Neurons, Synapses, and Signaling

Key Concepts

48.1 Neuron organization and structure reflect function in information transfer
48.2 Ion pumps and ion channels maintain the resting potential of a neuron
48.3 Action potentials are the signals conducted by axons
48.4 Neurons communicate with other cells at synapses

Framework

This chapter describes the transmission of nervous impulses along and between neurons. Ion channels maintain the membrane potential of a neuron, and the rapid flow of ions through voltage-gated channels creates the rapid depolarization of an action potential. The release of neurotransmitters at synapses converts electrical signals to chemical signals that pass information to receiving cells.

Chapter Review

Neurons transfer long-distance information via electrical signals and usually communicate between cells using short-distance chemical signals. The higher-order processing of nervous signals may involve clusters of neurons called ganglia or more structured groups of neurons organized into a brain.

48.1 Neuron organization and structure reflect function in information transfer

Information Processing  The three stages of information processing are sensory input, integration, and motor output. Sensors detect external stimuli or internal conditions. Sensory neurons transmit this information to the brain or ganglia, where interneurons integrate it and send output through neurons bundled into nerves that triggers muscle or gland activity. Motor neurons carry impulses to muscle cells.

A central nervous system (CNS), found in many animals, includes the brain and longitudinal nerve cord. The peripheral nervous system (PNS) consists of nerves connecting the CNS with the rest of the body.

Neuron Structure and Function A neuron consists of a cell body, which contains the nucleus and organelles, and numerous extensions. The highly branched, short dendrites receive signals from other neurons; the longer axon transmits signals to other cells. Axons originate from a region of the cell body called the axon hillock.

Terminal branches of axons end in synaptic terminals, which usually release neurotransmitters that relay signals across the synapse to another neuron, muscle, or gland cell. The transmitting cell is called the presynaptic cell; the receiving cell is the postsynaptic cell.

The very numerous supporting cells called glia give structural integrity and physiological support to neurons.

Interactive Question 48.1

Label the indicated structures on this diagram of a neuron. Indicate the direction of impulse transmission. What happens at part e?

---

The text continues beyond the visible portion of the page.
48.2 Ion pumps and ion channels maintain the resting potential of a neuron

A voltage, or membrane potential, exists across the plasma membrane of all cells. The membrane potential of a typical nontransmitting neuron, called the resting potential, is between −60 and −80 mV.

**Formation of the Resting Potential** In a mammalian neuron, the concentration of K⁺ is 140 mM inside the cell and 5 mM outside. The Na⁺ concentration is 150 mM outside and 15 mM inside. Sodium-potassium pumps maintain these gradients.

Ion channels that are selectively permeable allow specific ions to diffuse across the membrane. The diffusion of K⁺ out of a cell results in a buildup of negative charge within the neuron, creating the membrane potential.

**Modeling the Resting Potential** Ions diffuse through channels down their concentration gradient until balanced by the electrical gradient across the membrane. The membrane voltage at this equilibrium, or equilibrium potential (E\text{ion}) is determined for a single ion with a 1⁺ charge at 37 °C by the Nernst equation:

\[
E_{\text{ion}} = 62 \text{ mV} \log \left( \frac{[\text{ion}]_{\text{outside}}}{[\text{ion}]_{\text{inside}}} \right).
\]

The equilibrium potential for K⁺ (E_K) in a neuron is −90 mV. Using the concentration gradients for Na⁺, E_Na is +62 mV (the inside of the membrane is more positive than outside).

Neurons at rest have more K⁺ channels open than Na⁺ channels, and the resting potential is closer to E_K than E_Na.

---

**INTERACTIVE QUESTION 48.2**

a. What is the principal cation inside the cell? outside the cell? **Inside K⁺, outside Na⁺**

b. Which side of the membrane has a negative charge? **Inside**

c. What change in the permeability of the cell’s membrane to K⁺ and/or Na⁺ could cause the cell’s membrane potential to shift from −70 mV to −90 mV? **More K⁺ channels open**

---

48.3 Action potentials are the signals conducted by axons

In addition to the ungated potassium and sodium ion channels that create the resting potential, neurons also have gated ion channels that open or close in response to stimuli and increase or decrease the membrane potential. Electrophysiologists measure membrane potential by placing microelectrodes connected to a voltage recorder inside and outside a cell.

A stimulus that opens K⁺ channels will result in hyperpolarization, as K⁺ flows out and the membrane potential moves toward E_K (−90 mV). When Na⁺ channels open and Na⁺ flows in, a depolarization occurs as the inside of the cell becomes less negative. With this type of graded potential, the magnitude of a voltage change is proportional to the strength of the stimulus; the stronger the stimulus, the more gated ion channels that open.

**Production of Action Potentials** Voltage-gated channels respond to a change in membrane potential, which may trigger their opening and lead to a massive change in membrane voltage called an action potential. Once depolarization of a typical neuron reaches a certain membrane voltage called the threshold, an action potential is triggered. The action potential is an all-or-none event, always creating the same voltage spike once the threshold is reached.

**Time Course of Action Potentials** Action potentials last only about 1–2 milliseconds. The frequency of action potentials increases with the intensity of a stimulus.

Both Na⁺ and K⁺ voltage-gated channels are involved in an action potential. Sodium channels open rapidly in response to depolarization, but become inactivated when a part of the channel blocks the opening. Potassium channels open slowly in response to depolarization, but remain open throughout the action potential.

As a stimulus depolarizes the membrane to threshold, Na⁺ channels open; the influx of Na⁺ causes further depolarization, which opens more channels. This positive-feedback cycle during the rising phase brings the membrane potential close to E_Na. The inactivation of Na⁺ channels and opening of voltage-gated K⁺ channels rapidly brings the membrane potential back toward E_K during the falling phase.

During the undershoot, the membrane's permeability to K⁺ is higher than at rest, and the continued outflow of K⁺ temporarily hyperpolarizes the membrane. During the refractory period, which occurs while the Na⁺ channels remain inactivated, the neuron cannot respond to another stimulus.
INTERACTIVE QUESTION 48.3

This diagram shows the changes in voltage-gated channels during an action potential. Label the channels and inactivation gate, ions, and the components of the graph. Name and describe the five phases of the action potential. Place numbers on the graph to show where each phase is occurring.

1. Resting State
2. Depolarization
3. Rising Phase
4. Sodium Inactivation Gate
5. Undershoot
6. Falling Phase
7. Action Potential
8. Membrane Potential
9. Threshold
10. Resting Potential
11. Time

Extracellular fluid
Plasma membrane
Cytosol

a. Sodium Channel
b. Potassium Channel
d. Na⁺
c. K⁺
Conduction of Action Potentials Na\(^+\) influx in the rising phase depolarizes adjacent sections of the membrane, bringing them to the threshold. Local depolarizations and action potentials across the membrane result in the propagation of serial action potentials along the length of the neuron. Because of the brief refractory period, the action potential is propagated in only one direction.

Resistance to current flow is inversely proportional to the cross-sectional area of the conducting “wire.” The greater the axon diameter, the faster action potentials are propagated. Some invertebrates, such as squid, have giant axons that conduct impulses very rapidly.

In vertebrates, oligodendrocytes (in the CNS) and Schwann cells (in the PNS) insulate axons in a myelin sheath by forming layers of membranes. Voltage-gated ion channels are concentrated in the nodes of Ranvier, small gaps between successive Schwann cells. Action potentials can be generated only at these nodes, and a nerve impulse “jumps” from node to node, resulting in a faster mode of transmission known as saltatory conduction.

48.4 Neurons communicate with other cells at synapses

Electrical synapses allow electrical current to flow directly from cell to cell via gap junctions. Electrical synapses are found in the giant axons of squid and lobsters and in many neurons of the vertebrate brain.

A chemical synapse involves the release of neurotransmitters. A synaptic terminal contains synaptic vesicles, in which thousands of molecules of neurotransmitter are stored. The depolarization of the presynaptic membrane opens voltage-gated calcium channels in the membrane. The influx of Ca\(^{2+}\) causes the synaptic vesicles to fuse with the presynaptic membrane and release neurotransmitter into the synaptic cleft.

**INTERACTIVE QUESTION 48.5**

Identify the components of this chemical synapse following the depolarization of the synaptic terminal.

![Diagram of a chemical synapse]

Generation of Postsynaptic Potentials Binding of neurotransmitter to a receptor on ligand-gated ion channels in the postsynaptic cell membrane allows ions to cross the membrane, creating a postsynaptic potential. If the channel allows both Na\(^+\) and K\(^+\) to diffuse through, the net inflow of positive charge depolarizes the membrane, creating an excitatory postsynaptic potential (EPSP) that brings the membrane potential closer to threshold. If binding of neurotransmitter opens K\(^+\) or Cl\(^-\) channels, the membrane hyperpolarizes, producing an inhibitory postsynaptic potential (IPSP).

The effect of neurotransmitters is terminated when the molecules diffuse away, are taken up and repackaged into synaptic vesicles, or are broken down by enzymes.

Postsynaptic potentials are graded potentials. Their magnitude depends on the number of neurotransmitter molecules that bind to receptors. The membrane potential of the axon hillock at any given time is determined by the sum of all EPSFs and IPSPs.

**Modulated Synaptic Transmission** Some neurotransmitters bind to receptors that trigger a signal transduction pathway in the postsynaptic cells. This modulated synaptic transmission begins more slowly but lasts longer. Binding of neurotransmitter to a receptor often leads to the production of cAMP as a second messenger and the phosphorylation of channel proteins, opening or closing ion channels.

**Neurotransmitters** Neurotransmitters may have many different receptors and may produce very different effects in postsynaptic cells.

**Acetylcholine** is a common neurotransmitter in invertebrates and vertebrates. Depending on the type of receptor, it can be inhibitory or excitatory. In neuromuscular junctions, acetylcholine released from a motor axon produces an EPSP in a muscle cell. The enzyme acetylcholinesterase hydrolyzes the neurotransmitter.

**Biogenic amines**, neurotransmitters derived from amino acids, are often involved in modulating synaptic transmission in the CNS. Epinephrine, norepinephrine,
and dopamine are derived from tyrosine. Norepinephrine acts through a G-protein-coupled receptor to generate EPSPs in the PNS. Serotonin (synthesized from tryptophan) and dopamine affect sleep, mood, attention, and learning. Imbalances of these neurotransmitters have been associated with several disorders.

The amino acids gamma aminobutyric acid (GABA) and glutamate function as neurotransmitters in the CNS. GABA is the most common inhibitory transmitter in the brain. Glutamate is excitatory. Glycine is inhibitory in parts of the CNS outside the brain.

Neuropeptides are short chains of amino acids that activate signal transduction pathways. Substance P is an excitatory neurotransmitter that functions in pain perception. Endorphins are neuropeptides produced in the brain during physical or emotional stress that have pain-killing and other functions. Opiates bind to endorphin receptors in the brain.

Some neurons use nitric oxide (NO) and carbon monoxide as local regulators. The release of NO triggers relaxation of smooth muscle cells and vessel dilation. CO produced by neurons in the brain affects the release of hypothalamic hormones.

**INTERACTIVE QUESTION 48.6**

Acetylcholine stimulates skeletal muscle contraction but inhibits or slows cardiac muscle contraction. How can this neurotransmitter have such opposite effects?

---

**Word Roots**

- **bio-** = life; **genic** = producing (biogenic amines: neurotransmitters derived from amino acids)
- **dendro-** = tree (dendrite: one of usually numerous, short, highly branched processes of a neuron that receive signals from other neurons)
- **de-** = down, out (depolarization: an electrical state in an excitable cell whereby the inside of the cell is made less negative relative to the outside)
- **endo-** = within (endorphin: a hormone produced in the brain and anterior pituitary that inhibits pain perception)
- **glia** = glue (glia: supporting cells that are essential for the structural integrity of the nervous system and for the normal functioning of neurons)

**Structure Your Knowledge**

1. Develop a flowchart, diagram, or description of the sequence of events in the creation and propagation of an action potential and in the transmission of this potential across a chemical synapse.

**Test Your Knowledge**

**MULTIPLE CHOICE: Choose the one best answer.**

1. Which of the following is not true of the resting potential of a typical neuron?
   - a. The inside of the cell is more negative than is the outside.
   - b. There are concentration gradients with more sodium outside the cell and a higher potassium concentration inside the cell.
   - c. It is about ~70 mV and can be measured by using microelectrodes placed inside and outside the cell.
   - d. It is formed by the sequential opening of voltage-gated channels.
   - e. It results from the combined equilibrium potentials of potassium and sodium.
2. Interneurons
   a. may connect sensory and motor neurons.
   b. are more common in the PNS than the CNS.
   c. are involved in the integration of sensory information.
   d. typically have more axons than dendrites.
   e. Both a and c are correct.

3. Nodes of Ranvier are
   a. gaps where Schwann cells abut and at which action potentials are generated.
   b. neurotransmitter-containing vesicles located in the synaptic terminals.
   c. the parts of neurons where action potentials are initiated.
   d. clusters of receptor proteins located on the postsynaptic membrane.
   e. ganglia adjacent to the spinal cord.

4. After the depolarization of an action potential, the fall in the membrane potential occurs due to the
   a. closing of sodium inactivation gates.
   b. closing of potassium and sodium channels.
   c. refractory period in which the membrane is hyperpolarized.
   d. delay in the action of the sodium-potassium pump.
   e. opening of voltage-gated potassium channels and the closing of sodium inactivation gates.

5. The threshold of a membrane
   a. is exactly midway between \( E_K \) and \( E_{Na} \).
   b. opens voltage-gated channels and permits the rapid outflow of sodium ions.
   c. is the depolarization that is needed to generate an action potential.
   d. is a graded potential that is proportional to the strength of a stimulus.
   e. is an all-or-none event.

6. Which of the following is incorrectly paired with its function?
   a. axon hillock—region of neuron where action potential originates
   b. Schwann cells—create myelin sheath around axon in PNS
   c. synapse—space between presynaptic and postsynaptic cell into which neurotransmitter is released
   d. synaptic terminal—receptor that is part of an ion channel that is keyed to a specific neurotransmitter
   e. dendrite—receives signals from other neurons

7. Which of the following is not true of chemical synapses?
   a. Synaptic terminals at the ends of branching axons contain synaptic vesicles, which enclose the neurotransmitter.
   b. The influx of sodium when an action potential reaches the presynaptic membrane causes synaptic vesicles to release their neurotransmitter into the cleft.
   c. The binding of neurotransmitter to receptors on the postsynaptic membrane usually opens or closes ion channels.
   d. An excitatory postsynaptic potential forms when sodium channels open and the membrane potential moves closer to an action potential threshold.
   e. Neurotransmitter is often rapidly degraded in the synaptic cleft.

8. An inhibitory postsynaptic potential occurs when
   a. sodium flows into the postsynaptic cell.
   b. enzymes do not break down the neurotransmitter in the synaptic cleft.
   c. binding of neurotransmitter opens ion gates that result in the membrane becoming hyperpolarized.
   d. acetylcholine is the neurotransmitter.
   e. norepinephrine is the neurotransmitter.

9. Which of the following do (does) not function as a neurotransmitter or local regulator released by neurons?
   a. amino acids such as glutamate
   b. neuropeptides such as endorphin
   c. biogenic amines such as dopamine
   d. steroids
   e. NO

10. How is an increase in the strength of a stimulus communicated by a neuron?
    a. The spike of the action potential reaches a higher voltage.
    b. The frequency of action potentials generated along the neuron increases.
    c. The length of an action potential (the duration of the rising phase) increases.
    d. The action potential travels along the neuron faster.
    e. All action potentials are the same; the nervous system cannot discriminate between different strengths of stimuli.
11. Why is signal transmission faster in myelinated axons?
   a. These axons are thinner, and there is less resistance to the voltage flow.
   b. These axons use electrical synapses rather than chemical synapses.
   c. The action potential can jump from node to node along the insulating myelin sheath.
   d. These axons are thicker and provide less resistance to voltage flow.
   e. These axons have higher depolarization values than do unmyelinated axons.

12. What is the main effect of the neurotransmitter GABA in the CNS?
   a. increase pain
   b. create inhibitory postsynaptic potentials
   c. create excitatory postsynaptic potentials
   d. induce sleep
   e. decrease pain and induce euphoria

13. If the binding of a neurotransmitter to its receptor opens Cl⁻ channels, what would be the effect on the postsynaptic cell? (Cl⁻ is in higher concentration outside the cell.)
   a. It would hyperpolarize, receiving an IPSP.
   b. It would reach threshold, and an action potential would fire.
   c. It would depolarize and form an EPSP but probably not fire an action potential.
   d. It would initiate a signal transduction pathway.
   e. Its membrane potential would not change because neither sodium nor potassium channels opened.

14. Movement of an action potential in only one direction along a neuron is a function of
   a. saltatory conduction.
   b. the pathway from dendrite to axon.
   c. the refractory period when sodium inactivation gates are still closed.
   d. the localized depolarization of the surrounding membrane.
   e. the reaching of threshold, which creates an all-or-none firing.