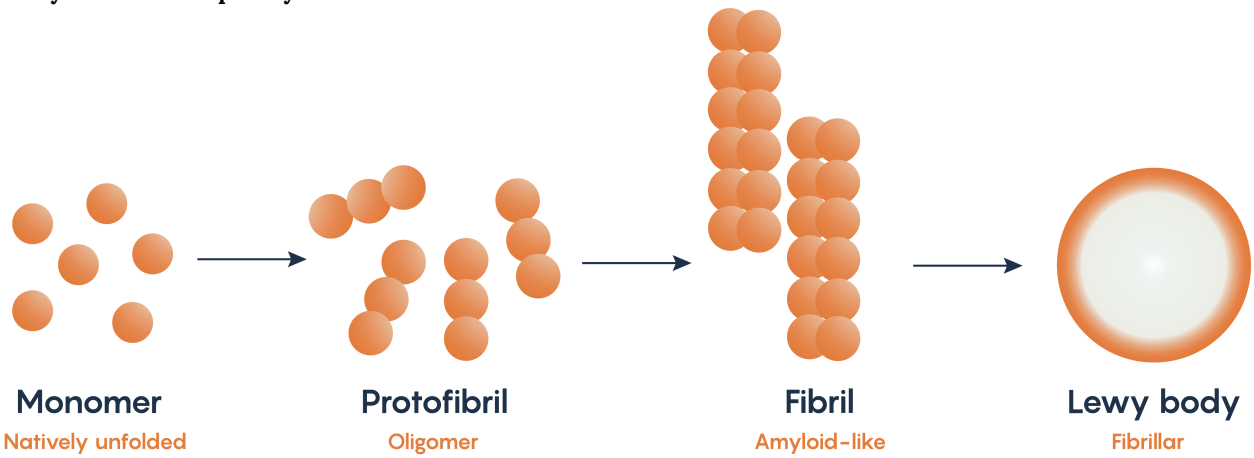


Figure 2. *Misfolding and subsequent accumulation of alpha-synuclein.*

Alpha-synuclein is a naturally occurring protein within neurons. Mutations in the PARK1 and PARK4 genes which normally encodes for alpha-synuclein, have been associated with Parkinson's Disease. As such, many animal models of Parkinson's Disease look for the production of the fibrillary form of alpha-synuclein as it misfolds

and then accumulates within the substantia nigral neurons known as Lewy bodies (Figure 2.). The misfolding and accumulation of alpha-synuclein has been hypothesized to be the reason that neurons undergo apoptosis, although the exact mechanism for how this occurs remains to be elucidated.

Animal Models of Parkinson's Disease

The lack of candidate genes (except for alpha-synuclein, Parkin and DJ-1) has meant that most scientists have looked at toxin models. Most of the toxins that produce features that resemble changes in movement as well as Lewy-body like formation use catecholaminergic destruction. In fact, most of these toxins are incredibly powerful and dangerous mitochondrial complex inhibitors such as reserpine, MPTP, methamphetamine, 6-OH-dopamine, rotenone, and paraquat). In fact one toxin, MPTP is a by-product of synthetic heroin production suggesting that there may be a synthetic substance that causes Parkinson's Disease and some epidemiological studies show a correlation with pesticide (such as paraquat and rotenone) usage and Parkinson's Disease.

Alzheimer's Disease: Overview and General Pathology

Another neurodegenerative condition is Alzheimer's Disease (AD). This neurodegenerative condition is a form of dementia characterized the most common symptoms associated with Alzheimer's Disease notably memory loss, problems with communication and difficulty finding words, attention problems, confusion and spatial disorientation, decreased or poor judgement, changes in mood and personality.

Affected areas explain the AD pathology, which is characterized by memory loss due to shrinkage of the hippocampus, and other problems which include higher level thinking and performance which are controlled by the cortex. Brain atrophy typically begins in the medial temporal lobe (i.e. hippocampus), moves on to the association cortices and therefore affects sensory and motor areas. It also affects the Nucleus Basalis of Meynert which has multiple cholinergic projections to the cortex (and is thought to be responsible for control of sleep, attention, and consciousness) as highlighted in Figure 3.

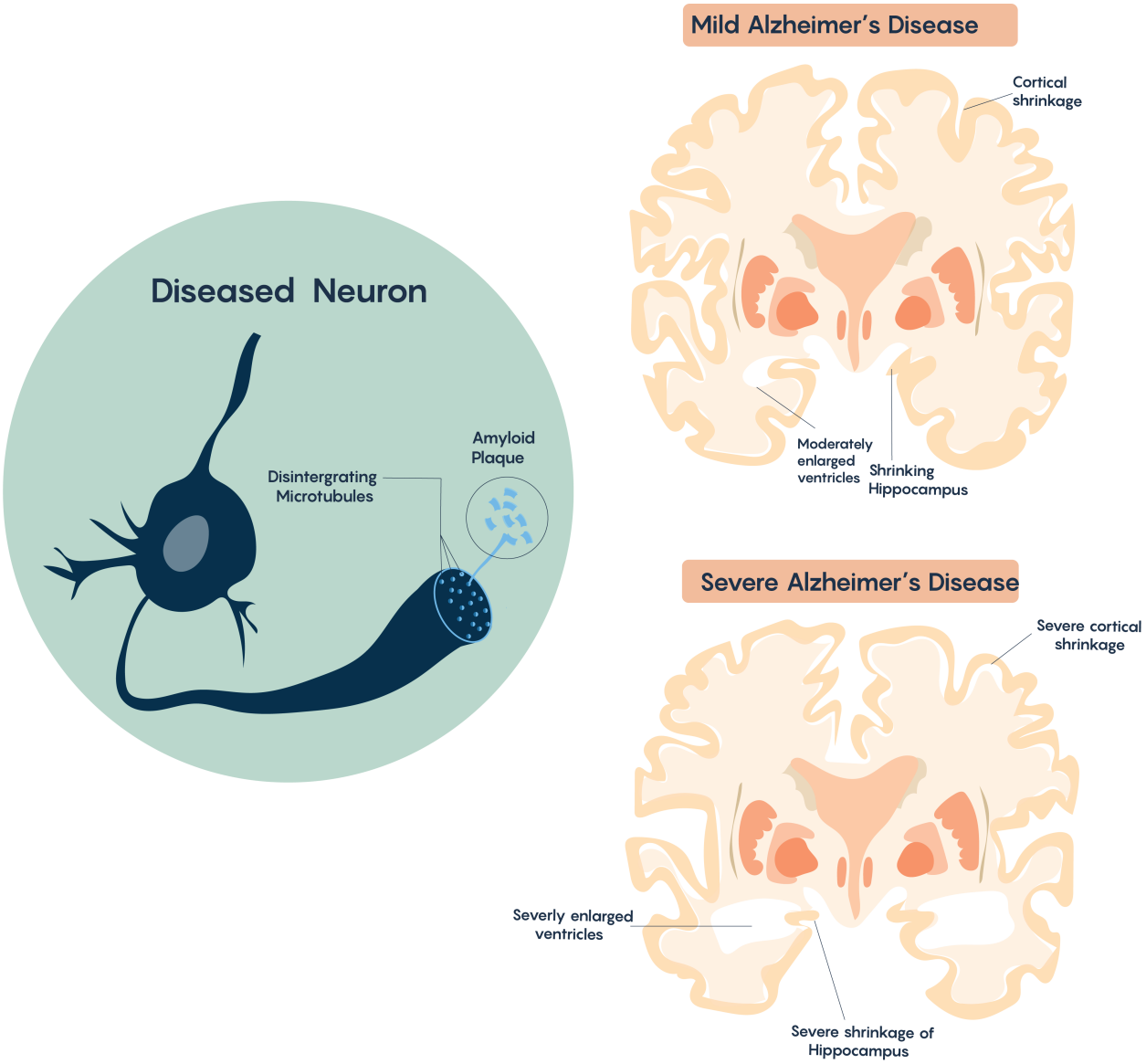


Figure 3. *Shrinkage and loss of specific regions of the brain.*

Cellular Pathology

The typical AD brain is characterized by the loss of neurons, progressive loss of synapses and cholinergic projections, the accumulation of extracellular β-amyloid (Aβ) plaques and intracellular neurofibrillary tangles (NFTs). With increased time and pathology this will often correlate with the formation of a glial scar (involving reactive astrocytes). There is also very strong evidence that this disorder may also have a strong immune component as there is often the infiltration of microglial cells in the Alzheimer's Disease brain.

β-amyloid (Aβ) plaques: βA Cascade hypothesis

One of the hallmark histopathological and molecular features of Alzheimer's Disease is the presence of extracellular aggregates that include ?-amyloid plaques. These plaques are believed to induce cytotoxicity by disrupting normal neuronal functions, ion concentrations, action potential generation. As with the modern theory of neurodegeneration, these plaques are composed of the cleaved form of **amyloid precursor protein (APP)**.

APP can be processed via two different pathways:

- **Non-amyloidogenic pathway** (cleaved by α- and γ-secretases)
- **Amyloidogenic pathway** (cleaved by β- and γ-secretases)

APP Processing

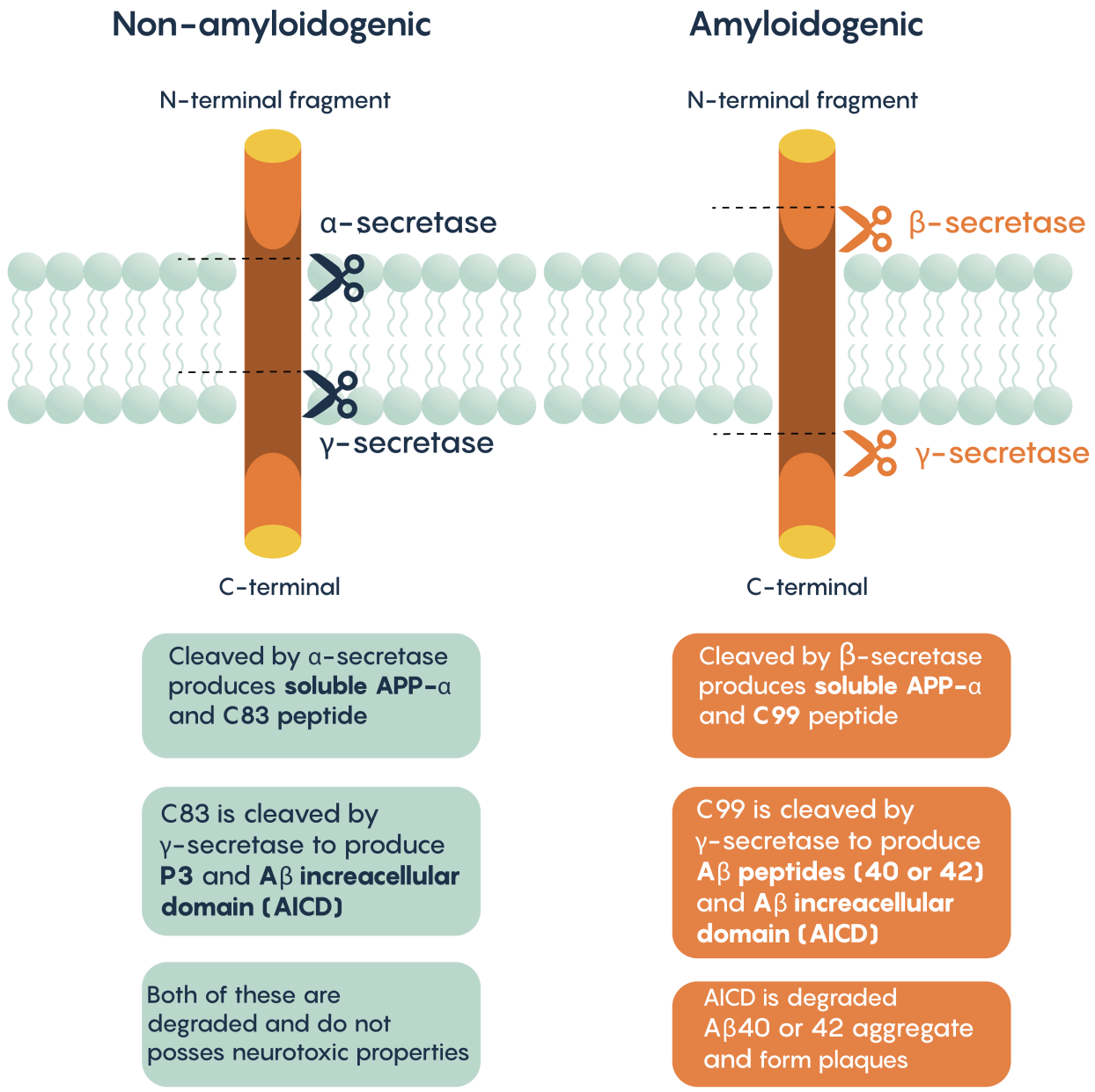


Figure 4. *APP processing pathways leading to the production and aggregation of β-Amyloid.*

Neurofibrillary Tangles (NFTs)

Another feature of the Alzheimer's Diseased brain is the appearance of neurofibrillary tangles (NFTs) that are composed of hyper-phosphorylated tau protein. Normally within neurons (and in fact most cells), tau binds to and stabilizes microtubules (MTs), however, when this is phosphorylated by kinases, tau loses its affinity to MTs and dissociates from the MT complex. This causes the microtubules in turn to disassemble which interferes with proper axonal transport and eventually leads to loss of neuronal integrity. As such the Phospho-tau proteins form intracellular aggregates (NFTs) that become another defining feature of this disease as well as a potential target for therapeutic intervention.

Genetics of Alzheimer's Disease

While sporadic AD cases account for the majority of AD patients, familial AD (FAD) accounts for only 5% of them. The familial form, FAD manifests earlier (around 40-50 years of age) compared to >65 years of age in sporadic cases. Despite this drastic difference in disease onset, symptoms are identical. Only 50% of FAD cases can be explained by known mutations in genes encoding **APP** and **presenilins 1 and 2**.

APP mutations are relatively rare and is characterized by individuals showing symptoms with an average age onset in their early 50's. The conclusion that APP mutations might cause Alzheimer's Disease is based on the observation that most Down Syndrome patients also develop AD after age 40 since they have an extra copy of Ch21 (which codes for APP). However, most inherited forms of APP mutations alter APP processing to:

- increase cleavage via the β-secretase pathway
- increase the Aβ42/40 ratio
- therefore, lead to production of peptides with higher fibrillogenic potential (Figure 2.)

UNIT 3 – FUNDAMENTAL NEUROSCIENCE TECHNIQUES (AND WHEN TO USE THEM)

3.1 Patch-Clamp Electrophysiology

Overview of Cellular Methods

Since we have learned that neurons contain channels, receptors and transporters in Unit 1, one of the most useful parameters that neuroscientists examine, involves determining the movement of ions and the resultant modulation of neuronal membrane potential. Specifically, electrophysiological techniques used in excitable tissues rely on the ionic conductance of ion-channels and how these influence changes in the membrane potential of the cell being examined. Various electrophysiology techniques have been developed to detect and manipulate ion-channel function and/or action potential generation. Determining when to use each electrophysiological technique depends on many different factors including the biophysical properties of the recorded cell, the type of tissue being examined, the use of current- and/or voltage-clamp, whether the intra- and/or extracellular environments will be modulated in the experiments, and most importantly whether a single channel or several ion channels will be recorded.

Patch-clamp Electrophysiology

The most common method used to assess ion-channel function is known as the patch-clamp electrophysiological technique that was developed in the 1970s by Nobel Prize Laureates Erwin Neher and Bert Sakmann. The patch-clamp technique allows a researcher to measure the biophysical properties of ion-channels on millisecond timescales. Patch clamp requires the initial formation of a Giga-ohm (GΩ) seal between the plasma membrane and the blunt tip (0.5–2 μm in diameter) of a heat-polished glass or quartz micropipette (electrode). Once a Giga-ohm seal has been created, this '*cell-attached configuration*" (Figure 1.) maintains the integrity of the plasma membrane (i.e. the membrane seal is not ruptured) preventing the intracellular solution inside the micropipette from dialyzing into the cell. However, this also restricts electrical access to the cell intracellular space resulting in an inability to control the membrane potential of the cell. In this configuration, only the patch membrane potential relative to the cell's resting potential can be directly controlled. By altering either the magnitude of the seal resistance (a *loose seal* vs. *tight seal*) and/or whether the recording electrode is current- *vs.* voltage-clamped, the cell-attached configuration can be used to measure single channel currents, spontaneous neuronal cell firing and synaptic potentials as well as evoked action potentials within the cell. The other main advantage of this configuration is that although it is limited for the reasons outlined above, this configuration is the starting point for the majority of the types of patch-clamp recordings.

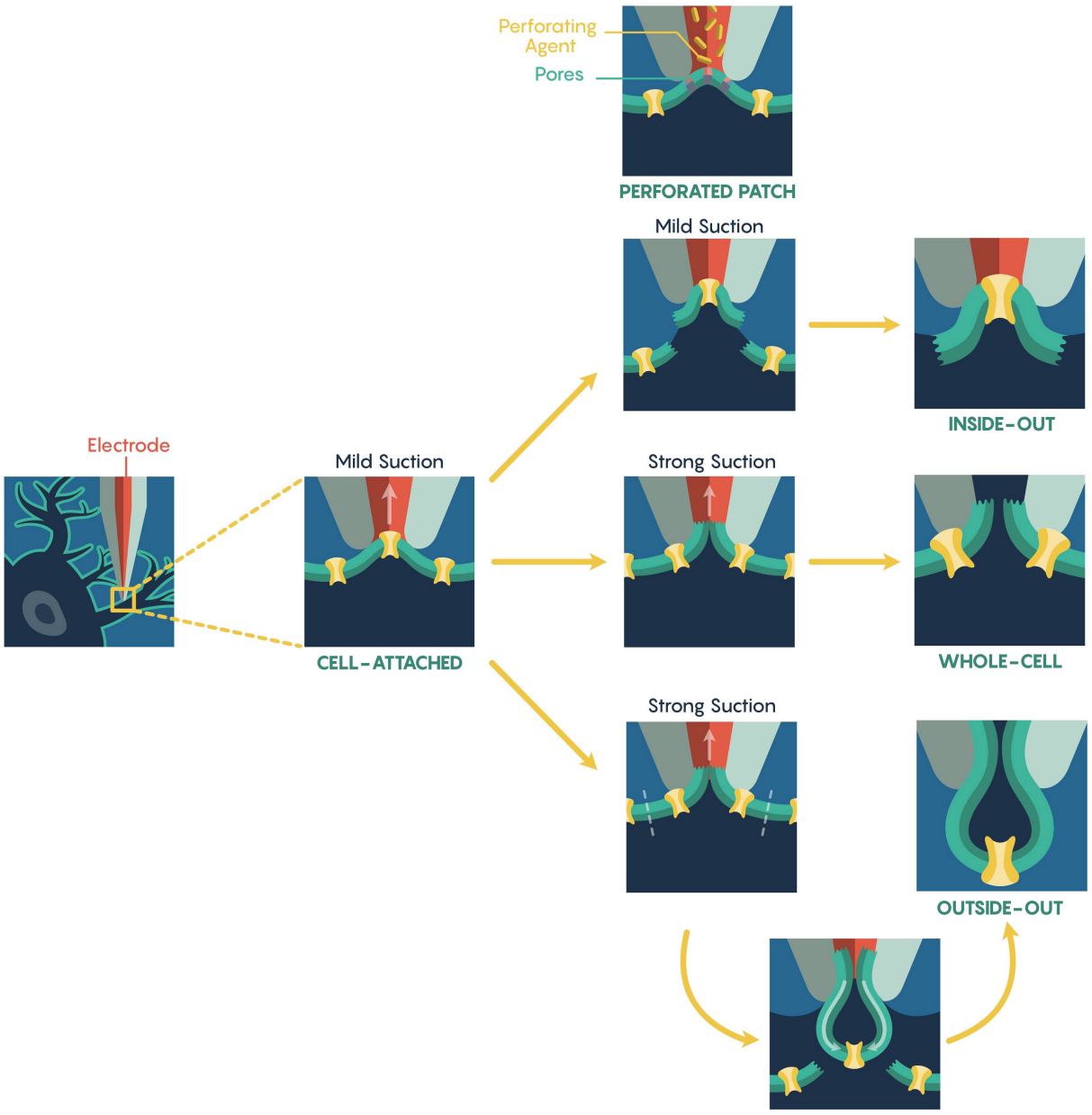


Figure 1. *Electrophysiological methods. The cell-attached patch-clamp method. The perforated patch, outside-out and inside-out configurations. To show potential dialysis, the pipette lumen and cytoplasm are represented by red and navy blue, respectively.*

To increase electrical access to the cell interior, two different methods are used. First, the internal pipette solution contains antibiotic or antifungal agents (e.g., nystatin, gramicidin, amphotericin-B), these agents form small, monovalent ion-permeable pores that 'perforate' (Figure 1.) the membrane allowing access to the entire cell. Importantly, these pores do not allow passage of proteins thus ensuring that the intracellular contents remain intact preserving intracellular signaling pathways. However, this perforated patch technique has several limitations including higher electrical noise, loss of single channel resolution and patch instability. Additionally, creating a perforated patch requires a significantly long period of time.

An alternative approach to the perforated patch technique is to apply a strong suction, or brief voltage

transient, after Giga-ohm seal formation in order to rupture the intact plasma membrane. Upon rupture, a low-resistance electrical and physical continuity is established between the pipette and the cell interior and this new configuration is known as the whole-cell configuration (Figure 1.). Accordingly, this configuration permits direct measurements of the cell's membrane potential (via current-clamp) and its manipulation (via voltage-clamp). Due to the physical continuity between the cell interior and the pipette solution, the cytosolic contents can be reasonably controlled. Furthermore, unlike the perforated patch, pharmacological or ionic manipulations of both the intracellular and extracellular environment can lead to the eulicidation of individual ion-currents. However, this physical continuity between the pipette lumen and cytosol may also dialyze out and/or alter the activity of endogenous second messenger systems. Thus, whole cell recordings are vulnerable to this limitation and it is critical to assess current 'rundown' of the system and cells within these types of whole-cell recording systems.

It is also possible to create 'Cell-free' variations of patch-clamp techniques also exist. For instance, upon giga-seal formation, the electrode can be gently retracted pulling the membrane patch into the bath solution. This arrangement, known as the inside-out configuration (Figure 1.), enables the complete manipulation of the cytoplasmic face of the plasma membrane via the bath perfusion – a feature not possible in the cell-attached configuration. As a result, inside-out patches allow for the manipulation the immediate environment of the inner membrane face. Unfortunately, this arrangement suffers from the loss of intracellular signaling pathways acting on the ion-channels following patch excision; a particularly important consideration when examining altered channel activity.

Similarly, an outside-out patch (Figure 1.) also requires the gentle retraction of the patch electrode from the whole-cell configuration. However, in this situation the pipette retraction forces the plasma membrane surrounding the electrode tip to detach from the cell and reseal forming a cell-independent patch whose extracellular membrane is facing the bathing solution. This allows an experimenter to have complete control over the intracellular environment and can rapidly exchange different external physiological or pharmacologic drugs over the same patch.

3.2 Molecular toolbox – Neural Circuits: The Basics

Key Takeaways

- Precision targeting of neurons
- Optogenetics the basics
- Channelrhodopsins
- Inhibitory Opsins

Precision Targeting of Neurons

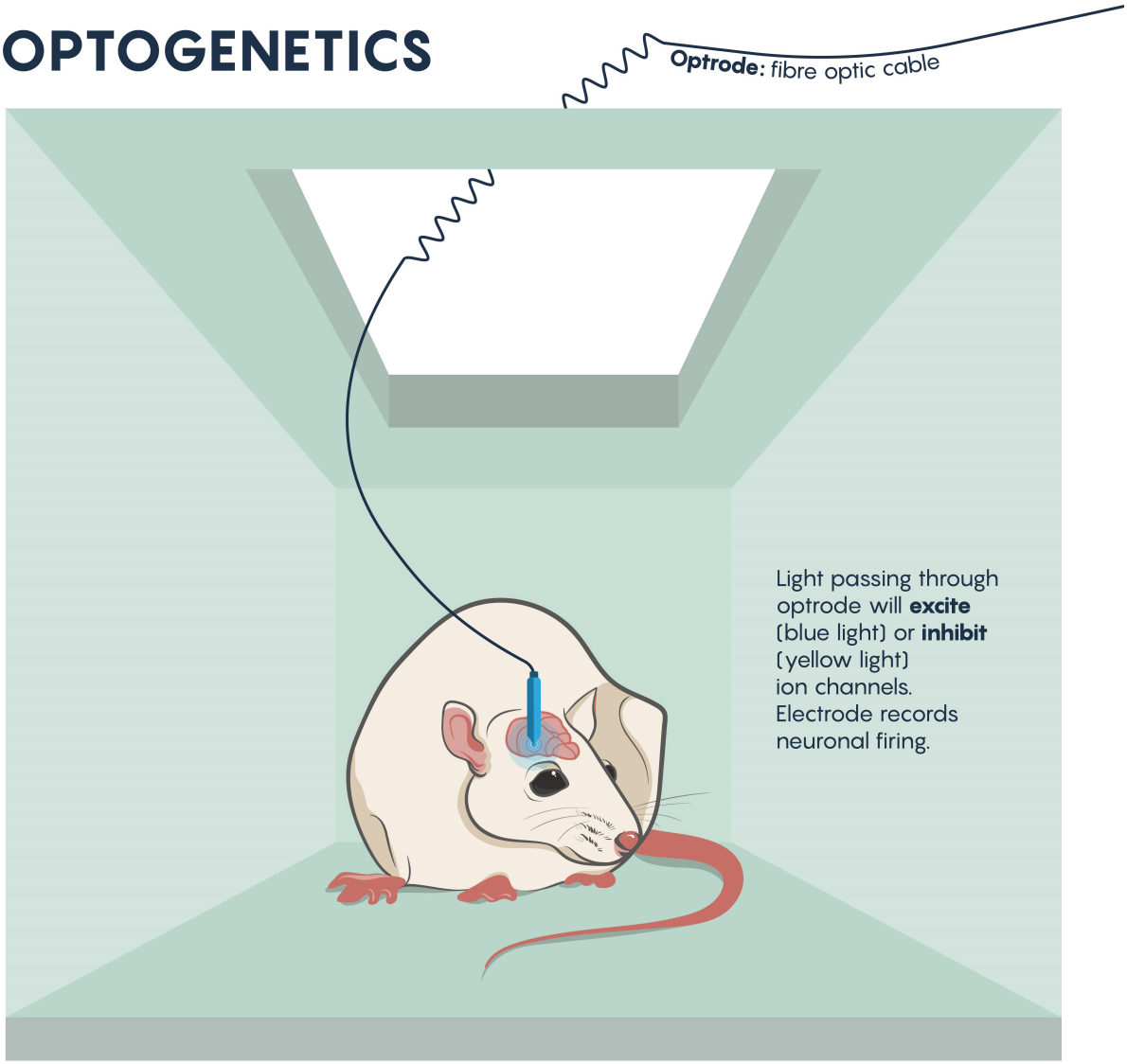


Figure 1. *The beginnings of brain circuit studies in mice using optrodes to excite or inhibit ion channels. Adapted from Nature 2016 (open access cc by 4).*

Neurons don't work in isolation and they typically make synaptic connections that resemble circuits. Most investigations of behaviour and development have relied on mapping the neural circuits within the brain and CNS. Understanding the connectivity of these circuits allow neuroscientists to understand behaviour and pathologies (Figure 1.). In the past, this has meant lesioning or destroying parts of these circuits, or electrophysiologically stimulating these circuits and examining the resulting behaviour. These older methods have allowed us to dissect the detailed workings of the neural circuits underlying natural behavior, and have also

enabled us to understand how some neural circuits become dysfunctional in disease states such as Parkinson's disease or epilepsy.

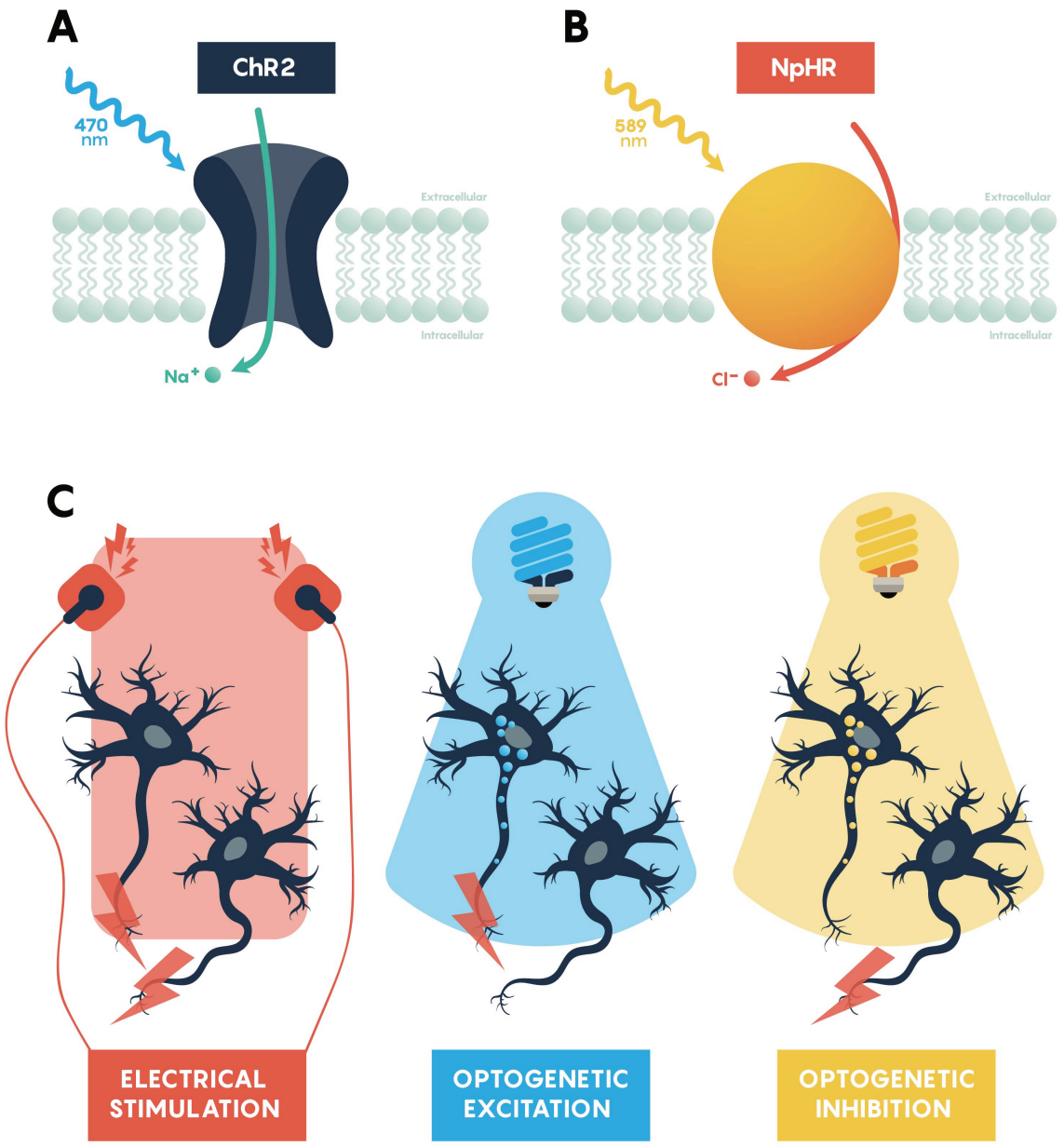


Figure 2. *Panels summarizing the features of excitatory, ChR2, (A) and inhibitory, NpHR, (B) opsins. Panel C showing that all neurons would be excitable using a standard electrode. However, optogenetic excitation (blue light) and inhibition (yellow light) only work on specific neurons that express the appropriate opsin.*

The vertebrate brain (mice, rats, primates and humans), contains many different cell types with distinct molecular expression patterns, physiological activity, and topological connectivity, which are intermingled in a highly heterogeneous network. Studying specific groups of neurons in this milieu becomes very challenging and

scientists using lesion, stimulation and tracing studies were never sure about the spatial (i.e. were only specific neurons affected) and temporal (i.e. can the lesion be reversed, allowing for reversal of behaviour).

The questions around specificity and temporal reversibility changed with the introduction of optogenetics. Since the late 2000s, optogenetics has ushered in a new era of potent and targeted control over multiple aspects of neural function. Genetic and optical methods applied together allow tight spatial and temporal control of the activity of specific kinds of neurons in the living brain, a revolutionary advance that will allow us to achieve an unprecedented understanding of neural circuit function in behaving animals. Using this technique, neurons are first genetically engineered (using a variety of mechanisms, described later) to express light-sensitive proteins (opsins). When these neurons are then illuminated with light of the correct frequency they will be transiently activated or inhibited or their signaling pathways will be modulated, depending on the particular kind of opsin that was chosen for expression. Cell type–specific expression is typically achieved with transgenic animals, viral vectors, or a combination, and spatially restricted light application allows for further refinement in targeting to specific brain regions. Light can be applied in a variety of temporal patterns in order to optimally influence neuronal function (permitting experimental control of spike frequency and burstiness, among other parameters), and may be restricted to specific short behavioral periods of examination.

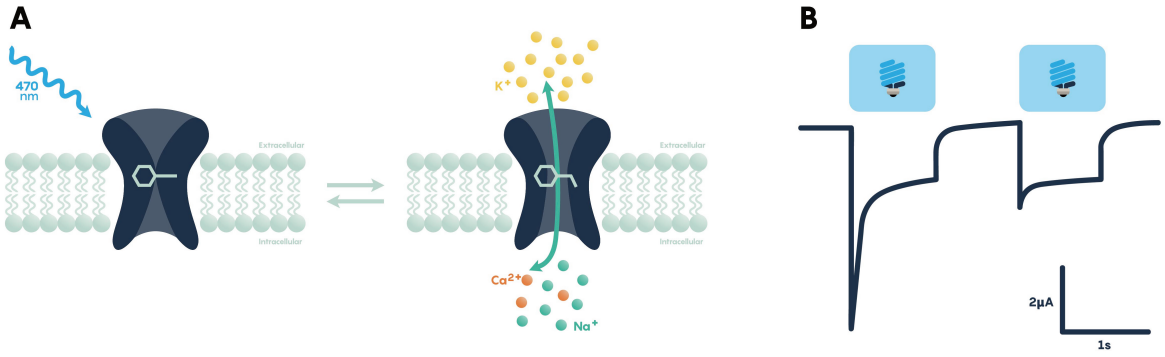


Figure 3. *Panel A showing the excitatory effect of blue light on a membrane-bound opsin functioning as a channel. Panel B showing action potentials in response to blue (excitatory) light.*

Optogenics: The Basics

What Are Optogenetic Actuators?

Optogenetic actuators are proteins that modify the activity of the cell in which they are expressed when that cell is exposed to light (Figure 3.). These actuators can be used to induce single or multiple action potentials (which can be organized into regular spike trains or which can be pseudo-random at a user-controlled rate), suppress neural activity, or modify biochemical signaling pathways, with millisecond control over the timing of events. The most powerful and widely used actuators are opsins—naturally occurring light-sensitive transmembrane proteins—that are found in a variety of organisms ranging from microbes to primates, and that can be used as found in nature or engineered to optimize functioning. Naturally occurring opsins can be broadly categorized into two major classes: microbial opsins (Type I) and vertebrate opsins (Type II). Type I opsins are found in

prokaryotic and eukaryotic microbial organisms, including bacteria, archaea, and algae, and are composed of a single membrane–bound protein component that functions as a pump or channel. These opsins are used by their host microorganisms for a variety of functions, including navigation towards sources of energy and away from hazardous environments, and control the intracellular concentrations of a variety of ions and the beating of flagella.

Type I opsins were used in the first optogenetics experiments to control neuronal function, both because of the ease of genetic engineering using a single component protein and because of their faster kinetics, and remain the primary (but not exclusive) source for new natural and engineered opsins.

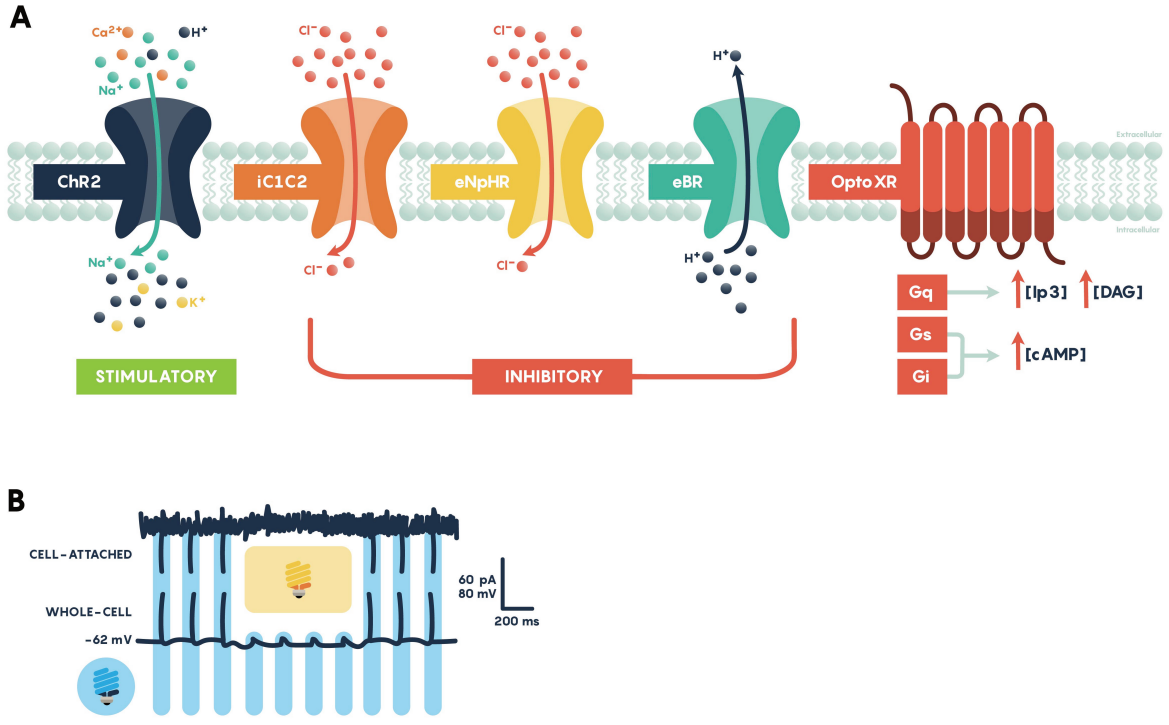


Figure 4. *Opsins are membrane-bound proteins that are activated with light, which results in cell activation (depolarization), inhibition (hyperpolarization), or modulation of intracellular signaling cascades (panel A). Illustrated here are ChR2 (a cation channel used to stimulate neural activity), iC1C2 (a newly developed chloride channel used to inhibit neural activity), eNpHR3.0 (a chloride pump used to inhibit neural activity), eBR (a proton pump used to inhibit neural activity), and OptoXR (a G protein–coupled receptor used to modulate intracellular signaling cascades). (Panel B) Cell-attached and whole-cell recordings from a neuron expressing both ChR2 and NpHR. Note that individual spikes can be elicited with a short pulse of blue light (which activates ChR2) and that these spikes can be blocked with continuous yellow light (which activates NpHR). Panel A adapted with permission from Fenno et al., 2011, and panel B adapted with permission from Zhang et al., 2007.*

How Do Optogenetic Actuators Work?

Opsins of both types require retinal, a form of vitamin A that isomerizes upon absorption of a photon, in order to function. When retinal binds to the opsin the retinal-opsin complex becomes light sensitive, and if a photon strikes the retinal in this state its resulting photoisomerization will induce a conformational change in

the opsin. This leads to channel opening or pump activation, a change in membrane potential, and ultimately the activation or inhibition of neuronal activity. Therefore, retinal must be present in order for optogenetic actuators to function. Fortunately, particularly for the early proof-of-principle experiments, retinal is already present in sufficient quantities in mammalian neural tissue to permit the use of optogenetic tools without exogenous retinal supplementation. However, invertebrate model systems such as *Drosophila* do need retinal supplementation through their diet in order for optogenetic effectors to function. Here we review the different classes of optogenetic actuators, grouped by their effect on neural activity or signaling.

Optogenetic Stimulation of Neural Activity: How to Turn Neurons "On"

Channelrhodopsins

Channelrhodopsins (ChRs) are light-gated ion channels discovered in *Chlamydomonas reinhardtii*, a unicellular green alga. The first use of a microbial opsin to control the spiking activity of neurons utilized Channelrhodopsin-2 (ChR2), one of two channelrhodopsins expressed by this organism. ChR2 is a light-gated nonspecific cation channel which, when illuminated with blue light, opens and allows the passage of cations and the subsequent depolarization of the cell. In 2005 ChR2 was introduced into cultured hippocampal neurons and successfully used to control spiking activity with fine temporal precision. As demonstrated by this pioneering paper, very brief (millisecond) pulses of blue light can be used to induce single action potentials in ChR2-expressing neurons, and spiking activity driven by the activation of this opsin can be controlled with high precision at frequencies approaching 30 spikes per second.

Optogenetic Inhibition of Neuronal Activity: How to Turn Neurons "Off"

Chloride Pumps

Inhibiting neuronal activity in neural circuits can complement excitatory tools by allowing investigators to test the role of individual neuronal circuit components. One of the most efficient and widely used optogenetic inhibitory opsins, NpHR, is a halorhodopsin from the archaeon *Natronomonas pharaonis*. NpHR pumps chloride ions into the cell upon long wavelength light activation, resulting in hyperpolarization. Genetic engineering has led to a series of revisions producing eNpHR3.0, an opsin with improved surface membrane localization and a larger photocurrent. With an excitation maximum at 590nm, eNpHR3.0 can be driven by green, yellow, or red wavelengths of light, enabling the use of less expensive laser systems.

Proton Pumps

Proton pumps can also be used to inhibit neurons through hyperpolarization, by pumping protons out of the cell, and have some features that make them desirable alternatives to chloride pumps, which include fast recovery from inactivation and larger sized currents following activation. Arch (archaerhodopsin-3 from *Halorubrum sodomense*), Mac (from the fungus *Leptosphaeria maculans*), ArchT (an archaerhodopsin from *Halorubrum* strain TP009), and eBR (an enhanced version of bacteriorhodopsin from *Halobacterium salinarum*) are proton pumps that show robust efficiency in inhibition. Recent work has demonstrated that inhibition of eNpHR3.0-expressing neurons may render the inhibited neuron transiently more excitable due to a chloride-driven shift in the type-A γ-aminobutyric acid (GABAA) receptor reversal potential which may point towards a proton pump inhibitor as the opsin of choice for some experiments especially involving this system.

Practice questions:

Which opsin, when expressed, would allow for the neuron to be excited?

1. A) ChR2
2. B) NpHR
3. C) 0
4. D) None of the above

What opsin functions as a proton pump?

3.4 Chemogenetic Methods to Examine the Brain and Behaviour

Although optogenetics provides a superior level of temporal (it's quick – you flash on pulses of light to elicit immediate activity) and spatial control of a neuronal circuit, it requires specialized fibre optic cables (also called optrodes), lasers and actuators. As such, this can lead to higher than expected costs as well as a significant investment of time and training.

Another precision method for examining the function of specific groups of neurons within a known circuit to alter behaviour is known as chemogenetics or pharmacogenetics. Instead of using light, unique and specific drugs can activate exogenously expressed receptors. The most popular of these precision pharmacogenetic techniques is known as DREADDs. This is an acronym for **D**esigner **R**eceptor **E**xclusively **A**ctivated by a **D**esigner **D**rug and as mentioned above this requires the incorporation of a synthetic receptor (from the hMxDx family from the Acetylcholinergic muscarinic receptor) into an animal's genome and the neuronal function is controlled by the synthetic ligand clozapine-N-oxide (CNO). As with optogenetics, the experimenter decides which neurons (or other cells within the nervous system) have the machinery to express the receptor and once expressed, DREADDs may be used to tightly control neuronal activity.

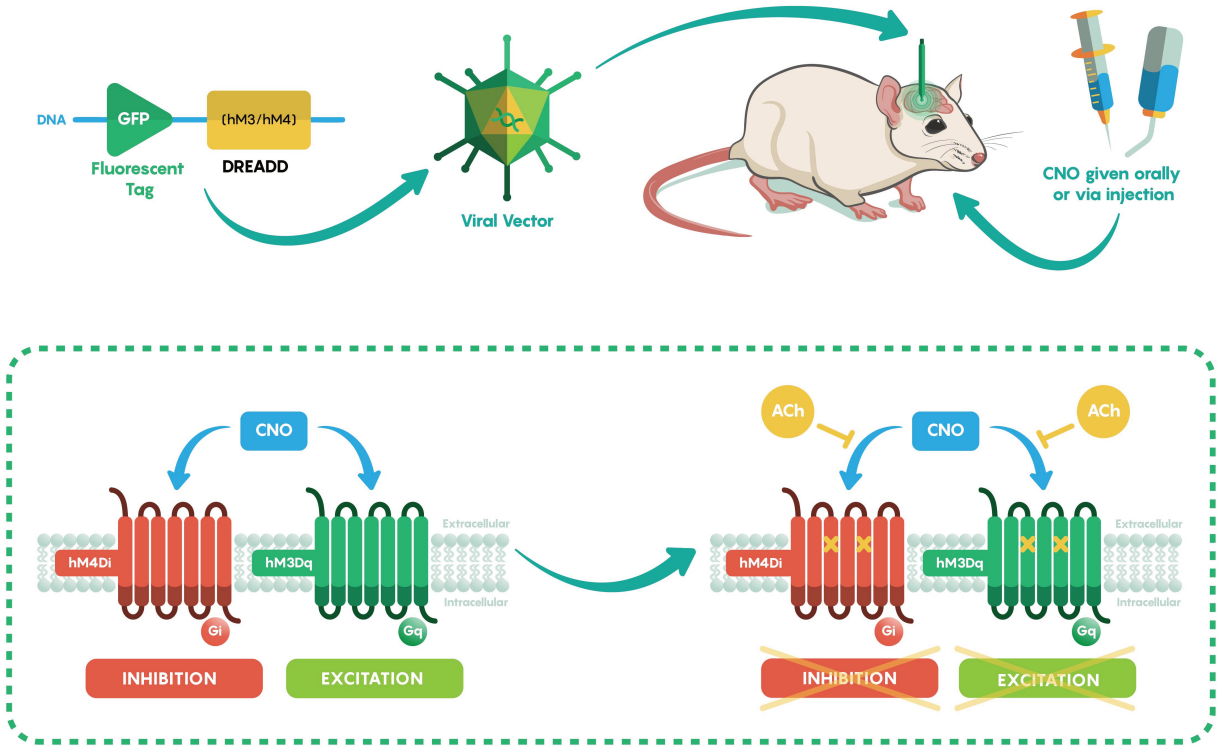


Figure 1. *Schematic overview of how different variants of DREADDs (hM3Dq and hM4Di) can be used to activate and also inhibit groups of neurons using CNO. The figure also shows achetylcholine's (ACh) inhibitory effects on CNO.*

Similar to optogenetics, different DREADDs, once expressed on the appropriate groups of neurons can both cause excitation (HM3D) of the neurons or their inhibition (HM4D) in the presence of CNO. Importantly CNO can

be injected into the test animal or be added to their drinking water so there is no requirement for any additional equipment. As CNO is a compound that is designed to work specifically on DREADDs, it was thought that there would be no activation of any endogenous receptors that were not genetically engineered.

However, a recent report in 2017 by Gomez et al., in the journal Science (ref), suggested that CNO was metabolized in peripheral tissues and formed the metabolite clozapine. Clozapine can bind to a number of different serotonergic, dopaminergic and adrenergic receptors within the brain, and it was suggested by Gomez et al., that care should be taken when interpreting behavioural data using the CNO-DREADD system.

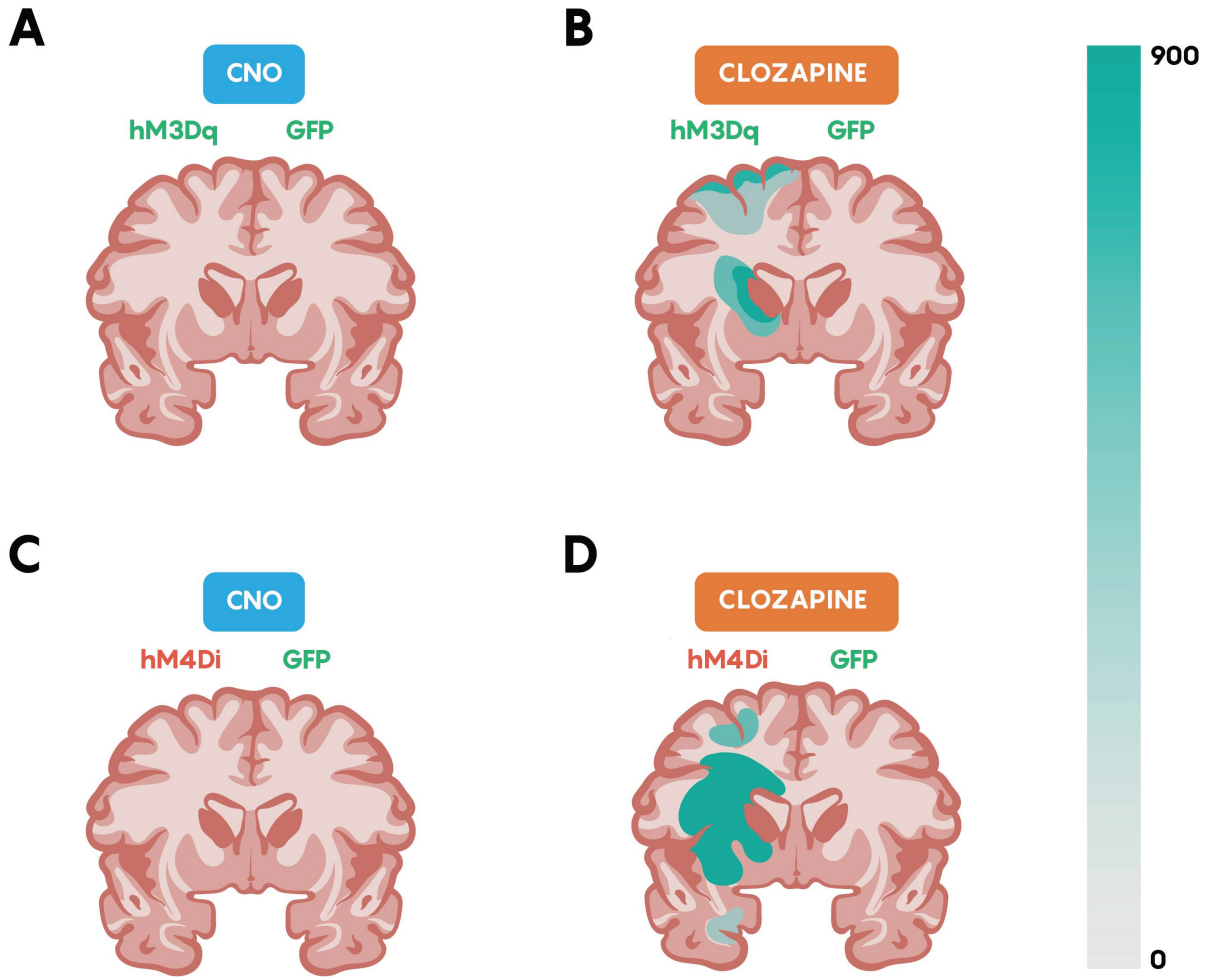


Figure 2. *Figure adapted from Gomez et al., showing the lack of relative binding of the ligand CNO (A and C) to the DREADDs versus the metabolite clozapine which shows significant binding to the same DREADDs (B and D) as indicated by the darker intensity stains.*

3.5 Cre-Lox, Driver Lines, and Next Order Specificity

Key Takeaways

- What is the Cre-Lox system?
- What is the advantage of mouse Cre-driver lines?
- Examples of Cre-driver Lines used in neuroscience.

What is the Cre-lox system and why do we need it?

In the previous chapters we have examined the use of recombinant molecular techniques that help neurobiologists to understand the role of specific neurons within a brain circuit in a complex behaviour. However, we haven't yet examined how to ensure delivery to specific neurons to ensure that the construct (i.e.ChR2, hM3DR or other constructs) is not inappropriately expressed in other cell types nor other neurons. Instead of relying only on the cells internal machinery being driven by cell specific gene promoters, the Cre-lox system is often used in neuroscience. This is a powerful method to selectively manipulate gene expression in specific subsets of tissues. There are 2 elements to make this system work effectively; loxP sequences that are created de novo and the presence of Cre-recombinase (an exogenous nuclease). Importantly neither the nuclease enzyme Cre recombinase nor loxP sequences are normally found in mammal systems, so their introduction has no functional consequences to the DNA nor to the neurons. Genetically engineered loxP sites are 34 bp DNA sequences that bind to the protein Cre-recombinase (and the nuclease always needs to bind to 2 loxP sites). Interestingly, as shown in Figure 1, when loxP sites are in the same orientation (5' to 3') and Cre-recombinase binds to both, this causes deletion of the DNA sequence between the loxP sites while leaving one loxP. This type of "floxing" reaction is known as excision. If the loxP sites are in the opposite orientation then the sequence between them is inverted or "flipped".

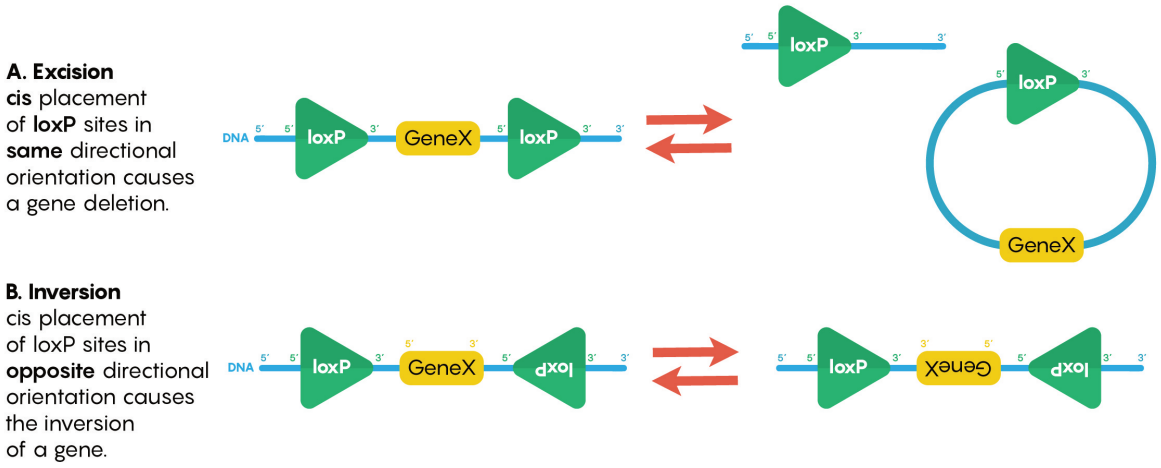
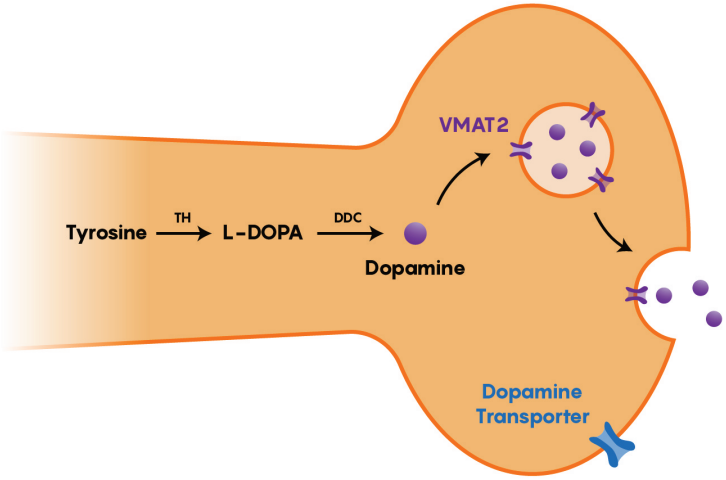


Figure 1. *Different orientations of the loxP sites around the DNA sequence of interest will cause either excision (removal of the DNA) or inversion of the DNA sequence.*

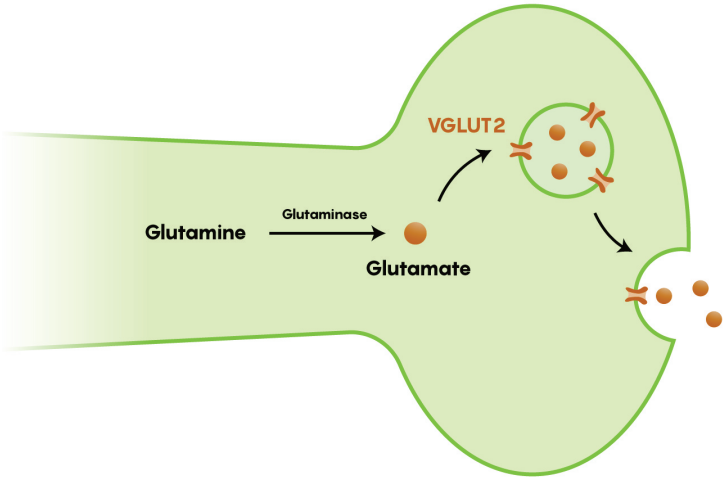
Cre-driver lines: A special type of transgenic mouse

As Cre-recombinase has no effect on DNA except for those that contain loxP sites (which are never found in mammalian DNA), generating transgenic Cre-recombinase mouse models was a logical step in examining specific expression of genetic tools (optogenetic, chemogenetic or other) in neurons. As different neurons have different cellular machinery to activate and express certain genes, Cre-recombinase was targeted to specific neuronal (or other brain cell types) with this in mind. As the Cre-recombinase expression was being "driven" by the machinery specific to a cell type, the term Cre-driver lines has become embedded within neurobiology. As shown in Figure 2 below, different types of neurons, whether inhibitory, excitatory or other have specific proteins and therefore genes that would allow for the specific expression of the exogenous Cre-recombinase. For example the TH::IRES-Cre-recombinase mouse only expresses Cre-recombinase within dopaminergic neurons as TH (Tyrosine Hydroxylase) is the synthetic enzyme that converts the amino acid tyrosine to dopamine in neurons. In the same vein, VGAT::IRES-Cre-Recombinase would be a transgenic mouse line that would be used to investigate inhibitory GABAergic neurons. A list of different genes/protein products is found in both Figure 2 and the following table.

DOPAMINERGIC DRIVERS



EXCITATORY/GLUTAMATERGIC DRIVERS



INHIBITORY/GAGAERGIC DRIVERS

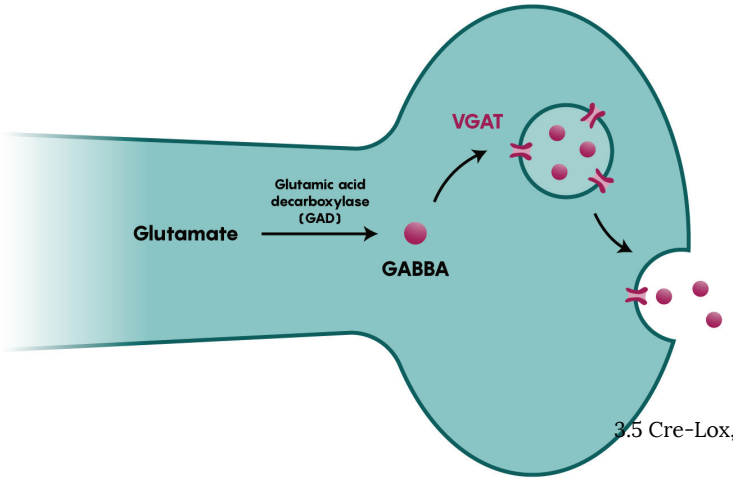


Figure 2. *Differential expression of proteins in specific groups of neurons including dopaminergic, excitatory glutamatergic and inhibitory GABAergic types that allow for the directed expression of Cre-recombinase in specific subsets of neurons.*

Examples of cells targeted with Cre-Recombinase	
Driver line	**Specific cell types – Cre-Recombinase**
GFAP-Cre	Astrocytes or neuronal stem cells
Nestin-Cre	Neuronal stem cells or precursor cells
CAG-Cre	General promoter: Ubiquitous expression in all cells of the brain
Synapsin I-Cre	All neurons (all types of neurons
EF1a-Cre	General promoter: Ubiquitous expression in all cells of the brain

3.6 Viral Mediated Delivery of Genes to Neurons

There are a number of ways to deliver DNA (or other genetic information) to neurons including transfection, electroporation, biolistic delivery, and nanoparticles, but within an intact biological system like the brain is challenging. Luckily, neurons are very easily infected by viruses (see Unit 1). Neurobiologists will therefore package genetic material that they want to be expressed within specific groups of neurons inside different types of viruses (Figure 1.).

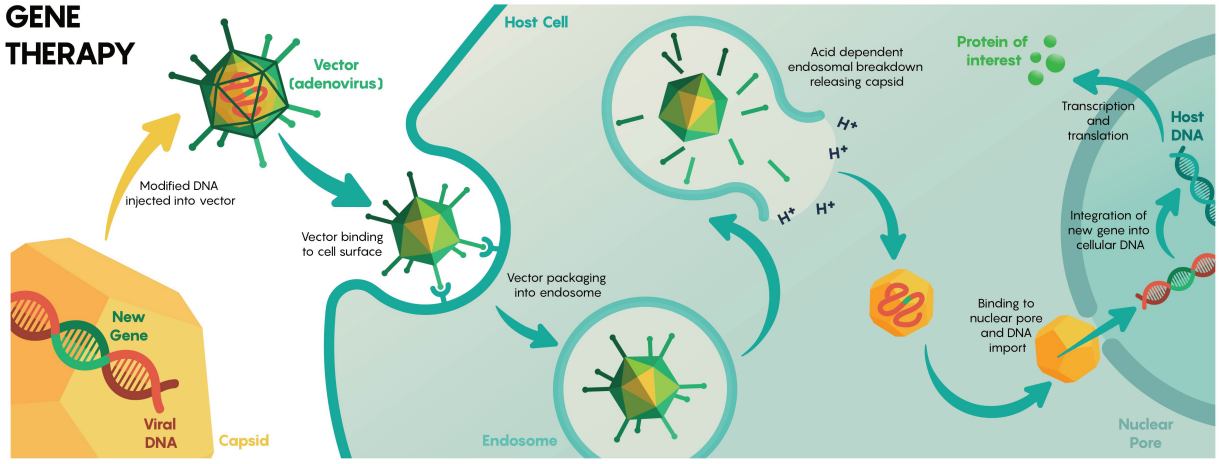


Figure 1. *Schematic overview of how viruses (i.e. adenovirus) can be used to deliver recombinant genetic material to neurons, or other cell types within the nervous system. Steps include viral binding to cell membrane, endosomal packaging and breakdown, delivery and integration of vector into host DNA, and ending with the expression of the desired protein.*

In fact, as molecular neurobiologists, we often have a number of different viral vectors that we can use to our benefit. Some viruses for example package only a small amount of genetic material (AAV for example) while others like HSV will be able to package up to 150 kb worth of genetic material (and this is a lot) into the virus. Speed of expression and how long the expression of the recombinant genetic material will persist for, are often considerations on the choice of viral vector (see Table 1).

Properties of recombinant viral vectors useful for gene delivery in the adult nervous system

	Adeno-Associated Virus (AAV)	**Lentivirus**	**Herpes Simplex Virus (HSV) Amplicon**
Genetic material	Single-stranded DNA	RNA	Double-stranded DNA
Capacity for genetic material	~5 kilobases	~8 kilobases	~150 kilobases
Speed of expression	Weeks	Weeks	Days
Duration of expression	Years	Years	Weeks to months, but elements can be added for persistent expression

One technical consideration that is often overlooked – how are viruses containing the gene of interest that we hope to express in neurons generated? Viruses aren't truly alive so how does this work? We often use a cell line like the HEK293 cell which is a non-neuronal cell line. We transfect 3 separate plasmids into the HEK293 cells in

culture. 2 of the plasmids are viral (pVSV-G and packaging plasmids for example for lentiviruses, and the last one is the construct that we want to specifically deliver. Figure 2. shows the workflow for production of lentiviruses (upper panel) and AAV viruses (lower panel). In both cases, viral particles are released from the transfected HEK293 cells and the virus is collected from the cells and spun on a gradient using ultracentrifugation and a final purification step. The purified fluid then contains live virus that can infect neurons.

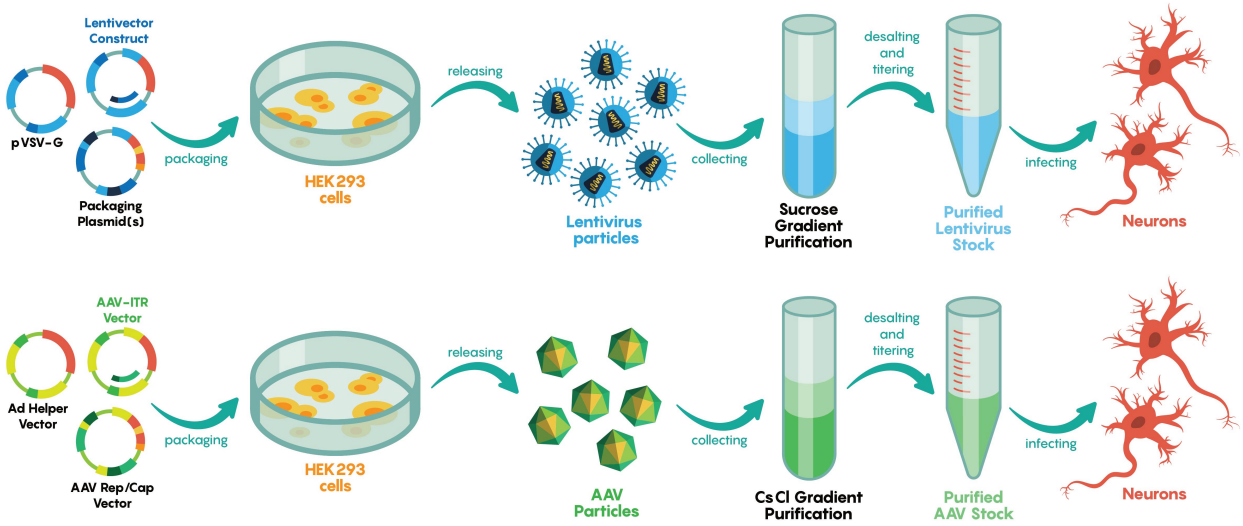


Figure 2.Lentivirus *(upper panel) – Part of the retroviridae family (viral sizes are 80-100 nm diameter) derived from HIV-1 virus. To produce lentiviruses with the gene of interest as the lentiviral DNA construct, first transfect cells with a packaging plasmid and the envelope vector* (VSVG).***Adeno Associated Virus (AAV)*** *(lower panel) – Member of the parvoviridae family (20 nm diameter). To produce AAV, package a gene of interest into the AAV-ITR vector and transfect cells with a Helper vector and the Rep/Cap DNA integration vector.*

3.7 A Very Interesting Transgenic Mouse for Neuroscience

One of the very exciting aspects of neuroscience is the use of transgenic mice to aid in our understanding of behaviour. One particular mouse, not originally intended for use in neuroscience was the Rosa or iDTR mouse. The Rosa or iDTR (for inducible Diphtheria Toxin Receptor) mouse utilizes a transgene very similar to the Cre-driver lines. In this mouse (shown in Figure 1 below) all cells throughout the mouse's body carries the DNA sequence for the Diphtheria Toxin Receptor DTR). Note that this DTR DNA sequence is preceded by a STOP codon that is flanked by loxP sites. If Cre-recombinase was introduced by vector injection then the STOP codon is removed and the DTR is now transcribed and translated in the area or tissue where the Cre-recombinase was injected. Normally this does not present a problem as the mouse has had no exposure to diphtheria toxin. However, we can inject the toxin systemically into the mouse and only those cells expressing the receptor will undergo apoptotic cell death.

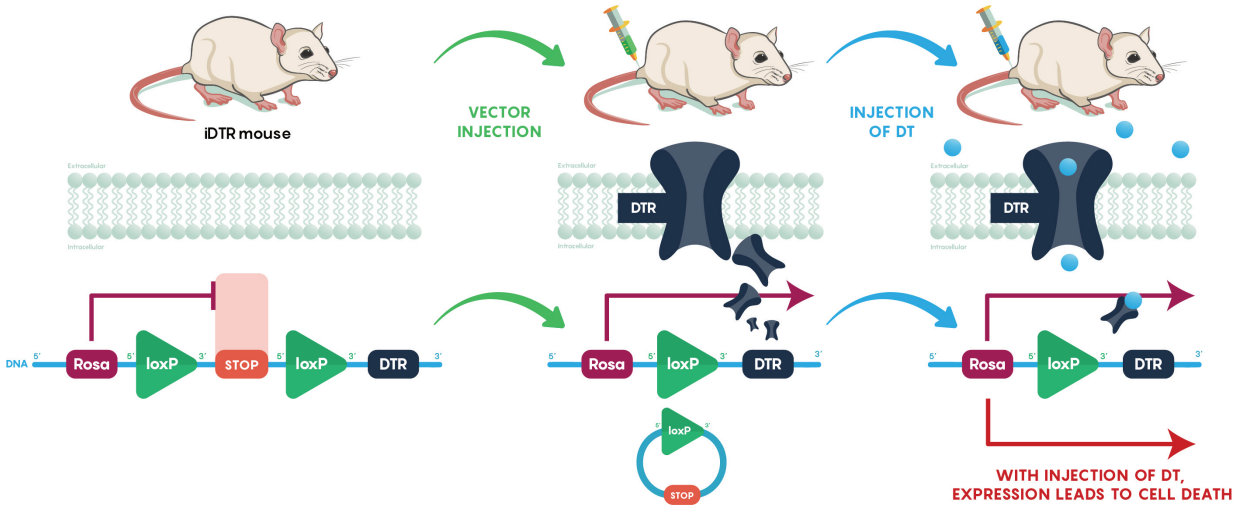


Figure 1. *Schematic diagram illustrating the concept of using the Rosa/iDTR mouse to eliminate specific groups of cells. Much like the Cre-Lox system, there is a reliance on driver lines. All cells in the mouse's body carries the DNA sequence for Diptheria Toxin Receptor(DTR). However, due to the STOP codon being upstream of the DTR, the DTR is never transcribed. However, when a vector is injected into the mouse, the LoxPs excise the STOP codon and thus DTR is able to be transcribed and translated in the tissue where Cre-recombinase was injected. When injected with the diptheria toxin, the cells are able to accept it with the expressed DTR and thus undergo apoptosis.*

3.8 Molecular Biological Measures of Neuronal Activity: "CatFish"

Although electrophysiological techniques allow researchers to examine the activity of neurons, it is often challenging to know a priori, which neurons will respond during a particular behaviour. At the cellular level, neuronal activity can now be visualized using compartment analysis of temporal activity by fluorescence *in situ* hybridization (catFISH), can map the distribution of neurons activated during two discrete behaviours by visualizing the sub-cellular localization of various immediate early gene (IEG) mRNA. The catFISH method examines the activity history of neurons at two different time points and estimates the numbers of neurons active based on the staining of particular IEG mRNAs during a distinct behavioural episode. This makes the technique similar to electrophysiological estimates under comparable conditions (i.e. before and after stimulation) and researchers typically measure "active" neurons by looking for the expression of ***c-fos*** or ***Arc mRNA*** before and after stimulation/behaviour etc.

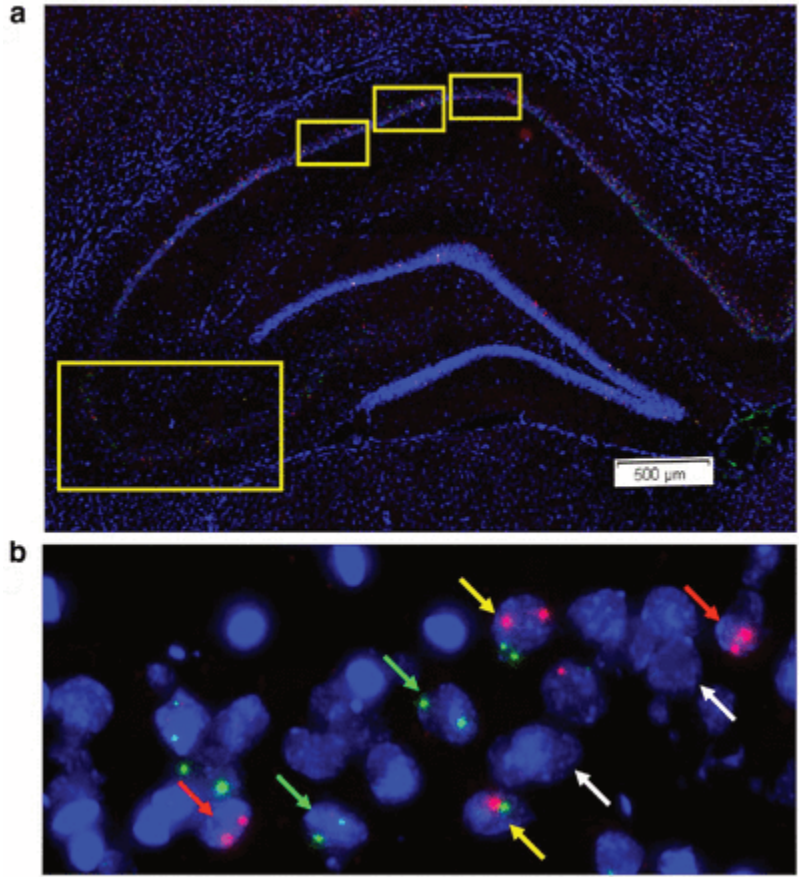


Figure 1. *IEG expression in dorsal hippocampus. (a) Low-magnification image of DAPI-stained dorsal hippocampus indicating the fields imaged for CA1 and CA3. The relative positions analyzed for CA1 (top) and CA3 (bottom, left) are indicated by yellow boxes. (b) Representative 20× projection image of CA3 from rat trained in context discrimination conditioning, showing Arc+ (red arrows), H1a+ (green arrows), Arc/H1a+ (yellow arrows), and negative (white arrows) neurons. Image from: https://doi.org/10.1523/JNEUROSCI.0542-14.2014. Under CC by 4.0.*

References

From Acute Neuroinflammation Impairs Context Discrimination Memory and Disrupts Pattern Separation Processes in Hippocampus

Jennifer Czerniawski and John F. Guzowski

Journal of Neuroscience 10 September 2014, 34 (37) 12470-12480; DOI: https://doi.org/10.1523/JNEUROSCI.0542-14.2014

Front. Neurosci., 05 April 2011 | https://doi.org/10.3389/fnins.2011.00048

3.9 Genetic Approaches to Examine the Intact and Living Brain

Labeling the Living Brain

Owing to the complexity of the mammalian brain, it has remained a major challenge to decipher the patterns of connectivity made onto and by newborn neurons as they integrate into circuits of the adult brain. With major advances in both molecular genetics and light microscopy, our ability to query not only neuronal morphologies, but also the molecular and cellular composition of individual neurons and their associated synaptic networks has become possible.

Arguably, one of the most influential contributions to contemporary neuroscience has been the use of fluorescent proteins (FPs) and their targeted expression in living neurons of the mammalian brain tissue. The wide array of FPs available provides an ever-expanding toolbox of vital reporters and gene expression tags. Applications for these proteins range from vital reporters expressed throughout the cytoplasm to subcellular protein fusion tags, which together can be used to monitor the process of circuit integration *in vivo* using both electrophysiological methods and fluorescent imaging.

Beyond merely marking cells for identification, a number of other methods have been developed to exploit the vital properties of FPs to investigate neuronal properties. For example, superecliptic pHluorin, which fluoresces at neutral pH but is quenched at acidic pH, can be used to monitor the trafficking and exchange of intracellular compartments within neurons. This variant allows direct imaging of membrane dynamics, exocytosis and endocytosis of synaptic receptors, and neurotransmitter release *in vitro* and *in vivo*. More recently, a new method termed GFP reconstitution across synaptic partners (GRASP) shows promise for revealing synaptic interactions between contacting neurons. By tethering split GFP fragments to separate pre- and post-synaptic proteins, reconstitution of GFP fluorescence can be observed when genetically targeted cells form synaptic pairs. Although this technology has been successfully applied to reveal invertebrate synapses, it has yet to be demonstrated in rodents (Gordon and Scott, 2009).

The range of FP reporters for visualizing neuronal morphologies, cellular dynamics, and synapse function continues to expand. However, perhaps the single-most limiting factor for using FPs in neuroscience is our incomplete knowledge of neuronal gene regulation. Often transgenic reporters fail to recapitulate endogenous patterns of gene expression, or such patterns are too broad to identify neuronal subtypes with cellular precision.

Trans-Synaptic Circuit Tracing

A major goal toward understanding mechanisms of neuronal development, synapse formation, and circuit wiring has been to elucidate nodes and patterns of synaptic connectivity. A creative angle to address this challenge has been the incorporation of genes encoding FPs and FP-fusion proteins into neurotropic viral vectors, which show the innate ability to infect neurons and trans-synaptically spread throughout the nervous system (Kuypers and Ugolini, 1990; Callaway, 2008).

Two types of viruses that have been broadly employed for this purpose include rabies and herpes. Herpes

viruses belong to a family of double-stranded DNA viruses, while rabies belongs to a family of negative-strand RNA viruses (Voyles, 1993). Although evolutionarily different, they are both endowed with the unique ability to bind to and infect neuronal cells. This cell type-specific infectivity is conferred to the viruses via their mature enveloped coat particles, which are made of both host membrane and virally encoded glycoproteins. The composite envelope proteins are the determinants that mediate neuronal membrane recognition and subsequent neuron-to-neuron infection by binding to membrane surface receptors.

Herpes viruses have been used to label neural circuits for years. Two common tracing strains are herpes simplex virus-1 (HSV-1; Lilley et al., 2001) and pseudorabies virus (PRV; Enquist, 2002). Both of these variants predominantly spread in a retrograde direction, and each has been effectively applied to dissect synapse and circuit connections in the rodent brain (Callaway, 2008). However, one limitation to using the herpes viruses for circuit analysis is polysynaptic spreading. Due to the vast cohort of cell types within brain tissue, the number of synapses formed on each of those cells, and the high degree of interconnectivity in intact neural circuits, this approach still poses a challenge to dissect precise patterns of neural connectivity. To simplify trans-synaptic circuit analysis, Wickersham et al. (2007b) devised a clever coat protein complementation strategy that allows for monosynaptic tracing of neuronal connections using a pseudotyped rabies virus (RV). Not to be confused with PRV (which as stated above is actually a herpes virus), pseudotyping a viral particle refers to synthetically modifying the viral envelope to recognize a foreign receptor not normally present on the membranes of mammalian neurons. The strategy will be briefly discussed below, and for further reference also see Wickersham et al. (2007a), Arenkiel and Ehlers (2009), Hasenstaub and Callaway (2010).

The RV gene encoding its glycoprotein (termed G) has been the primary target for genetic modification and RV vector engineering. Removal of G from the RV genome renders the virus both incapable of generating infective particles and replication incompetent. However, even in the absence of the native glycoprotein gene, RV is still capable of expressing its genome. Thus, G can be replaced with sequences encoding FPs or FP-tagged biomolecules to generate RV vectors for vital reporter expression (Wickersham et al., 2007a). To make these replication incompetent viruses useful for circuit tracing studies, they must be "armed" by providing an envelope *in trans* by propagating and packaging the particles *in vitro* using cell lines engineered to synthesize the required glycoprotein.

To perform monosynaptic circuit tracing and target FP-expressing RV to desired neuronal subsets, the particles can first be pseudotyped with the foreign coat protein EnvA from avian sarcoma leukosis virus, which specifically binds to a class of avian membrane proteins called TVA receptors (Barnard et al., 2006). Genetic targeting of neuronal subsets for TVA expression directs RV infection to only those neurons. To facilitate monosynaptic tracing, Wickersham et al. (2007a) added a clever twist on this approach. By introducing a plasmid that encodes the wildtype RV G-protein, the disarmed EGFP-expressing virus is now able to undergo one round of subsequent infection to presynaptic partners of TVA-targeted neurons. Since only the initially infected neuron contains G, viral spread ceases after one round of monosynaptic jumping. Including a plasmid encoding a red FP allows the cell originally targeted for infection to be identified amongst the monosynaptic network of GFP labeled cells (Figure 1). Of course it must be considered that true monosynaptic tracing is dependent on targeting individual neurons for the expression of G. If for example synaptically coupled cells both harbor G, but only one of them serves as the primary source cell of TVA-mediated infection, then viral spread can become multisynaptic through subsequent rounds of viral packaging in presynaptic partners. Monosynaptic tracing control thus depends directly upon the precision of neuronal targeting for the RV tracing components.

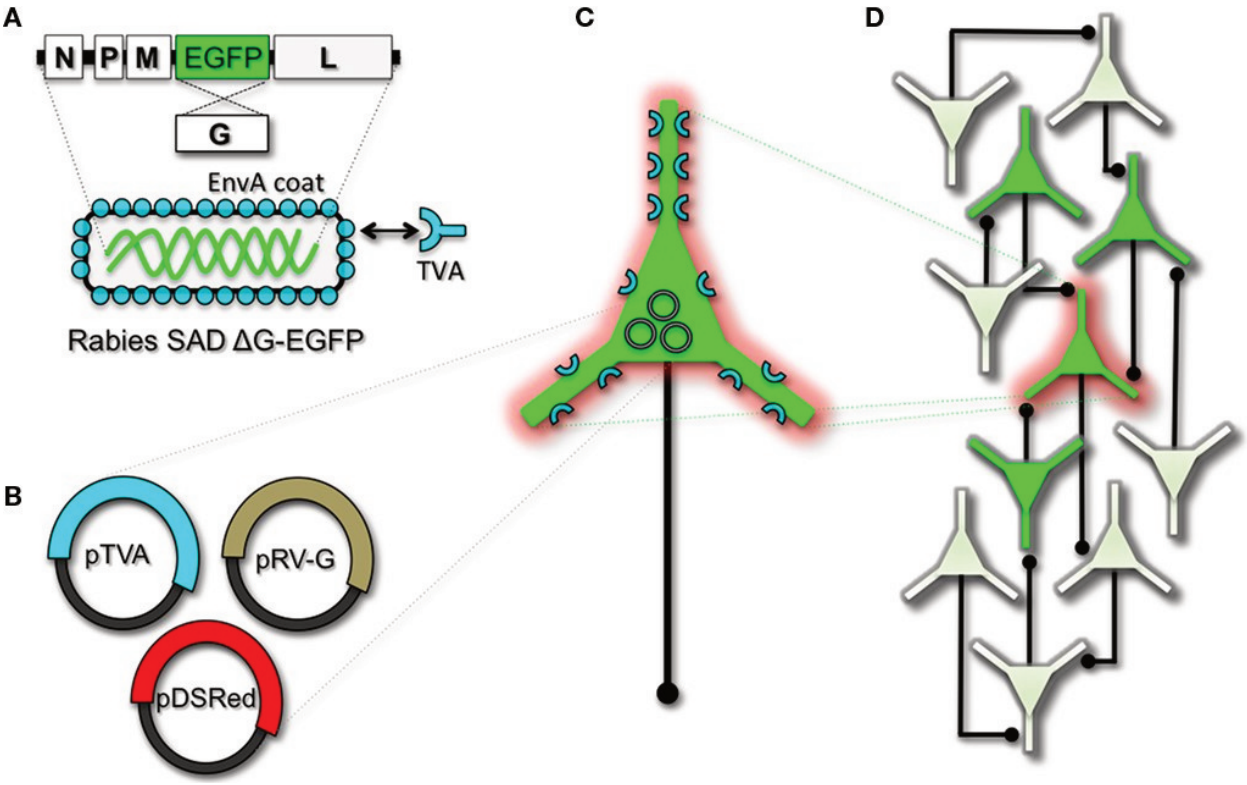


Figure 1. *Engineering and pseudotyping rabies virus (RV) for transneuronal tracing.* **(A)** *RV can be genetically engineered to express EGFP by replacing the genomic sequence encoding the G coat protein. The genetically modified G-deletion mutant RV must be propagated in vitro to supply a coat protein. The particle can thus be pseudotyped by providing a foreign coat protein such as EnvA, which originates from the avian leukosis virus and binds specifically to it its cognate receptor TVA. EnvA pseudotyped RV can be used to selectively infect neurons that have been genetically targeted for TVA expression. By including additional constructs that encode the wildtype G-capsid protein and a red-colored "cell fill"* **(B)**, *the modified RV can be genetically targeted to individual neurons for restricted circuit mapping and monosynaptic tracing* **(C).** *Since no endogenous receptors exist in the mammalian brain for EnvA, only neurons that are programmed to express TVA are capable of being infected by the EnvA pseudotyped virions. Because the wildtype G-protein sequence has been deleted from the RV genome, G must be supplied by complementation to allow trans-synaptic spread from the neurons targeted for infection.* **(D)** *Viral spread ceases monosynaptically due to the absence of G in unmodified neuronal populations.*

This new technology now makes it feasible to dissect complicated patterns of neuronal connectivity with synaptic precision (Stepien et al., 2010; Weible et al., 2010). Targeting adult-born neurons for monosynaptic circuit tracing holds certain promise toward elucidating the numbers, types, and synaptic inputs that might usher and/or promote the formation and maintenance of functional circuit integration. Unfortunately however, much needs to be learned about the viral mechanisms of infectivity, trans-synaptic propagation, and replication to make viral tracing methods broadly applicable for detailed circuit analysis throughout the nervous system. For example, one major limitation to viral-mediated circuit tracing using either HSV or RV type vectors is the inevitable deterioration of neuronal cell health with time (Callaway, 2008). Whereas the HSV particles show rapid and high levels of expression within 1–2 days, they also show a lytic-type phase of replication that induces neuronal loss within 1–2 weeks. Although most neurons appear to tolerate RV infection for longer periods of time, they too eventually show signs of dysfunction and poor health beyond 2 weeks. In addition, not much is known regarding the exact tropism for the various viruses to infect particular subtypes of neurons. Although it

is clear that viral particles can cross axo-dendritic, dendro-dendritic, glutamatergic, and GABAergic synapses (Willhite et al., 2006; Wickersham et al., 2007b; Stepien et al., 2010; Miyamichi et al., 2011; Rancz et al., 2011), the different efficacies of transfer have not been determined. Preferential binding of viral particles to different types of presynaptic proteins must exist, which would ultimately result in more efficient transfer of viruses between certain synaptic pairs. This information is currently unknown, thus it remains a challenge to reliably perform unbiased quantitative circuit analysis using viruses over extended periods of time.

Although current trans-synaptic circuit tracing methods are in their infancy, with further understanding of the viral mechanisms, and a subsequent "re-tooling" of existing vectors, one can easily imagine that this experimental avenue for intact circuit mapping will become indispensable. Moreover, this methodology holds definite promise to address outstanding questions in adult neurogenesis, ranging from identification of the types of connections that are dynamically made and broken during circuit development, to exposing the complete cohort of input types that are observed in mature circuits within the intact brain.

Manipulating Cell and Circuit Activity

Earmarking neuronal subsets and their associated networks for has been invaluable toward our current understanding of neuronal morphologies and circuit architecture. However, to fully understand the cellular and molecular mechanisms that guide adult-born neuron synapse formation and circuit integration, we must be able to probe neuronal connectivity. Recent advances in genetically encoded actuators now provide this possibility. Technologies such as heterologous receptor or channel expression, optogenetics, and genetically encoded synaptic toxins are beginning to allow functional circuit mapping with synaptic precision (Luo et al., 2008; Arenkiel and Ehlers, 2009; Figure 3). By targeting pre- or post-synaptic cell types for activity manipulations, coupled with functional imaging and/or electrophysiological recordings, it is now possible to genetically dissect circuit nodes by monitoring evoked synthetic output responses. Some of the earliest efforts to genetically control neuronal output relied on engineered expression of heterologous receptors in neurons that normally do not show their presence. For example, expression of modified opiate receptors in the brains of transgenic mice showed that introducing synthetic exogenous ligands could activate neuronal subsets (Zhao et al., 2003). To date, numerous variations on this theme have proven effective for both driving neuronal excitability and inhibition. Complementary strategies to these methods have been to genetically express small-molecules for inactivation of synaptic transmission (Karpova et al., 2005), or toxins that disrupt synaptic transmission (Harms et al., 2005; Ehlers et al., 2007).

Genetic strategies to mark and manipulate neurons and circuits

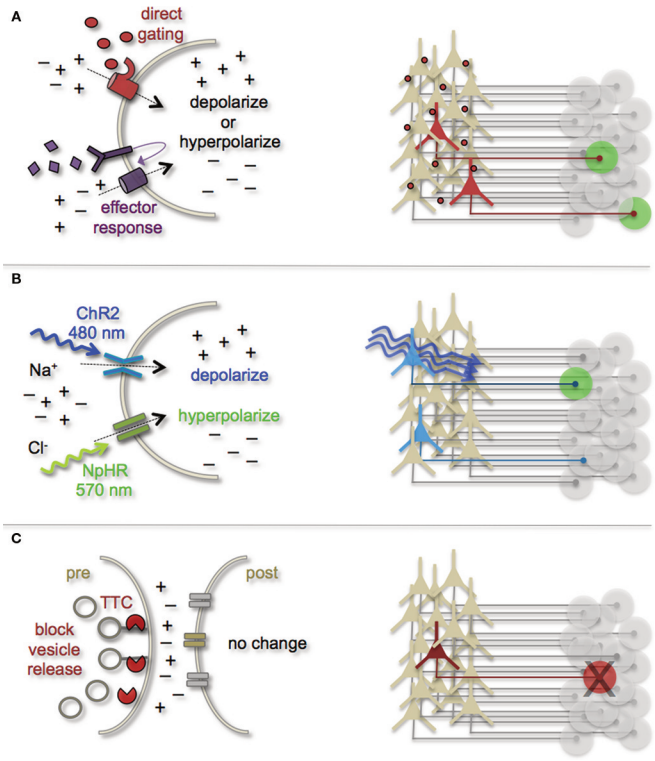


Figure 3. **(A)** *Neurons can be targeted for heterologous receptor expression. These foreign receptors can be either directly or indirectly gated by application of exogenous ligands (depicted as red ovals and purple diamonds). Left: heterologous receptor activation via application of synthetic ligands can be used to change a neuron's ionic equilibrium and thus firing properties. Right: depending on molecular properties, exogenous ligands spread variably throughout brain tissue. All neurons expressing the heterologous receptors are capable of being activated and driving target cell responses (represented as green circles).* **(B)** *Expression of light-gated channels can be used to modulate neuronal firing with photons. Left: ChR-2 is a non-selective cation channel that responds optimally to blue light. Photostimulating this channel results in positive inward currents, depolarization, and neuronal firing. NpHR is a photoactive chloride pump that responds optimally to greenish-yellow light. Photostimulating this pump protein results in negative inward currents, hyperpolarization, and neuronal silencing. Right: FP-fusion reporters can be used to identify cells that express photoresponsive proteins (represented by blue coloring). Only neurons expressing the photoresponsive channels and receive photons show light activated modulation, whereas downstream circuit targets can be monitored for post-synaptic photo responses (green coloring).* **(C)** *Targeted expression of synaptic toxins in neurons can be used to block synaptic vesicle release and inhibit neurotransmission to post-synaptic targets. TTC, tetanus toxin.*

3.10 – in vitro Neuronal Models

A variety of *in vitro* models can be used to examine circuits as well as to test many of the techniques mentioned in this unit and to help understand development of the nervous system. Often these *in vitro* models have been developed to provide a simplified understanding of the much more complex *in vivo* condition. These reduced complexity models allow for a simplified approach to studying key neuronal processes on both the cellular and molecular level. At the same time, some tissue preparations suffer several limitations due to their simplicity, reducing direct *in vivo* comparisons.

Expression systems and immortalized cell lines

The simplest *in vitro* electrophysiological models include heterologous and recombinant expression systems which are cells/cell lines that can be maintained in culture for an extended period of time. The cells/cell lines typically used as heterologous (*e.g.*, *Xenopus* oocytes; or recombinant expression systems (*e.g.*, human embryonic kidney 293 (HEK-293) cells, Chinese hamster ovary (CHO) cells)) that are easily maintained, allow for manual and automated electrophysiological techniques and express high levels of desired protein within a short period of time that can be consistently observed. As such, these systems have been used extensively to evaluate the pharmacological properties and structure-function relationships of multiple neuron ion-channels. However, despite their simplicity and ubiquitous use, these cells lack many of the complexities associated with neuronal function within the intact brain (e.g. network associations, glial interactions, and developmental regulation) – a disadvantage when modeling the brain. Furthermore, these cells are typically of a non-neuronal origin and thus lack the same sophisticated level of cellular architecture, sub-cellular organization or biochemistry associated with native neuronal preparations.

Early efforts to address these non-neuronal concerns focused on neuronal cells derived from mouse neuroblastoma C-1300 tumor (e.g. N1E-115)) or the human SH-SY5Y neuroblastoma cell line. However, subsequent advances in molecular biology enable the use of neural stem cells (NSCs). NSCs are uncommitted cells with self-renewal potential and the ability to differentiate into cells of all neural lineages. These cells can be derived from several sources such as pluripotent embryonic stem cells isolated from the blastocyst, human umbilical cord blood, induced pluripotent stem cells and multipotent somatic progenitors derived from several tissues including the CNS. Electrophysiologically, these cells possess Na^+, K^+ and Ca^{2+} currents that resemble the known patterns described for their *in vivo* neuronal counterparts, even at early stages of differentiation. Furthermore, these cells are also capable of forming rudimentary, yet functional, glutamatergic and GABAergic synapses in culture. Limitations in the use of cells obtained from adults offer limited neural lineage potential and senesce after only a few passages (Jakel, Schneider, & Svendsen, 2004). Moreover, NSC cultures may possess mixtures of both undifferentiated and differentiated neurons, for which some neurons are developmentally immature, and thus hinder extrapolation of data to the adult *in vivo* condition.

Dissociated neuronal primary cultures

Increasing in complexity, dissociated neuronal primary cultures represent another common tissue preparation.

These cultures are mechanically and enzymatically dissociated from various brain regions (*e.g.*, hippocampus, cortex, cerebellum, striatum, midbrain, superior cervical ganglion, etc.) and consist of either one predominant neuronal cell type, a co-mixture of different neuronal populations or mixed neuronal–glial cultures. Dissociated neurons and astrocytes retain much of their functional capacity *in vitro* enabling these preparations to address many important processes observed in the *in vivo* condition such as network dynamics and neuronal-glial interactions but dissociated neurons cannot be maintained in culture for extended periods of time and thus are required to be freshly isolated and grown on a regular basis.

Three-dimensional (3D) neuronal organoid models

The 3D neuronal model represents the next level of complexity for CNS *in vitro* models. Like the two-dimensional (2D) preparations discussed above, 3D brain cell cultures can consist of a co-mixture of different neuronal and non-neuronal populations. Interestingly, instead of being cultured in a traditional planar monolayer, 3D brain cultures are created up to 10 cell diameters thick within reaggregate or spherical cultures (i.e. spheroids), hydrogel/scaffold cultures or rotary bioreactor cultures with cell aggregates or microcarriers. When grown in a 3D environment, neural cells demonstrate better survivability and behave differently when compared to traditional 2D-models. As such, these models promote better development of native voltage-gated ion-channel functionality, resting membrane potentials, intracellular Ca2 + dynamics, Na+/H+ exchange, enhanced neurogenesis and differentiation, synapse formation, neuronal mobility and axon myelination (Lancaster & Knoblich, 2014; Lancaster et al., 2013; LaPlaca et al., 2010; van Vliet et al., 2007).

UNIT 4 – EMERGENT TOPICS IN NEUROSCIENCE

As a discipline, neuroscience encompasses the entire range of biology from genetics and molecules to system level approaches to understanding neurons and the brain. Often this means that neuroscientists are finding new and previously unsuspected influences on how neurons function, and therefore affect behaviour. This unit highlights some of the exciting areas of neuroscience that have emerged over the past decade that promise to give the discipline new avenues of research for the next generation of neuroscientists.

4.1 The Gut Microbiome and its Impact on the Brain

Previously it was believed that micro-organisms were solely responsible for the production of disease/ pathology. However, more recently many different researchers and scientists have begun to re-evaluate this concept that microbes were ***only*** present or only useful in studying diseases.

Scientists have known for a very long period of time that there are a number of ***microbiota*** which consists of all of the bacteria, viruses and eukaryotes (i.e. fungi) that either grow in and or on the body (1014 bacteria internally; 1010 bacteria on skin; and an estimate quadrillion viruses). Since the microbiota are present on humans throughout almost our entire lifetime, current theories now highlight the possibility that the microbiota might also play a role in health, not only in disease. Conceptually, the genes encoded by all of the microbiota are known collectively as the **microbiome**. As the number of bacteria within the gut far exceeds all of the other microbiota, most research has started to investigate the role that the gut microbiome might have in health and disease, and more importantly in brain health and disease.

Specifically, within all fields of biology there is an emerging theme that an organ (such as skin) can be colonized by different types of microbes and this colonization does not have to be homogeneous across a particular organ. Although many of these gut bacteria can be treated pharmacologically in order for them to be eliminated, this may not be always be the best treatment. From a research perspective then, one key question that dominates, can controlling our gut microbiome produce changes in our biology, physiology and even behaviour?

What factors affect the gut microbiome?

Many factors have now been identified to affect the gut microbiome. As shown in Figure 1, an individual's genetics, the types of drugs or antibiotics they are taking, hygiene, physical activity and other factors, all play a role in either mainintaining or, if changed, altering the gut microbiome.

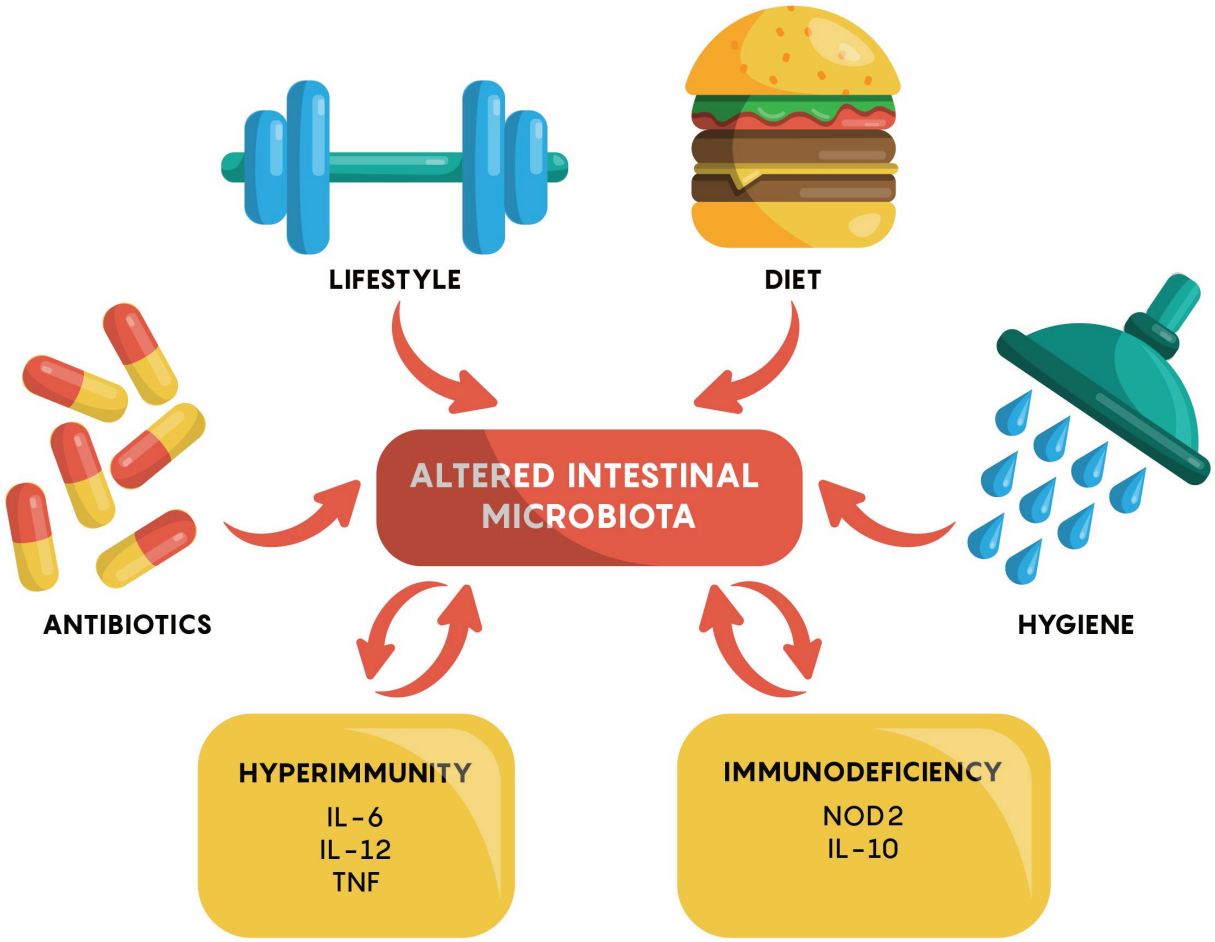


Figure 1.

The "Normal" Gut Microbiome

As the intestine is an anaerobic environment, the majority of the gut bacteria species have been found to be anaerobic. Between 500-1000 different bacterial species have been identified in the gut through genetic sequencing, although these species belong to a very small number of phyla. In most healthy adult individuals, the most abundant phyla include ***Bacteriodetes (Gram(-) rods)*** and ***Firmicutes (Gram(+))*** although other phyla such as *Proteobacteria*, *Verrumicrobia*, and *Actinobacteria* have also been identified.

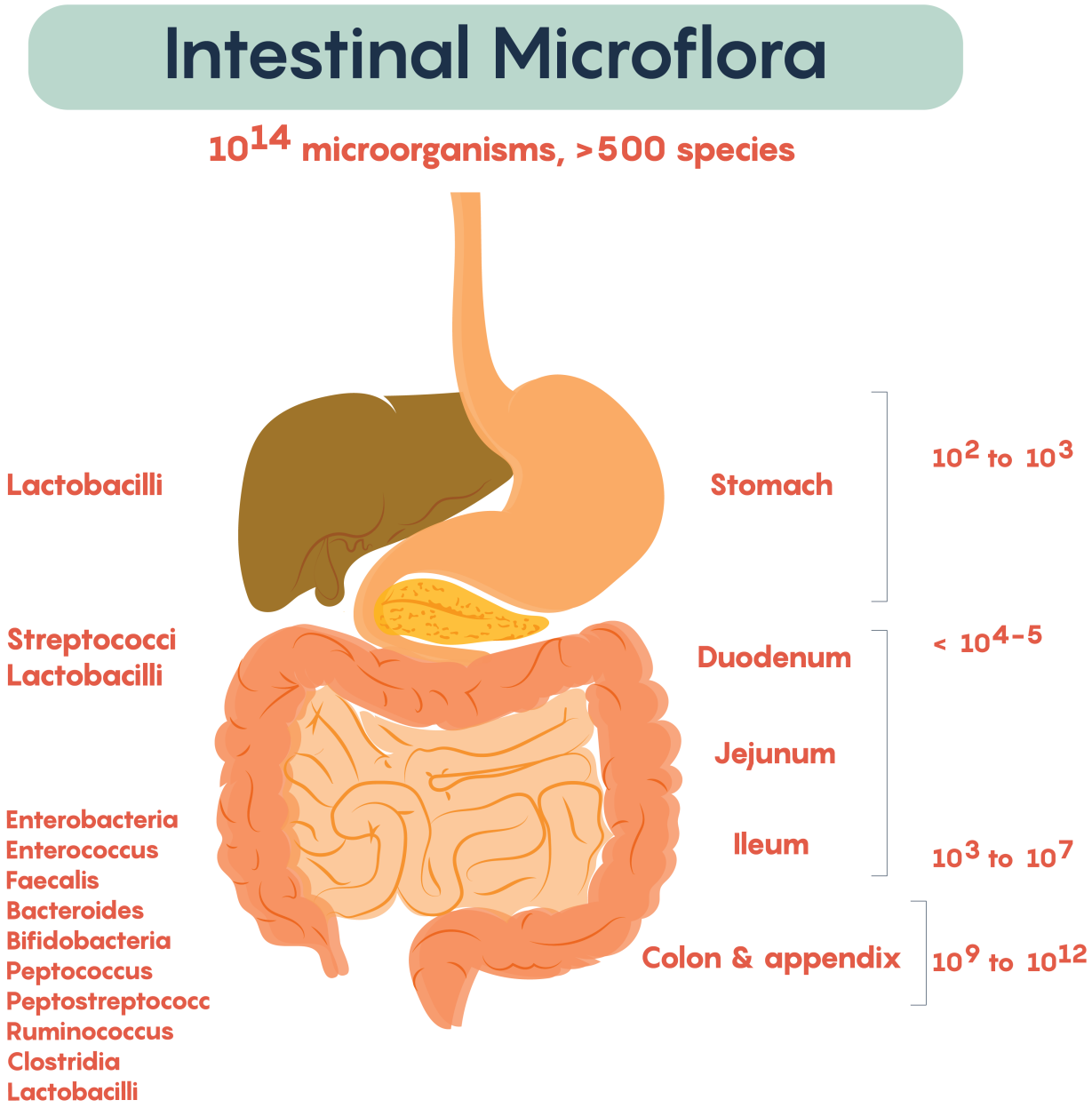


Figure 2. *Microbial density in the gut. Overall, there are 10^{14} microorganisms residing in the human gut, with over 500 unique species. In the stomach, the majority are the Lactobacilli, making up about 10^2 to 10^3. In the Duodenum, there are Streptococci and Lactobacilli, with a concentration of 10^4 or 10^5. As we descend past the jejunum and into the ileum, the concentration of bacteria increase dramatically – up to ten million bacteria reside here. Bacteria such as Enterobacteria, Enterococcus, Faecalis, Bacteroides, Bifidobacteria, Peptococcus, Peptosteptococc, Ruminococcus, Clostridia, and Lactobacilli. These bacteria are also common in the colon and appendix, but the microorganism concentrations increase yet again, to 10^9 to 10^{12}. There is a general trend that complexity and concentration of bacteria increases as we descend the GI tract.*

Frequently, researchers not only measure the typical bacteria living in various parts of the gastrointestinal (GI) tract but also measure the microbial density within various regions of the gut. As shown in Figure 2., the types of resident or commensal bacteria found in the lumen of the gut regions as well as the density of bacteria (numbers

on the right) show the density. Not surprisingly, the numbers as well as the complexity of bacteria increases distally down the length of the GI tract. This complexity started at birth and continues throughout development into adulthood.

But what types of bacteria dominate?

The gut microbiota is dominated by bacteria of which the major divisions of bacteria consist primarily of ***Bacteriodetes*** and ***Firmicutes***. As mentioned previously there seems to be variation in bacteria between individuals although there is a suggestion that individuals normally have gut microbiota that dominate (the dominating bacterial fingerprint of each individual is referred to as an ***enterotype***). The dominating bacterial enterotypes in a healthy individual typically consists of the genera of ***Bacteroides***, ***Prevotella*** or ***Ruminococcus*** (everyone has all 3 bacteria genera but the ratios between each individual will differ from having more or less of each genera).

Changes to the gut microbiota and the gut microbiome

Interestingly, although everyone has a common "core" group of bacteria as outlined in the previous section, lifestyle effects on microbiota (i.e. changes in diet and physiological status) seem to have the ability to quickly modify the types and numbers of bacteria living in the gut. This offers both a therapeutic opportunity by introducing new bacteria that may be beneficial through probiotics that contain bacteria capable of colonizing the gut.

From the earliest developmental age, our but show large changes in the bacterial genera and their numbers 2 during development, changes again depending on lifestyle changes and ageing. The stability of the gut microbiota and the changes in the types of bacteria is emerging as an important factor that has increasingly been implicated in impacting our health status and may be contributing to neurodegenerative processes (and other changes to the brain) as shown in Chapter 2.

Developmental Changes

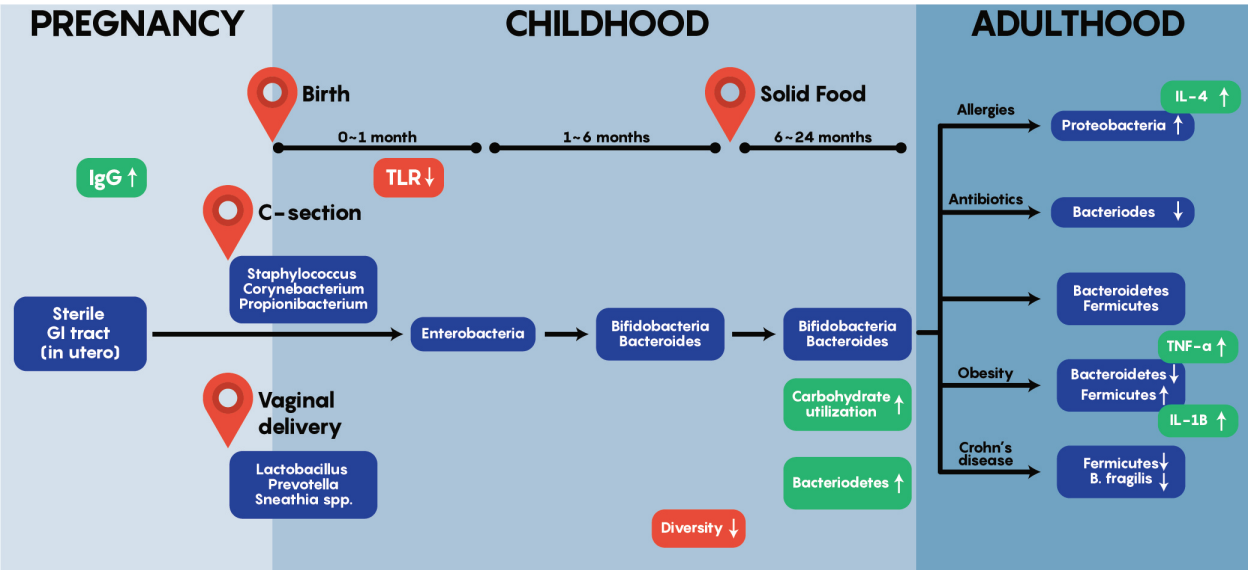


Figure 3. *An illustration of the typical developmental colonization of the gut by bacteria. The initial colonies of bacteria that settle depend on the delivery method. In the first week of life, TLR is reduced, which may allow for the formation of stable bacterial colonies in the gut. During the first 6 months, as children are subjected to solid foods, the diversity of microbiota increases. The immune system is able to differentiate the difference between pathogenic and helpful bacteria. Disease appears to correlate with bacteria concentration and composition.*

As shown in Figure 3. above, early bacterial gut colonizers such as *Lactobacilli* etc. are aerobic and most likely come from maternal sources – these are almost entirely unique and different by the first year of life. *Bacteroides* and *Enterobacteria* are anaerobic bacteria and tend to dominate later between 1-6 months of age. One of the most interesting aspects of gut colonization is that the source of bacteria is dependent on the environment as babies born via C-section tend to have colonization by *Staphylococcus*, *Corynebacterium*, *Propionibacterium spp* etc. which are normally found on the skin. This differs from the bacteria found in the gut of babies born through vaginal delivery as *Lactobacilli*, *Prevotella* and *Sneathia* dominate early on. Note that regardless of origin and initial colonization, that stability within the gut is reached around 1-2 years of age and is maintained into adulthood – where a unique balance between *Bacterioidetes* and *Firmicutes* exist while an individual stays healthy but can be altered by allergies, obesity, drugs and others to change this balance as shown in Figure 3.

Dysbiosis: The Basics

Dysbiosis represents an imbalance in the normal microbial community within your body. Experiments show that in adults, the bacteria, viruses and eukaryotes populations stay relatively stable. However, this stability occurs only in healthy individuals and these populations can change with diet, disease, treatment and environmental effects. For example, gut viromes (an extension of viral genomes) have been shown to have >95% stability in their sequences over the course of a year in healthy individuals – however this changes with alterations in an individual's diet.

The effect of diet on the gut microbiome

- **In mice models –** shifting diet from low-fat, plant-polysaccharide rich to high-fat, high sugar (Westernized) diet able to change the bacterial content within a day (Turnbaugh et al., 2009 Science Translational Medicine)
- ***In human studies*** – similar changes in gut microbiota observed within 24 hours (Wu et al, 2011 Science).
- This study showed that diet correlates with changing bacteria – high fat diet ***Bacteroides*** dominate, carbohydrate rich diet ***Prevotella*** dominate

In diet induced animal models of obesity there is a shift in dominant gut phyla with a decrease in *Bacteroidetes* and increase in *Firmicutes*. Similar results have been shown in human twin studies with decrease in *Bacteroidetes* but increase in *Actinobacteria*. The shift between these two phyla results in increased capacity for increasing energy from food but also results in inflammatory responses. By altering the gut microbiota in animal models, this seems to be sufficient to induce obesity as a phenotype (Turnbaugh et al., 2006 and 2008). These data suggest that the gut microbiota is capable of not only responding to changes in diet but can also induce phenotypes such as obesity.

4.2 Gut Microbiome and the Brain

Dysbiosis

As previously outlined in Chapter 1, a state of microbial imbalance inside the body known as dysbiosis, has recently been linked to the development of many diseases and disorders. These include obesity, colorectal cancer, and cardiovascular disease. There is therefore increasing and substantial evidence that homeostasis of the gut microbiota is essential to human health. Exercise, diet, antibiotic use, and personal hygiene are all important factors in maintaining this balance.

There are several ways in which the gut microbiota interacts with the brain. Components of bacteria, such as lipopolysaccharides, activate the innate immune system. In dysbiosis, the innate immune system is overactive, which may result in inflammation of the central nervous system. Certain bacterially-derived metabolites, such as D-lactic acid and ammonia, have also been found to have neurotoxic effects. In addition to these metabolites, many gut bacteria interact with the brain through the production of neurotransmitters, such as serotonin and dopamine. Finally, the gut microbiota communicates with the brain through the vagus nerve, which connects the brainstem to the heart, lungs, and digestive tract (Galland, 2014).

Dysbiosis has also been found to play a role in several neurological and psychiatric disorders, such as Major Depressive Disorder, Parkinson's Disease, and Alzheimer's Disease. Many of these diseases and disorders are often comorbid with gastrointestinal disorders. In some cases (e.g. Parkinson's Disease), it is possible to induce disease in a healthy animal by exposing it to the gut microbiota of a diseased human. The gut and the brain have been shown to communicate bidirectionally, but this link and the mechanism behind it are not fully understood.

Case study: Gut Microbiome, the Brain and Parkinson's Disease

Evidence for interactions between the gut and brain

Traditionally, neurological diseases have been studied solely through the lens of issues occurring within the CNS, although taking in to account that peripheral influences have been implicated in the onset and/or progression of diseases that impact the brain. One of these peripheral influences that has been gaining increasing interested in the impact that the gut microbiome has on the brain (Dinan and Cryan, 2015). Emerging data suggest bidirectional communication between the gut and the brain in anxiety, depression, nociception, and autism spectrum disorder (ASD).

Gastrointestinal (GI) physiology and motility are influenced by signals arising both locally within the gut and from the CNS suggesting that such a synergistic interplay could exist. Neurotransmitters, immune signaling, hormones, and neuropeptides produced within the gut may, in turn, impact the brain (Selkrig et al., 2014, Wall et al., 2014) but still remain largely unknown.

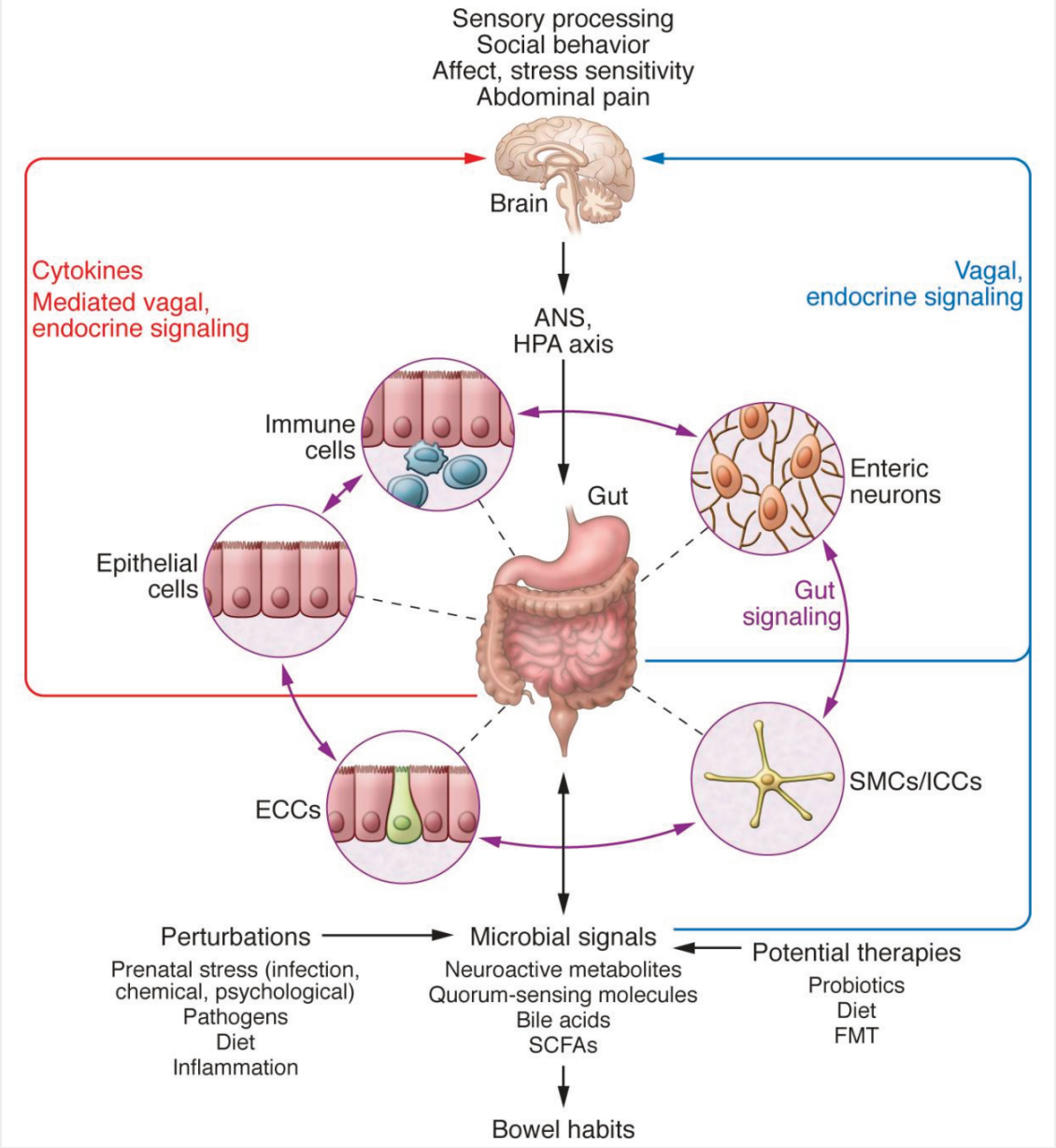


Figure 1. *(taken from opensource https://www.jci.org/articles/view/76304/figure/3) A network of specialized target/transducer cells in the gut wall functions as an interface between the microbiota and the host lumen. In response to external and bodily demands, the brain modulates these specialized cells within this network via the branches of the ANS (sympathetic and parasympathetic/vagal efferents) and the HPA axis. Such modulation can be transient, such as in response to transient perturbations, or long lasting, such as in response to chronically altered brain output. The microbiota is in constant bidirectional communication with this interface via multiple microbial signaling pathways, and this communication is modulated in response to perturbations of the microbiota or the brain. The integrated output of the gut microbial–brain interface is transmitted back to the brain via multiple*

afferent signaling pathways, including endocrine (metabolites, cytokines, and microbial signaling molecules) and neurocrine (vagal and spinal afferents). While acute alterations in this interoceptive feedback can result in transient functional brain changes (GI infections), chronic alterations are associated with neuroplastic brain changes. Potential therapies aim to normalize altered microbiota signaling to the ENS and central nervous system. FMT, fecal microbial transplant; ICC, interstitial cell of Cajal.

Research is beginning to uncover the profound impacts that microbiota can have on neurodevelopment and the CNS (Sharon et al., 2016). Germ-free (GF) mice and antibiotic-treated specific-pathogen-free (SPF) mice exhibit altered in hippocampal neurogenesis, resulting in impaired spatial and object recognition (Möhle et al., 2016). The gut microbiota have been shown to regulate expression of the 5-hydroxytryptamine receptor (5-HT1A), brain-derived neurotropic factor (BDNF), and NMDA receptor subunit 2 (NR2A) (Bercik et al., 2011, Diaz Heijtz et al., 2011, Sudo et al., 2004). The microbiota promotes enteric and circulating serotonin production in mice (Yano et al., 2015) and affects anxiety, hyperactivity, and cognition (Clarke et al., 2013, Diaz Heijtz et al., 2011, Neufeld et al., 2011, Selkrig et al., 2014).

Dysbiosis in Neurodegeneration

Dysbiosis of the human microbiome has been reported in subjects diagnosed with several neurological diseases. For example, fecal and mucosa-associated gut microbes have been found to be different between individuals with Parkinson's Disease (PD) and healthy controls although it is not clear what this link is.

Individuals with PD also tend to exhibit intestinal inflammation, and GI abnormalities such as constipation which often precede clinical motor defects by many years (Braak et al., 2003, Verbaan et al., 2007). One theory (Braak's hypothesis) has suggested that aberrant αSyn accumulation initiates first within the gut and then propagates via the vagus nerve to the brain in a mechanism that resembles prion diseases where infectious proteins spread from one area to the other (Del Tredici and Braak, 2008). A hallmark feature of PD involves αSyn (alpha Synuclein) inclusions, and these appear early in the enteric nervous system (ENS) and the glossopharyngeal and vagal nerves (Braak et al., 2003, Shannon et al., 2012).Interestingly, vagotomized individuals (where the vagus nerve has been surgical cut) are at reduced risk for PD (Svensson et al., 2015). This suggests that there is evidence that in PD an alteration in the gut microbiome might somehow produce neurodegeneration in the brain, and that this factor travels along the vagus nerve.

How would you prove this? What would a researcher need to do?

- Can gut bacteria regulate the hallmark motor deficits and pathophysiology of synucleinopathies such as PD?
- Are changes in the gut microbiota necessary to promote αSyn pathology, neuroinflammation,

and characteristic motor features in a proper mouse model?
- Try to prove that gut microbes may play a critical and functional role in the pathogenesis of synucleinopathies such as PD

Recent papers that answered all of the above lines of evidence used germ free mice to examine the effects of the gut microbiota on microglial activation in the brain. Furthermore it was found that the gut bacteria modulate microglia activation during viral infection through production of microbial metabolites, namely short-chain fatty acids (SCFAs). To address whether SCFAs impact neuroimmune responses in a mouse model of PD, animals were treated with a mixture of the SCFAs acetate, propionate, and butyrate (while the animals remained microbiologically sterile). These results demonstrated that the gut microbiome and changes to the gut microbiome could alter production of SCFAs which in turn could signal to alter brain microglia and that this might be the mechanistic link between gut microbiomes, immune system activation and damage to the brain.

The main effect of the gut microbiota perturbations on the brain may occur at times of lower diversity and instability of the gut microbiota (infants and the elderly) and during brain development (perinatal and infant period). During the prenatal period, the developing brain is first exposed to maternal gut-derived metabolites and may be exposed to intrauterine microbes. During birth, the newborn's gut microbiota is shaped by the maternal vaginal (or skin) microbiota (reviewed earlier). Even though the possibility that pre- and postnatal influences on the microbiota can affect brain development is intriguing, there has not been any research in humans characterizing the effect of maternal microbiota modulation on fetal brain development and adult sequelae of such modulation as might be suspected in autism spectrum disease. Again, it is intriguing to consider the possibilities associated with elderly changes in the gut microbiome and the onset of neurodegenerative conditions but further research is needed in this exciting new area of neuroscience research.

Chapter 2 References

Galland, L. (2014). The Gut Microbiome and the Brain. *Journal of Medicinal Food*, 12, 1261-1272.

4.3 Exercise and the Brain

Overview

For centuries, researchers have sought to elucidate the mechanisms behind the axiom that a healthy body leads to a healthy mind. It has now been established that exercise, even among minimal commitment exercise routines, has an array of robust effects on the brain, such as enhanced memory, mood, cognitive functioning, plasticity, and learning capabilities (Erickson et al., 2011; Spalding et al., 2013; Phillips et al., 2014). Most notably, exercise has been implicated in having anti-depressant effects and counteracting disease or age-related mental impairment and atrophy, such as Alzheimer's disease or dementia (Laurin et al., 2001). Yet, until recently, the intermediaries between exercise and its health benefits have not been well-understood.

However, it has been shown that—contrary to the age-old notion that the number of neurons in the brain remains static after prenatal and neonatal development—new neurons can be generated in the adult brain via a process known as neurogenesis, which can attenuate the deleterious effects of neurodegeneration (van Praag et al., 1999). This phenomenon has been linked to exercise, with a significant portion of subsequent neural growth occurring in the dentate gyrus of the hippocampus (Cotman and Berchtold, 2002). Since the hippocampus is critical for memory consolidation and learning, the generation of new neurons and increased plasticity in this brain region may explain the improved cognition and emotional state that accompanies exercise (Gandy et al., 2017; Trinchero et al., 2017). Furthermore, preliminary research has suggested that neurogenesis may also occur in numerous other areas of the brain, including the amygdala and hypothalamus, which may explain the diversity of exercise-derived benefits (Fowler et al., 2008). However, this research is not as extensive or conclusive as hippocampal neurogenesis research, nor is the extent to which neurogenesis occurs in other brain regions as robust as it is in the hippocampus, with the exception of the olfactory bulb (Cotman et al., 2007). One key molecule, brain-derived neurotrophic factor (BDNF), has been shown to modulate neurogenesis and exercise likely influences BDNF levels to alter areas of the brain.

Exercise and Hippocampal Neurogenesis

In rodents, hippocampal neurogenesis as a function of exercise has been extensively demonstrated and replicated. To test this, rodents are injected with bromodeoxyuridine (BrdU), which signify actively mitotic cells and are incorporated by daughter cells, thereby allowing the tracing of cell division (del Rio and Soriano, 1989). In some of the earliest work in this field, it was shown that mice allowed to voluntarily exercise on a running wheel exhibited enhanced neurogenesis in the dentate gyrus. By utilizing BrdU as a tracing molecule, it was observed that exercise not only increased proliferation of the progenitor cells in the subgranular zone, but also increased their survival rate as they differentiated and matured (van Praag et al., 1999; Seri et al., 2001; for reviews of neural progenitors and lineage progression see Weissman et al., 2001; Seri et al., 2004; Göritz and Frisén, 2012).

Although it is much more difficult to study exercise-mediated neurogenesis in humans, there is significant evidence that neurogenesis occurs in the adult human brain, especially in the dentate gyrus. Indeed, exercise has been shown to increase the size of the hippocampus in human adults (Erickson et al., 2011). Through postmortem tissue analysis of cancer patients administered BrdU, it has been shown that mature granule

neurons are continually generated from the subgranular zone, even in the later stages of life (Eriksson et al., 1998). Interestingly, the participants in this study were not assigned to exercise conditions, and since they were cancer patients near death, it is unlikely they participated in any exercise regimen. This suggests that the hippocampus has the capability to generate new neurons in adulthood independent of exercise. Later sections in this review, however, provide evidence that exercise accentuates neurogenesis in humans and addresses how the amount of exercise modulates the degree of neurogenesis.

BDNF Mediation of Hippocampal Neurogenesis

Given these early findings establishing a connection between exercise and hippocampal neurogenesis, researchers next turned to examining the biological underpinnings. One of the strongest candidates for bridging the gap between exercise and neurogenesis is BDNF, a growth factor categorized under the neurotrophin family widely expressed in the brain and throughout the rest of the central nervous system (Salehi et al., 2003). Early research on this molecule found that during development in mice, BDNF expression is low during prenatal development, but then increases during the first few weeks after being born and peaks during the shift from embryonic to adult neurogenesis (Bath et al., 2012). This provides key insight into its potential for facilitating neurogenesis, which then spurred much more research interest in its connection to neurogenesis.

BDNF

As a whole, the neurotrophin family polypeptides are vital to the regulation of the neural processes in neurogenesis, such as proliferation, differentiation, maturation, and plasticity. Within this family, BDNF exhibits the highest degree of expression in the brain, and is primarily synthesized there during exercise (Reichardt, 2006). BDNF can also enter the brain via freely diffusing across the blood brain barrier (Pan et al., 1998; Mousavi and Jasmin, 2006). Furthermore, during exercise, proteins and their metabolic derivatives secreted from peripheral muscles, such as cathepsin B and FNDC5/irisin, also cross the blood brain barrier to mediate BDNF expression in the hippocampus and subsequent neurogenesis and memory improvement (Wrann et al., 2013; Moon et al., 2016). Indeed, mice injected with skeletal muscle endurance factors had elevated levels of hippocampal neurogenesis and increased spatial memory (Kobilo et al., 2010).

BDNF functions by binding to tropomyosin receptor kinase B (TrkB), which is largely expressed in hippocampal neurons. Upon binding, the BDNF-TrkB complex serves as a docking site for numerous signaling cascades, protein phosphorylation cascades, and secondary signaling systems (Huang and Reichardt, 2003; Nykjaer et al., 2005; Yoshii and Constantine-Paton, 2010). Through these pathways (shown in Figure 1), BDNF can exert significant regulatory control over many facets of a neuron's function and thereby influence how these neurons function as a whole within the hippocampus.

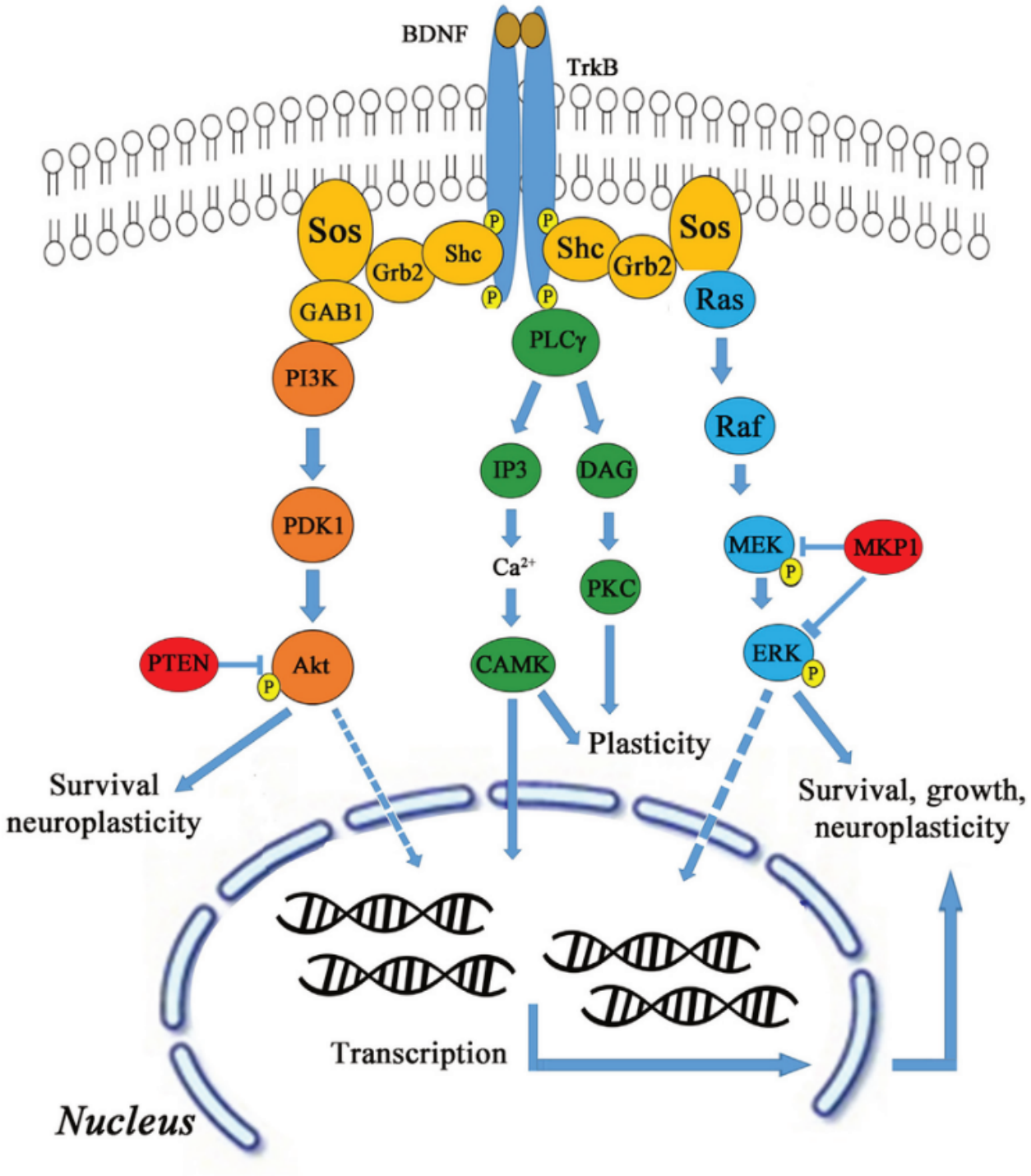


Figure 1. *Pathways that BDNF activates. Brain-derived neurotrophic factor activates TrkB through several downstream signaling pathways, such as AKT, CaMK, Ras/Raf/MEK/ERK leading to cell survival, growth, and neuroplasticity. BDNF activates TrkB stimulation via phosphatidylinositol-4,5-bisphosphate 3-kinase (PI3K) and also activates proteins like Shc, Grb-2, and Gab-1. The PI3K is also activated by binding to Ras homolog enriched by brain glutamine triphosphate (Ras-GTP). Image from: https://doi.org/10.3389/fneur.2016.00094. Under CC by 4.0*

Exercise and BDNF Expression

Thus far, both exercise and BDNF have been shown to be associated with increased neurogenesis. Further research has extended this to show that treadmill exercise in mice and aerobic exercise in humans increases BDNF expression by regulating BDNF gene expression in the hippocampus (Kim et al., 2015). This process is largely mediated by neurotransmitter and neuroendocrine systems, with extensive literature supporting acetylcholine (ACh) as a key regulator (Knipper et al., 1994).

In mice allowed to voluntarily engage in wheel running, an increase in BDNF mRNA levels in the dentate gyrus was observed after only a few days of exercise (Neeper et al., 1995). Surprisingly, these levels were maintained throughout several weeks of exercise and corresponded to proportional increases in BDNF protein expression (Russo-Neustadt et al., 1999). When the exercise conditions were supplemented with antibodies blocking TrkB, however, the mice had attenuated learning capabilities involving the hippocampus. Furthermore, these mice also lacked synaptic-specific proteins in the hippocampus, thereby demonstrating that BDNF signaling is necessary to allow the benefits of exercise to manifest (Vaynman et al., 2004, 2006).

Research has also shown that metrics of overall health quality in humans follow a dose-dependent relationship with the duration and intensity of exercise, with the best outcomes linked to moderate exercise (Larson et al., 2006). Further work illustrates that mice show greater improvements in acquisition and retention based learning in hippocampus-dependent tasks following long-term exercise rather than shorter regimes of exercise (Handschin and Spiegelman, 2008; Parachikova et al., 2008; Ploeger et al., 2009). It was found that in mice, even just one session of exercise increased BDNF levels. This effect, however, became amplified following a period of exercise in mice that regularly exercised, with an increased response in BDNF levels relative to mice after just a single session of exercise (Johnson et al., 2003; van Praag et al., 2005; Rasmussen et al., 2009). Consistent with these findings is a meta-analysis of 29 studies spanning 1,111 human participants that analyzed BDNF expression levels across various exercise paradigms. However, many of the studies only examined moderate exercise, and several studies did not report intensity level. Interestingly, considerable evidence from this meta-analysis suggests that humans also experience a dose-response relationship in which each session of exercise corresponds to a dose of increased BDNF expression. Furthermore, regular exercise in moderate amounts has been shown to increase the magnitude of BDNF expression following individual sessions of exercise (Szuhany et al., 2015).

There is not a perfect positive correlation, however, between the amount and intensity of exercise and BDNF expression levels and subsequent health benefits. Extreme exercise has been shown to disrupt a number of metabolic and physiological processes and lead to impaired cognitive performance in humans (Aguiló et al., 2005). Since oxygen is rapidly metabolized during physical exertion, reactive oxygen species (ROS) are naturally produced as a metabolic byproduct. When produced at high levels, such as during bouts of intense exercise, ROS can lead to oxidative damage and increased cellular mortality in both rodents and humans (Radak et al., 2016). Moderate levels of exercise enforce the human body's antioxidant defense system, but extreme levels of exercise lead to the generation of more ROS than the antioxidant system can defend against, thereby allowing their accumulation as oxidative stress (Mastaloudis et al., 2001). In fact, when treated with hydrogen peroxide, a potent ROS, hippocampal cell cultures taken from rodents showed an inverse relationship between BDNF expression levels and hydrogen peroxide concentration (Kwon et al., 2013). The *in vivo* production of BDNF as a function of ROS production, however, is less clear and warrants further study.

Not all BDNF is created equal

In humans there are frequent polymorphisms in the BDNF gene which are typically found on position 66 that converts valine to a methionine. Previous work in the early 2000s suggested that somehow this gene was not working well in people with schizophrenia and that this Met66 polymorphism would be linked to disorders of the brain including schizophrenia.

When researchers examined the polymorphisms in the gene and schizophrenia and effect on hippocampal dysfunction in a study of 641 individuals reported in Cell 2003 by Egan et al. cohorts of schizophrenia, siblings and normal individuals were examined to see if there was a relationship. However, it turned out that this polymorphism had no difference on cognitive recall skills in individuals with schizophrenia but normal individuals (i.e. their siblings) who did not have symptoms showed dramatically reduced memory recall with the Met66 mutation. Later research showed that this polymorphism makes it harder to release BDNF, therefore affecting neuronal health. So even if an individual exercised, there is no guarantee that more BDNF will be released! The effectiveness of exercise is literally in your BDNF genes!

License

4.4 Integrative and Contemplative Neuroscience

Introduction to Contemplative Science

Neuroplasticity is the innate property of the brain to alter its structure and function depending on our experiences. The theoretical framework of neuroplasticity is often associated with learning a new skill, such as how to juggle or speak a new language. A new field of scientific study, contemplative science, is concerned with how training the mind through meditation can induce neuroplasticity. In this chapter, we explore how contemplative practices, such as mindfulness meditation, influence neural activity and the architecture of the brain. Contemplative practices involve training a complex array of cognitive processing, including attentional and emotional regulation. In this chapter, we will take a closer look at the methodology used to understand the effects of meditation on the brain and behaviour, as well as the implementation of meditation in psychotherapy.

Meditation

The practice of meditation has rich roots that extend back to century old traditions of Eastern religions. In Western society, the practice of meditation has been adopted and utilized as a self-help tool for stress reduction (Cutshall *et al.*, 2011). Both secular and non-secular forms of meditation involve the regulation of attention and emotions, utilizing the techniques of **focused attention (FA)** and **open monitoring (OM)**. FA requires that individuals actively directs their attention to an object, sensation, or idea (i.e. a mantra). OM involves attending to the transiency of thoughts and bodily sensations as they change from moment-to-moment (Lutz et al., 2009).

The most widely practiced form of meditation is **mindfulness meditation** (**MM**), which is based on the concept that **mindfulness** is the ability to; pay attention, on purpose, to thoughts and sensations in the present moment, non-judgmentally (Kabat-Zinn,1994). Mindfulness meditation has been integrated into therapies used to treat psychiatric disorders such as major depression and anxiety (Shonin & Van Gordon, 2016).

Making the Connection Between Meditation and Neuroscience

Identifying Effects on Neural Activity

Initial research on meditation focused on identifying how long-term practice influenced cortical activity using electroencephalography (EEG). Seminal work by Lutz *et al.* (2004), uncovered that long-term Buddhist practitioners exhibited EEG patterns in the lateral frontoparietal area that were indicative of phase synchrony of gamma band oscillatory activity (25-70 Hz). This pattern of cortical activity has been associated with the integration of information across neural networks through short and long-term synaptic changes that underlie processes of cognitive and affective regulation. These findings suggest that the practice of meditation may

promote functional changes of activity in the brain, consistent with the experience-dependent nature of neuroplasticity (Pascual-Leone et al. 2005; Travis & Arenander 2004).

Although these studies provided evidence for the meditation-brain connection, it is important to consider the limitations of utilizing EEG to characterize neural changes associated with meditation practice. EEG is a method that measures cortical activity by using electrodes placed on the scalp to detect extracellular currents produced by postsynaptic apical dendrites of pyramidal neurons. These electrical signals however, are distorted as they pass through the skull. As a result, using EEG makes it difficult to infer the source of observed cortical activity. To this point, it is also difficult to detect changes in neural activity in deeper cortical structures due to their distance from surface electrodes. These limitations are referred to as the inverse problem of EEG. The advantage of EEG is that the technique offers a high degree of temporal resolution, as it can be used to detect changes in cortical on the order of milliseconds (Grech et al. 2008).

To address the limitations of EEG, subsequent studies utilized techniques such as **functional magnetic resonance imaging (fMRI)** to measure local changes in blood oxygenation as a level of neuronal activity, referred to as the **BOLD response.** It was found that individuals that practiced meditation exhibited reduced activity in the **default mode network (DMN)** during the practice of meditation compared to rest. The DMN is a collection of cortical structures including; the posterior cingulate cortex, medial prefrontal cortex, and the angular gyrus. The DMN has also been referred to as a **task negative network** as activity in these regions are associated with self-referential processing and mind wandering that divert attention while completing a task. Considering this, the practice of attentional regulation through meditation practice has been hypothesized to suppress activity of this network to improve focus on tasks outside of meditation practice (Garrison et al. 2015; Pagnoni 2012).

Knowledge Checkpoint

1. What changes in neural activity can be observed in meditation practitioners and what are these patterns of activity associated with?
2. What are the limitations of using EEG to infer the localization of changes in cortical activity?
3. Which imaging technique can be used to improve spatial resolution to determine changes in the activity of brain structures that occur during the practice of meditation?

Identifying Effects on Cortical Grey Matter Structure

Using **magnetic resonance imaging (MRI)**, it was found that experienced meditators exhibit increased cortical thickness in the prefrontal cortex and right anterior insular cortex which correlated with their level of experience (Lazar et al., 2005). The prefrontal cortex has been shown to integrate emotion and cognition, a skill that is hypothesized to develop through meditation practice (Gray et al. 2002). As well, an increase in thickness of the right anterior insular cortex is related to visceral awareness that is developed by attending to bodily sensations through **OM**. These findings support the theory that long-term meditation practices induce changes in cortical structure. The **cross-sectional design** of this study did not allow for the observation of how meditation practice changes the structure the brain over a period of time, especially in naive meditators.

A **longitudinal study** conducted by Holtzel *et al.*, (2011) was conducted to observe changes in grey matter

volume throughout the brain after individuals completed an 8-week long **mindfulness-based stress reduction program (MBSR)**. It was found after program completion, individuals exhibited increased grey matter volume in regions of the brain including the posterior cingulate cortex, part of the **DMN**. Other studies have found increased grey matter volume in emotion processing and regulatory regions including the insula, anterior cingulate cortex (ACC) and the amygdalae of meditators (Marchand, 2014).

Identifying Effects on White Matter Structures

In addition to examining changes in grey matter volume in the brain after meditation practice, white matter tracts that integrate information across brain regions have also been a focus of study. Using **diffusion tensor imaging (DTI)**, it was found that after a short period of meditation practice, individuals exhibited an increase in white matter connectivity from the anterior cingulate cortex (ACC) through the corona radiata to other regions of the brain. This supports that meditation increases connectivity in a region of the brain that is involved in self-regulation, a skill that is central to the meditation practice. This finding is extremely interesting because the observed alterations in white matter structure were viewed after a short training period (11 hours), whereas in previous studies examining the white matter effects of skill training, months to years were required to induce changes in white matter structure (Tang et al., 2010).

Knowledge Checkpoint

1. Explain which type of study design can be used to measure changes in brain structure that occur over a period of time and how this differs from other study designs.
2. What neuroimaging techniques can use to alterations in grey matter volume and white matter structure?

Applications of Meditation

Psychotherapy

Given that meditation has been found to induce neuroplastic changes in brain structure and neural activity, extensive research has been conducted focusing on the psychological effects of these changes. For example, mindfulness interventions have been integrated into traditional cognitive behavioural therapies to treat individuals that suffer from affective disorders This form of mindfulness-informed psychotherapy is referred to as **mindfulness-based cognitive therapy (MBCT).** A study by Ives-Deliperi et al.(2013), examined how an MBCT intervention influenced the brain activity of bipolar disorder patients, using **fMRI,** and how these changes were associated with behavioural factors such as anxiety and emotional regulation. After treatment, patients were found to have improved anxiety and emotional regulation. As well, patients exhibited a decrease in mPFC

activation during a mindfulness task compared to controls. This indicates that mindfulness practice suppresses activity within the default mode network to improve attentional regulation during the practice of mindfulness.

A recent systematic review on the efficacy of mindfulness based therapies found that this therapy has a similar efficacy to traditional cognitive behavioural (CBT), behavioural therapies, and pharmacological treatments. This indicates that mindfulness is a valid therapeutic intervention for the treatment of anxiety-related disorders and affective disorders (Khoury et al., 2013). Although these findings are promising, little is known about the long-term efficacy of mindfulness based therapies in relapse prevention. Recent studies have shown that MBCT is important for the prevention of major depression relapse patients (Matthew et al., 2010), however more studies of this nature must be completed.

Knowledge Checkpoint

1. What are the behavioural and functional changes observed after mindfulness based interventions?
2. What is a limitation of studies conducted on the efficacy of mindfulness based interventions?

Conclusion

As outlined in this chapter, meditation practice induces neuroplastic changes in the brain much like practicing other skills. Meditation induced changes occur at the level of grey matter and white matter, as well as neural activity. These changes are associated with regions of the brain that are involved in regulation of attention and emotion, skills that are developed through a regular meditation practice. These findings have important clinical implications for supplementing traditional cognitive behavioural therapies to treat psychiatric disorders such as major depression, anxiety, and bipolar disorder. The field of contemplative science however, still requires improvement in the methodology utilized to study changes in the brain and behaviour that occur as a result of meditation practice.

About the Author/Contributors

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I'm a third year student pursuing a degree in Immunology, Health & Disease, and Art History at UofT. Visual art has, and continues to be, a creative outlet for me. Working on this textbook has given me the opportunity to combine my scientific background with my artistic passion, driving the creation of many stimulating and informational graphics.

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I'm a third-year student studying Health & Disease and Cells & Systems Biology at the University of Toronto. It has been an absolute joy working with the team to make this textbook a reality. Many hours were spent researching, illustrating, editing, and collaborating. I hope that this will be an insightful and engaging window into neuroscience for current students and a reliable reference for all in the future.

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I'm a third-year student studying Nutrient Science, Human Physiology and Psychology at the University of Toronto. Creative and visual art has always been a huge part of my life. I love and have travelled around the world to different cities and visited the local art museum. These experiences helped me better at transforming complex thoughts and words into visual art. Being able to work with this team has given me an opportunity to converting ideas and words into a graphical design, to help the audience understand and learn material in entertaining and innovative ways.