12. Nervous System: Nervous Tissue

I. Introduction to the Nervous System

General functions of the nervous system
The nervous system has three basic functions:
1. Gather sensory input from the environment and the body itself.
2. Process and evaluate information and decide what to do; or, in a word, integration.
3. Initiate responses via motor output.

Another function that underlies the functions described above is communication. The nervous system enables different parts of the body to communicate with each other. What other organ system in the body has a similar job of communication within the body? How does this system compare with and differ from the nervous system?

Organization of the nervous system
The nervous system can be broadly divided into two major areas:
A. The central nervous system (CNS) includes the brain and spinal cord.
B. The peripheral nervous system (PNS) is all of the nervous system outside of the CNS.

The PNS can be further divided into two components:
A. The afferent division carries sensory information from receptors to the CNS.
B. The efferent division carries commands from the CNS to effectors, which are either muscles or glands.

The afferent division can be further divided into two components:
A. Somatic sensory information is perceived consciously, such as vision and taste.
B. Visceral sensory information is not perceived consciously, such as your body monitoring blood pressure or levels of carbon dioxide.

The efferent division can be further divided into two components:
A. The somatic nervous system innervates skeletal muscles and it is associated with voluntary control.
B. The autonomic nervous system innervates the viscera (intestine, heart, vessels), and is associated with involuntary activities.

The autonomic system has two divisions:
A. The sympathetic nervous system, which is best known for the “fight or flight response.”
B. The parasympathetic nervous system, which restores the body to normal function.
II. Nervous Tissue: Neurons

Neuron structure
The major functions of the nervous system are accomplished by cells called neurons. Refer to Fig. 12.2 of your text for a diagram of a typical neuron.

A neuron is composed of a cell body (or soma) and various projections from the body. Within the cell body are the nucleus and other materials responsible for normal cell function. This includes an extensive rough endoplasmic reticulum (also known as chromatophilic substance or Nissl bodies), which is the site of protein and membrane production. Bundles of microscopic filaments inside the cell body, called neurofibrils, help maintain the shape of the neuron. Dendrites are projections from the cell body that are responsible for receiving information from other neurons.

The axon is a projection from the cell body that is responsible for sending information to other neurons (or effectors). Since axons are typically long and thin, they are often referred to as nerve fibers, or simply as “fibers.” Where the axon joins the cell body is the axon hillock. The plasma membrane of the axon is often referred to as the axolemma. While each neuron has only one axon, the axon may split into branches called axon collaterals. At the very end of each axon (or axon collateral) there are many smaller branches called telodendria. At the end of each telodendrion is a knob-like swelling called a synaptic knob (or synaptic terminal, or synaptic end bulb, or bouton). A synaptic knob is where an axon connects to either another neuron or to an effector.

Portions of an axon may be wrapped by glial cells (e.g., Schwann cells) that form a myelin sheath around the axon. The exposed (visible) portion of the Schwann cell is called the neurilemma, and gaps between the Schwann cells are the neurofibril nodes (also known as nodes of Ranvier). The functions of these structures will be discussed during the section on membrane potentials.

Draw and label a diagram of a neuron in the space below.
Classification of neurons
Structurally, neurons can be classified into four basic types (Table 12.1). Be familiar with the appearance of each.

A. **Multipolar neurons** have many dendrites and one axon extending from the cell body. This is the most common type of neuron in the human body.

B. **Bipolar neurons** have two processes extending from the body: one axon and one dendrite, both of which typically have branches. These are rare and found only in special sense organs.

C. **Unipolar neurons** have a single process that extends from the cell body. They are usually sensory neurons. One end (the **peripheral process**) has dendrites to receive information; the other end (the **central process**) functions as an axon and sends information to the CNS.

D. **Anaxonic neurons** have dendrites but no axons. They do not conduct action potentials, and we will not discuss them further.

Functionally, neurons fall into three general categories (Fig. 12.3):
A. **Sensory neurons** transmit information collected from external or internal stimuli to the CNS. Most sensory neurons are unipolar, and some are bipolar. Axons of sensory neurons (called **afferent fibers**) travel toward the brain or spinal cord.

B. **Motor neurons** carry signals to effectors. Axons of motor neurons (called **efferent fibers**) travel from the brain or spinal cord toward the effectors. **Somatic motor neurons** innervate the skeletal muscles, and **visceral motor neurons** innervate all other effectors. Motor neurons are multipolar.

C. **Interneurons** (or “**association neurons**”) make connections between other neurons. Interneurons are found within the CNS and some ganglia. Nearly all Interneurons are multipolar.

Relationship of neurons and nerves
A **nerve** is a cordlike bundle of axons traveling through the body and connecting to the CNS (Fig. 12.4). A nerve is, by definition, part of the PNS. Within a nerve, each axon is surrounded by a layer of connective tissue called the **endoneurium**. Groups of axons are bundled together into collections called **fascicles**. Each fascicle is wrapped in a layer of connective tissue called the **perineurium**. Finally, the entire nerve is wrapped in a layer of connective tissue called the **epineurium**.

A **ganglion** is a collection of neuron bodies located in the peripheral nervous system.

III. Synapses

The **synapse** is where parts of two neurons meet, or where a neuron connects to an effector. The **presynaptic cell** at a synapse is the neuron that is sending a message down its axon to the synapse. The **postsynaptic cell** at a synapse is the neuron (or effector) that is receiving the message. If the postsynaptic cell is a neuron, then it typically receives the message on its body or at a dendrite. As you will see later, transmission of information across the synapse is generally accomplished by chemicals called **neurotransmitters** (or **neurotransmitter substances**). The narrow gap between the presynaptic and postsynaptic cells is the **synaptic cleft**.
IV. Nervous Tissue: Glial Cells

Glial cells (also called “neuroglia”) are involved with supporting neurons (Figure 12.5). If you consider the neurons to be the “actors” of the nervous system, then neuroglia are the “stage hands.” Various functions of neuroglia are as follows:

1. They provide a physical, structural support for the neurons.
2. They provide nourishment for neurons.
3. They may guide the growth of young neurons.
4. Some neuroglia provide electrical insulation by wrapping around axons to create the myelin sheath. These glial cells and the function of myelin will be discussed in detail later.

V. Introduction to Neuron Physiology

Neurons and Ohm’s law
The word “electricity” has been defined in many ways. For our purposes, it will mean the movement of charged particles. Current is a quantitative measure of the amount of charges moving from one point to another per unit time.

Typically, net movement of charged particles from one point to another (a current) is caused by a difference in “electric potential” between the two points. For example, a charged battery has a positive electrode and a negative electrode. When the two electrodes are connected by a circuit, current flows through the circuit. Another term for electric potential is voltage. The battery in your car has a potential difference between the positive and negative electrodes of approximately 12 Volts. The terms “potential” and “potential difference” are often used in physiology with essentially the same meaning as voltage.

A third term that is important for a basic understanding of electricity is resistance. Resistance is a measure of opposition to the flow of electrical charges. You should soon learn that a plasma membrane provides considerable resistance to the flow of electricity (current), but the resistance can be reduced by the opening of channels.

Ohm’s law shows that there is a mathematical relationship among current, voltage, and resistance:

\[ \text{current} = \frac{\text{voltage}}{\text{resistance}} \]

Although I won’t expect you to do any calculations with this equation, I expect you to know what happens to the current if voltage or resistance increases, or if voltage or resistance decreases.
Neurons at rest
The job of a neuron is to send signals to other neurons and/or effectors. These signals depend upon the creation of a voltage across the plasma membrane, often called the membrane potential. There are various important principles to understanding membrane potentials; here are two of them:

1. Intracellular fluids and extracellular fluids have different ionic compositions. Extracellular fluids contain high concentrations of sodium and chloride, whereas intracellular fluids contain high concentrations of potassium and negatively charged proteins.

2. Charged particles cannot move freely across cell membranes. How might a charged particle, such as Na⁺ get across a membrane?

The differences in sodium and potassium concentrations are maintained by pumps in the plasma membrane called the Na⁺/K⁺-ATPase. Each pump is able to move three sodium ions out of the cell and two potassium ions into the cell as it breaks down one molecule of ATP. What process from Chapter 4 is this?

At the same time sodium and potassium are being pumped, they also leak back across the membrane. The plasma membrane has channels for both ions that are open all of the time, and these are sometimes called “leak channels.” The membrane has considerably more leak channels for potassium than sodium. The leakage of potassium to the outside of the cell leads to excess positive charge on the outside and thus excess negative charge on the inside. The amount of potassium that leaks out of the cell is limited by the fact that as positively-charged potassium leaks out, the inside of the cell becomes negatively charged. Since negative charges attract positive charges, eventually this attraction offsets the tendency of potassium to diffuse down its concentration gradient. The equilibrium point for potassium is about -90 mV (measured inside the cell).

Sodium also leaks across the plasma membrane, but there are much fewer leak channels for sodium than for potassium. Movement of sodium through these channels makes the voltage inside the cell somewhat more positive (or you could say less negative) than it would be if only potassium crossed the membrane. In the typical human neuron, the resulting voltage inside the cell is about -70 mV. This is referred to as the resting membrane potential.

VI. Physiologic Events in the Neuron Segments
At rest, a neuron tends to sit at its resting potential of -70 mV. However, the purpose of a neuron is not to sit at rest forever, but to send a signal. The signal is sent when the voltage changes to what is called the threshold. In order to reach threshold, the voltage must change. The way to get the voltage to change is by opening more channels.

Two types of channels are going to be important in changing the voltage: voltage-gated channels and chemical-gated channels. A voltage-gated channel opens in response to a certain change in the potential across the membrane. A chemical-gated channel opens in response to binding of a certain chemical to the channel.
There are various chemical- and voltage-gated channels in the plasma membrane of a neuron, but we will continue to focus on channels for sodium and potassium. **Under conditions we have described so far, the net movement of sodium through ion channels will always be into the cell, and the net movement of potassium through ion channels will always be out of the cell.** Thus, the opening of gated sodium channels allows more positive charge to enter the cell, reducing the voltage across the plasma membrane. A reduction in voltage (bringing the voltage toward zero) is called **depolarization** of the membrane. Opening gated potassium channels allows more positive charge to exit the cell, increasing the voltage across the membrane. An increase in voltage beyond the resting potential (more negative than -70 mV) is called **hyperpolarization**.

**Receptive segment**

**Graded potentials** are local changes in the membrane potential (Fig. 12.15). They are called “graded” potentials because the magnitude of the change varies with the intensity of the stimulus.

The opening of chemical-gated channels in the cell membrane produces graded potentials. For example, opening chemical-gated sodium channels* will allow sodium ions to diffuse into the cell (Fig. 12.15a). This influx of positive charge will cause a local change in the membrane potential, making it more positive. This shift in the membrane potential toward 0 mV is a depolarization. The greater the number of sodium channels that opens, the greater the magnitude of the depolarization.

*Although I use the term “chemical-gated sodium channel,” these channels allow the passage of both sodium and potassium. However, when a neuron is below threshold, K⁺ is much closer to its equilibrium point than is Na⁺. Thus, the driving force to move sodium through the channel is much greater than the driving force for potassium, more positive charge enters the cell than leaves, and the cell is depolarized.

The opening of chemical-gated potassium channels will allow more potassium to move out of the cell (Fig. 12.15b). This makes the membrane potential more negative, which is hyperpolarization. (This can also be accomplished by opening chemical-gated chloride channels, which allow a net movement of Cl⁻ into the neuron.)

**Graded potentials** occur on what is known as the **receptive segment** of a neuron. This is the part of the neuron where chemical-gated channels are located, including the dendrites and often the soma. When graded potentials occur on the receptive segment of a neuron, the graded potentials may be called **postsynaptic potentials**, since they are occurring on the membrane of a postsynaptic cell in response to activity at the synapse. For the rest of this chapter, the terms “graded potential” and “postsynaptic potential” are interchangeable.

A postsynaptic potential can be either excitatory or inhibitory depending upon the neurotransmitter that is released into the synapse. If the stimulus is excitatory in nature (Fig. 12.15a), then it acts by opening
chemical-gated sodium channels in the postsynaptic membrane. Excitatory postsynaptic potentials (EPSP’s) cause depolarization, which may lead to an action potential.

If the stimulus is inhibitory in nature (Fig. 12.15b), then it acts by opening chemical-gated potassium channels (or chloride channels) in the post-synaptic membrane. Inhibitory post-synaptic potentials (IPSP’s) cause hyperpolarization.

Initial segment

The initial segment of a neuron is where there is a transition from chemical-gated channels to voltage-gated channels. This region is typically found at the axon hillock. If the membrane potential at the initial segment reaches the threshold value, then an action potential begins.

As mentioned previously, postsynaptic potentials may be of varying magnitude. Another feature of the postsynaptic potential is summation. The effects of PSP’s are cumulative. For example, if the postsynaptic cell simultaneously receives an IPSP and an EPSP of equal magnitude they will cancel. Likewise, if the cell simultaneously receives multiple EPSP’s, then they will sum to a larger magnitude depolarization. If EPSP’s reach the threshold, then an action potential begins.

Summation must be thought of in both spatial and temporal terms (Fig. 12.17). Spatial summation occurs when a large number of presynaptic neurons fire action potentials at the same time. This results in summation as a large number or graded potentials occur simultaneously. Temporal summation occurs when one or more presynaptic neurons fire multiple action potentials in rapid succession. This results in summation as PSP’s occur repeatedly. Summation allows neurons to act in concert to provide an almost limitless number of patterns of neural activity.

As long as the voltage at the initial segment stays below threshold, this neuron does not fire an action potential. If the voltage at the initial segment does reach threshold, then an action potential begins. Action potentials are always of the same intensity; there are no “partial” action potentials. Thus we can say that an action potential is an “all or none” event.

Conductive segment

The conductive segment is the part of the neuron that has voltage-gated channels, generally the axon. The axolemma is sometimes referred to as the “excitable” portion of the neuron. An action potential is a change in the membrane potential that, once initiated, spreads across the entire conductive segment. An action potential is initiated when graded potentials cause a change in the voltage of the plasma membrane that is sufficient to open voltage-gated channels in the axonal membrane. Once initiated, the action potential spreads across the entire excitable membrane of the cell.

The membrane voltage required to trigger an action potential is called the threshold level. Threshold varies for different neurons, but it is typically around –55 mV. Once a cell reaches threshold, it will fire an action potential. Notice that the threshold level is always less negative than the resting potential. Thus, a depolarization is always required to trigger an action potential. On the other hand, hyperpolarization of a neuron takes it away from its threshold and makes it less likely to fire an action potential.
Here are the steps in the generation of an action potential (Fig. 12.18):

A. **Depolarization.** If the initial segment reaches threshold, then voltage-gated Na\(^+\) channels will begin to open. When the Na\(^+\) channels open, the positive charge flows in rapidly, causing rapid depolarization of the cell. Depolarization generally results in a change of potential inside the neuron from −70 mV to approximately +30 mV.

Depolarization is limited by two factors: Influx of Na\(^+\) is eventually resisted by the positive potential that builds up in the cell. Also, voltage-gated sodium channels rapidly close.

B. **Repolarization.** About the same time the sodium channels are closing, voltage-gated potassium channels open. These channels allow potassium to flow out of the cell. This leads to repolarization of the membrane. The membrane electrical potential returns to a value near the resting potential.

C. **Hyperpolarization.** Voltage-gated potassium channels remain open longer than necessary to restore the potential back to −70 mV. Therefore, enough potassium exits the cell to cause slight hyperpolarization. This is sometimes called the “undershoot.”

Eventually, the resting potential is restored. What components of a neuron are responsible for restoring the resting membrane potential?

You should become familiar with what an electrical recording of an action potential looks like, where depolarization and repolarization are occurring, and at which points the sodium and potassium channels are opening and closing. See Fig. 12.19.

**Refractory period**

Once a neuron has begun an action potential, a short period of time must pass before it can generate another action potential. This period of time is known as the refractory period (Fig. 12.20). More specifically, during the time that the voltage-gated sodium channels are open and then briefly closed in an inactive state; the neuron simply cannot respond to another stimulus. This specific period of time is the absolute refractory period. After the voltage-gated sodium channels have reset, the voltage-gated potassium channels remain open for a time. During this period (v-g Na\(^+\) channels closed, v-g K\(^+\) channels open) the neuron can be stimulated to fire another action potential, but it takes a stronger stimulus than normal because the neuron is hyperpolarized. This specific period of time is the relative refractory period.

**Continuous conduction and saltatory conduction**

Movement of the action potential along the axon is called propagation (Fig. 12.21). It is easier for me to explain this in class than in the notes, but here it is in brief . . .

As positively-charged sodium ions rush into the cell during depolarization, some will spread down the axon. This easily depolarizes more of the axonal membrane to threshold, and this causes more voltage-gated sodium channels to open. This allows more sodium ions to rush into the axon and spread further down the axon. This easily depolarizes more of the axonal membrane to threshold, and this causes more voltage-gated sodium channels to open.
You should see that the paragraph above is an example of a positive feedback loop. This loop allows the action potential to spread (propagate) along the axon until it reaches the axon terminals.

This process of conduction in which the action potential travels down the axon in a continuous wave is referred to as continuous conduction.

The conduction velocity (CV) of an axon is a measure of how fast the action potential travels along the axon. The CV is a function of the diameter of the axon; the larger the diameter of the axon, the faster the conduction. Among the largest known axons are those of the squid, and squid axons may conduct action potentials at velocities of about 35 meters per second. In smaller, unmyelinated axons of a human, CV is on the order of 1 m/s. Although vertebrates have axons with smaller diameters than the squid, many vertebrate axons have much faster conduction velocities. This is because of myelin. Glial cells (oligodendrocytes in the CNS and Schwann cells in the PNS) wrap around axons to form the myelin sheath. Each wrapping consists of multiple lipid bilayers (Fig. 12.23). Gaps between regions of myelin sheath are called neurofibril nodes, and voltage-gated channels are found at the nodes.

To keep things reasonably simple, just be aware that the presence of myelin allows positive current (Na⁺) to travel down the axon at a faster velocity. However, regardless of how fast it travels, the current that enters the axon at the axon hillock cannot make it all the way down the axon. Thus, nodes are required to periodically allow more sodium to enter the axon through voltage-gated channels, ensuring that the signal gets all the way to the axon terminal. Since the action potential only appears at the nodes, it is as if the action potential is jumping from node to node. This process is called saltatory conduction; “saltere” means “jump.” The largest myelinated axons in a human have conduction velocities on the order of 150 m/s.

Transmissive segment

Neurons make connections with other neurons or their effectors at junctions called synapses. Most synapses are chemical synapses in which the signal is transferred from the presynaptic cell to the postsynaptic cell as a chemical signal. These chemical signals are called neurotransmitters.

Recall that telodendria of an axon typically end in knob-shaped structures called synaptic knobs (Fig. 12.22). Each axon terminal contains vesicles called synaptic vesicles, which are filled with neurotransmitters. On the outside of the knob there is a high concentration of Ca²⁺.

When an action potential reaches the axon terminal, the following processes occur to send a signal across the synapse:

1. The change in voltage to threshold opens voltage-gated Ca²⁺ channels in the membrane of the synaptic knob. This allows calcium into the knob.
2. The vesicles inside the knob fuse to the membrane, and the neurotransmitters are dumped into the synaptic cleft by the process of exocytosis.
3. The neurotransmitters bind to receptors on the receptive segment of the postsynaptic cell.
4. Chemical-gated channels on the postsynaptic cell open in response to binding of the neurotransmitters. This causes a PSP on the postsynaptic cell, and we’re back to where we started!
Chemical-gated channels tend to remain open as long as the chemical is bound to the receptor. For the signal at the synapse to end, the neurotransmitters must be removed from the synaptic cleft. There are three basic processes by which this can happen:

1. Neurotransmitters can be broken down by enzymes. For example, acetylcholine in the synaptic cleft is broken down by the enzyme acetylcholinesterase.

2. Neurotransmitters can be removed from the synaptic cleft by the presynaptic cell or by astrocytes.

3. Neurotransmitters can diffuse out of the synaptic cleft into the interstitial space.