Clinical Case Study

A low-flying crop duster sprays a field worker. Within the hour, he develops blurry vision, excessive salivation, and a runny nose. As the minutes pass, he begins to experience nausea, vomiting, abdominal cramping, and coughing up of copious mucus. An observant paramedic called to the scene makes a diagnosis of organophosphate poisoning and promptly initiates therapy.

Can you account for each of the symptoms this man suffered by describing the normal response of individual organs to parasympathetic stimuli? Hexamethonium is a profoundly potent parasympathetic-blocking drug. What effect would this drug have on the eyes, salivary glands, and nose?
INTRODUCTION TO THE AUTONOMIC NERVOUS SYSTEM

The action of effectors (muscle tissue and glandular epithelium) is controlled to a large extent by motor neuron impulses. Skeletal muscles, which are the voluntary effectors, are regulated by somatic motor impulses. The involuntary effectors (smooth muscle tissue, cardiac muscle tissue, and glandular epithelium) are regulated by autonomic motor impulses through the autonomic nervous system.

Objective 1 Define the terms preganglionic neuron and postganglionic neuron and explain how the motor pathways of the somatic motor and autonomic motor systems differ.

Objective 2 Explain how the autonomic innervation of involuntary effectors differs from the innervation of skeletal muscle.

Objective 3 Compare single-unit smooth muscle tissue and multiunit smooth muscle tissue in terms of structure and regulation by autonomic nerve impulses.

Organization of the Autonomic Nervous System

The autonomic portion of the nervous system is concerned with maintaining homeostasis within the body by increasing or decreasing the activity of various organs in response to changing physiological conditions. Although the autonomic nervous system (ANS) is composed of portions of both the central nervous system and peripheral nervous system, it functions independently and without a person’s conscious control.

Autonomic motor nerves innervate organs whose functions are not usually under voluntary control. The effectors that respond to autonomic regulation include cardiac muscle tissue (within the heart), smooth muscle tissue (within the viscera), and glandular epithelium. These effectors are part of the organs of the viscer (internal organs), of blood vessels, and of specialized structures within other organs. The involuntary effects of autonomic innervation contrast with the voluntary control of skeletal muscles by way of somatic motor innervation.

Unlike the somatic motor system, in which impulses are conducted along a single axon from the spinal cord to the neuromuscular junction, the autonomic motor pathway involves two neurons in the motor transmission of impulses (table 13.1). The first of these autonomic motor neurons has its cell body in the gray matter of the brain or spinal cord. Rather than directly innervating the effector organ, the axon of this neuron synapses with a second neuron within an autonomic ganglion. (A ganglion is a collection of neuron cell bodies outside the CNS.) The first neuron is thus called a preganglionic, or presynaptic, neuron. The second neuron in this pathway, called a postganglionic, or

<table>
<thead>
<tr>
<th>TABLE 13.1 Comparison of Somatic Motor and Autonomic Motor Innervations</th>
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</thead>
<tbody>
<tr>
<td><strong>Feature</strong></td>
</tr>
<tr>
<td>Effector organs (target sites)</td>
</tr>
<tr>
<td>Presence of ganglia</td>
</tr>
<tr>
<td>Number of neurons from CNS to effector organs</td>
</tr>
<tr>
<td>Structure of neuromuscular junction</td>
</tr>
<tr>
<td>Effect of action potentials on muscle fibers</td>
</tr>
<tr>
<td>Type of nerve fibers</td>
</tr>
<tr>
<td>Effect of denervation (temporary or permanent disruption of action potentials)</td>
</tr>
</tbody>
</table>

viscera: L. viscera, internal organs
autonomic: Gk. auto, self; nomos, law
ganglion: Gk. ganglion, a swelling or knox
postsynaptic, neuron, has an axon that extends from the autonomic ganglion and synapses with the cells of an effector organ (fig. 13.1).

Preganglionic autonomic neurons originate in the midbrain and hindbrain and from the upper thoracic to the fourth sacral portions of the spinal cord, with the exception of the area between L3 and S1. Autonomic ganglia are located in the head, neck, and abdomen. Chains of autonomic ganglia also parallel the spinal cord along each side. The origin of the preganglionic neurons and the location of the autonomic ganglia help to differentiate the sympathetic and parasympathetic divisions of the autonomic system, discussed in later sections of this chapter.

Visceral Effector Organs

Unlike skeletal muscles, which enter a state of flaccid paralysis when their motor nerves are severed, the involuntary effectors are somewhat independent of their innervation. Smooth muscles maintain a resting tone (tension) in the absence of nerve stimulation. Damage to an autonomic nerve, in fact, makes its target muscle more sensitive than normal to stimulating agents.

In addition to their intrinsic (built-in) muscle tone, cardiac muscle and many smooth muscles contract rhythmically, even in the absence of nerve stimulation, in response to action potentials initiated by the muscles themselves. Autonomic nerves also maintain a resting tone in the sense that they maintain a baseline firing rate that can be either increased or decreased. Changes in tonic neural activity produce changes in the intrinsic activity of the effector organ. A decrease in the excitatory input to the heart, for example, will slow its rate of beat.

Cardiac Muscle

Like skeletal muscle fibers, cardiac muscle fibers are striated. The long, fibrous skeletal muscle fibers, however, are structurally and functionally separated from each other, whereas the cardiac fibers are short, branched, and interconnected by intercalated discs.

Action potentials that originate at any point in the mass of cardiac fibers called the myocardium can spread to all cells in the mass that are joined by intercalated discs. Because all of the cells in the myocardium are physiologi-
that propel the contents of these tubes in one direction. Waves myogenic action potentials automatically. Thus, cardiac muscle fibers can contract, cardiac muscle fibers are able to produce all-or-none contraction. Furthermore, whereas skeletal muscle fibers require stimulation by action potentials through somatic motor neurons before they can contract, cardiac muscle fibers are able to produce action potentials automatically. Thus, cardiac muscle fibers are myogenic (μ’s-je-n’ık), which means that they contract intrinsically independent from stimulation from action potentials. Cardiac action potentials normally originate in a specialized group of cells called the pacemaker (see fig. 16.11). However, the rate of this spontaneous depolarization, and thus the rate of the heartbeat, is regulated by autonomic innervation.

Smooth Muscles

Smooth (visceral) muscle tissue is arranged in circular layers around the walls of blood vessels, bronchioles (small air passages in the lungs), and in the sphincter muscles of the GI tract. However, both circular and longitudinal smooth muscle layers are found in the tubular GI tract, the ureters (which transport urine), the ductus deferentia (which transport sperm), and the uterine tubes (which transport ova). The alternate contraction of circular and longitudinal smooth muscle layers produces peristaltic waves that propel the contents of these tubes in one direction.

Smooth muscle fibers do not contain sarcomeres (which account for striations in skeletal and cardiac muscle). Smooth muscle fibers do, however, contain a great deal of actin and some myosin, which produces a ratio of thin-to-thick myofilaments of about 16:1 (in striated muscles the ratio is 2:1).

The long length of myosin myofilaments and the fact that they are not organized into sarcomeres helps the smooth muscles function optimally. Smooth muscles must be able to exert tension even when greatly stretched—in the urinary bladder, for example, the smooth muscle cells may be stretched up to two and a half times their resting length. Skeletal muscles, by contrast, lose their ability to contract when the sarcomeres are stretched to the point where actin and myosin no longer overlap.

Single-Unit and Multiunit Smooth Muscles

Smooth muscles are often grouped into two functional categories: single-unit and multiunit. Single-unit smooth muscles have numerous gap junctions (electrical synapses) between adjacent cells that weld them together electrically; thus, they behave as a single unit. Multiunit smooth muscles have few, if any, gap junctions; thus, the individual cells must be stimulated separately by autonomic action potentials through motor neurons. This is similar to the control of skeletal muscles, in which numerous motor units are activated.

Single-unit smooth muscles display pacemaker activity, in which certain cells stimulate others in the mass. Single-unit smooth muscles also display intrinsic, or myogenic, electrical activity and contraction in response to stretch. For example, the stretch induced by an increase in the luminal contents of a small artery or a section of the GI tract can stimulate myogenic contraction. Such contraction does not require stimulation by autonomic nerves. By contrast, contraction of multiunit smooth muscles requires nerve stimulation. Single-unit and multiunit smooth muscles are compared in table 13.2.

**Autonomic Innervation of Smooth Muscles**

The neural control of skeletal muscles and that of smooth muscles differ markedly. A skeletal muscle fiber has only one junction with a somatic nerve fiber, and the receptors for the neurotransmitter are localized at the neuromuscular junction in the membrane of the skeletal muscle fiber. By contrast, the entire surface of smooth muscle fibers contains neurotransmitter...
receptor proteins. Neurotransmitter molecules are released along a stretch of an autonomic nerve fiber that is located some distance from the smooth muscle fibers. The regions of the autonomic fiber that release transmitters appear as bulges, or varicosities, and the neurotransmitters released from these varicosities stimulate a number of smooth muscle fibers.

**Knowledge Check**

1. How does the neural regulation of cardiac and smooth muscle fibers differ from that of skeletal muscle fibers? How are these three types of muscle tissue affected by the experiment removal of their innervation?

2. Define the terms preganglionic and postganglionic neurons in the ANS and use a diagram to illustrate how motor innervation differs in somatic and autonomic nerves.

3. Distinguish between single-unit and multiunit smooth muscles. Explain how the two categories are regulated differently by action potentials through autonomic nerves.

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**STRUCTURE OF THE AUTONOMIC NERVOUS SYSTEM**

Both the sympathetic and parasympathetic divisions of the autonomic nervous system consist of preganglionic neurons with cell bodies located in the CNS and postganglionic neurons with cell bodies located outside of the CNS in ganglia. However, the specific origin of the preganglionic neurons and the location of the ganglia differ in the two subdivisions of the autonomic nervous system.

- **Objective 4** Describe the origin of preganglionic sympathetic neurons and the location of sympathetic ganglia.

- **Objective 5** Explain the relationship between the sympathetic division of the ANS and the adrenal medulla.

- **Objective 6** Describe the origin of the preganglionic parasympathetic neurons and the location of the parasympathetic ganglia.

- **Objective 7** Describe the distribution of the vagus nerve and comment on its significance within the parasympathetic division of the ANS.
Sympathetic (Thoracolumbar) Division

The sympathetic division is also called the thoracolumbar division of the ANS because its preganglionic neurons exit the vertebral column from the first thoracic (T1) to the second lumbar (L2) levels. Most sympathetic neurons, however, separate from the somatic motor neurons and synapse with postganglionic neurons within chains of sympathetic trunk ganglia located on either side of the vertebral column (fig. 13.2).

Because the preganglionic sympathetic neurons are myelinated and thus appear white, the “side branches” to the sympathetic ganglia are called white rami communicantes (ra’mi kō’myoo-nı˘-kan’tēz—singular, ramus communicans) (fig. 13.3). Some of these preganglionic sympathetic neurons synapse with postganglionic neurons located at their same level in the chain of sympathetic ganglia. Other preganglionic neurons travel up or down within the sympathetic chain before synapsing with postganglionic neurons. Because the postganglionic sympathetic neurons are unmyelinated and thus appear gray, they form the gray rami communicantes. Postganglionic axons in the gray ramus extend directly back to the anterior roots of the spinal nerves and travel distally within the spinal nerves to innervate their effector organs.

Within the sympathetic trunk ganglia, divergence is apparent as preganglionic neurons branch to synapse with numerous postganglionic neurons located at different levels in the chain. Convergence is apparent also when a postganglionic neuron receives synaptic input from a large number of preganglionic neurons. The divergence of impulses from the spinal cord to the ganglia and the convergence of impulses within the ganglia usually results in the mass activation of almost all the postganglionic neurons. This explains why the sympathetic division is usually activated as a unit and affects all of its effector organs at the same time.

Many preganglionic neurons that exit the spinal cord in the upper thoracic level travel through the sympathetic chain into the neck, where they synapse in cervical sympathetic ganglia (fig. 13.4). Postganglionic neurons from here innervate the smooth muscles and glands of the head and neck.

Peripheral Ganglia

Many preganglionic neurons that exit the spinal cord below the level of the diaphragm pass through the sympathetic trunk without synapsing. Beyond the sympathetic trunk, these preganglionic neurons form splanchnic (splank’nik) nerves (fig. 13.3). Preganglionic
neurons in the splanchnic nerves synapse in peripheral ganglia, which include the celiac (se’le-ak), superior mesenteric (mes’enter’ik), and inferior mesenteric ganglia (figs. 13.5 and 13.6).

The greater splanchnic nerve arises from preganglionic sympathetic neurons T4–T9 and synapses in the celiac ganglion. These neurons contribute to the celiac (solar) plexus. Postganglionic neurons from the celiac ganglion innervate the stomach, spleen, pancreas, liver, small intestine, and kidneys. The lesser splanchnic nerve terminates in the superior mesenteric ganglion. Postganglionic neurons from here innervate the small intestine and colon. The lumbar splanchnic nerve synapses in the inferior mesenteric ganglion, and the postganglionic neurons innervate the distal colon and rectum, urinary bladder, and genital organs.

**Adrenal Glands**

The paired adrenal glands are located above each kidney (see fig. 13.5). Each adrenal is composed of two parts: an outer adrenal cortex and an inner adrenal medulla. These two parts are actually two functionally different glands with different embryonic origins, different hormones, and different regulatory mechanisms (see chapter 14). The adrenal cortex secretes steroid hormones; the adrenal medulla secretes the hormone epinephrine (ep’ı-nef’rin) (adrenaline) and, to a lesser degree, norepinephrine when it is stimulated by the sympathetic system.

The adrenal medulla is a modified sympathetic ganglion whose cells are derived from postganglionic sympathetic neurons. The cells of the adrenal medulla are innervated by preganglionic sympathetic neurons originating in the thoracic level of the spinal cord; they secrete epinephrine into the blood in response to sympathetic stimulation. The effects of epinephrine are complementary to those of the neurotransmitter norepinephrine, which is released from postganglionic sympathetic nerve endings.

**Parasympathetic (Craniosacral) Division**

The parasympathetic division is also known as the craniosacral division of the autonomic system. This is because its preganglionic neurons originate in the brain (specifically, the midbrain, pons, and medulla oblongata of the brain stem) and in the second through fourth sacral segments of the spinal cord. These preganglionic parasympathetic neurons synapse in ganglia that are lo-
cated next to (or actually within) the organs innervated. These parasympathetic ganglia, which are called terminal ganglia, supply the postganglionic neurons that synapse with the effector cells.

Tables 13.3 and 13.4 show the comparative structures of the sympathetic and parasympathetic divisions. It should be noted that, unlike sympathetic neurons, most parasympathetic neurons do not travel within spinal nerves. Cutaneous effectors (blood vessels, sweat glands, and arrector pili muscles) and blood vessels in skeletal muscles thus receive sympathetic but not parasympathetic innervation.

Four of the twelve pairs of cranial nerves contain preganglionic parasympathetic neurons. These are the oculomotor (III), facial (VII), glossopharyngeal (IX), and vagus (X) nerves. Parasympathetic neurons within the first three of these cranial nerves synapse in ganglia located in the head; neurons in the vagus nerve synapse in terminal ganglia located in many regions of the body.

The oculomotor nerve contains somatic motor and parasympathetic neurons that originate in the oculomotor nuclei of the midbrain. These parasympathetic neurons synapse in the ciliary ganglion, whose postganglionic neurons innervate the ciliary muscle and constrictor muscles in the iris of the eye. Preganglionic neurons that originate in the pons travel in the facial nerve to the pterygopalatine (ter’i-go-pal’ə-tē) ganglion, which sends postganglionic neurons to the nasal mucosa, pharynx, palate, and lacrimal glands. Another group of neurons in the facial nerve terminate in the submandibular ganglion, which sends postganglionic neurons to the submandibular and sublingual glands. Preganglionic neurons of the glossopharyngeal nerve synapse in the otic ganglion, which sends postganglionic neurons to innervate the parotid gland.

Nuclei in the medulla oblongata contribute preganglionic neurons to the very long vagus nerves, which provide the most extensive parasympathetic innervation in the body (see fig. 12.11). As the paired vagus nerves pass through the thorax, they contribute to the cardiac plexus and the pulmonary plexuses within the mediastinum. Branches of the pulmonary plexuses accompany blood vessels and bronchi into the lungs. Below the pulmonary plexuses, branches of the vagus nerves merge to form the esophageal plexuses.

At the lower end of the esophagus, vagal neurons collect to form an anterior and posterior vagal trunk, each composed of neurons from both vagus nerves. The vagal trunks enter the abdominal cavity through the esophageal hiatus (opening) in the diaphragm. Neurons from the vagal trunks innervate the stomach on the anterior and posterior sides. Branches of the vagus nerves within the abdominal cavity also contribute to the celiac plexus and plexuses of the abdominal aorta.

vagus: L. vagus, wandering
CHAPTER 13

FIGURE 13.6 The autonomic nervous system. The sympathetic division is shown in red; the parasympathetic, in blue. Solid lines indicate preganglionic neurons and dashed lines indicate postganglionic neurons.
The preganglionic neurons in the vagus synapse with postganglionic neurons that are actually located within the innervated organs. These preganglionic neurons are thus quite long. They provide parasympathetic innervation to the heart, lungs, esophagus, stomach, pancreas, liver, small intestine, and upper half of the large intestine. Postganglionic parasympathetic neurons arise from terminal ganglia within these organs and innervate the smooth muscle tissue and glandular epithelium of these same organs.

Preganglionic neurons from the sacral levels of the spinal cord provide parasympathetic innervation to the lower half of the large intestine, the rectum, and to the urinary and reproductive systems. These neurons, like those of the vagus, synapse with terminal ganglia located within the effector organs. Parasympathetic nerves to the visceral organs thus consist of preganglionic neurons, whereas sympathetic nerves to these organs contain postganglionic neurons.

A composite view of the sympathetic and parasympathetic divisions of the ANS is provided in figure 13.6, and the comparisons are summarized in table 13.5.

### Knowledge Check

4. Compare the origins of preganglionic sympathetic and parasympathetic neurons and the locations of sympathetic and parasympathetic ganglia.
5. Using a simple line drawing, illustrate the sympathetic pathway from the spinal cord to the heart. Label the preganglionic neuron, postganglionic neuron, and the ganglion.
6. Use a simple diagram to show the parasympathetic innervation of the heart. Label the preganglionic and postganglionic neurons, the nerve involved, and the terminal ganglion.
7. Describe the distribution of the vagus nerve and discuss the functional significance of this distribution.
8. Define the terms white rami and gray rami and explain why blood vessels in the skin and skeletal muscles receive sympathetic but not parasympathetic innervation.
9. Describe the structure of the adrenal gland and explain its relationship to the sympathetic division of the ANS.
FUNCTIONS OF THE AUTONOMIC NERVOUS SYSTEM

The actions of the autonomic nervous system, together with the effects of hormones, help to maintain a state of dynamic constancy in the internal environment. The sympathetic division gears the body for action through adrenergic effects; the parasympathetic division conserves the body's energy through cholinergic effects. Homeostasis thus depends, in large part, on the complementary and often antagonistic effects of sympathetic and parasympathetic innervation.

Objective 8 List the neurotransmitters of the preganglionic and postganglionic neurons of the sympathetic and parasympathetic divisions.

Objective 9 Describe the effects of acetylcholine released by postganglionic parasympathetic neurons.

Objective 10 Explain the antagonistic, complementary, and cooperative effects of sympathetic and parasympathetic innervation.

The sympathetic and parasympathetic divisions of the ANS (fig. 13.6) affect the visceral organs in different ways. Mass activation of the sympathetic division prepares the body for intense physical activity in emergencies; the heart rate increases, blood glucose rises, and blood is diverted to the skeletal muscles (away from the visceral organs and skin). These and other effects are listed in table 13.6. The theme of the sympathetic division is aptly summarized in the phrase fight or flight.

The effects of parasympathetic nerve stimulation are in many ways opposite to the effects of sympathetic stimulation. The parasympathetic division, however, is not normally activated as a whole. Stimulation of separate parasympathetic nerves can result in slowing of the heart, dilation of visceral blood vessels, and increased activity of the GI tract (table 13.6). The different responses of visceral organs to sympathetic and parasympathetic nerve activity is due to the fact that the postganglionic neurons of these two divisions release different neurotransmitters.

Neurotransmitters of the Autonomic Nervous System

The neurotransmitter released by most postganglionic sympathetic neurons is norepinephrine (noradrenaline). Transmission at these synapses is thus said to be adrenergic (ad’rē-ner’jik). There are a few exceptions to this rule: some sympathetic neurons that innervate blood vessels in skeletal muscles, as well as sympathetic neurons to sweat glands, release acetylcholine (are cholinergic).

Acetylcholine (ā-sēt’-ko’lēn) (ACh) is the neurotransmitter of all preganglionic neurons (both sympathetic and parasympathetic). Acetylcholine is also the transmitter released by all parasympathetic postganglionic neurons at their synapses with effector cells (fig. 13.7). Transmission at the autonomic ganglia and at synapses of postganglionic neurons is thus said to be cholinergic (ko’līn-er’jik). In other words, a cholinergic fiber is a neuron that secretes ACh at the terminal end of its axon.

Responses to Adrenergic Stimulation

Adrenergic stimulation—by epinephrine in the blood and by norepinephrine released from sympathetic nerve endings—has both excitatory and inhibitory effects. The heart, dilatory muscles of the iris, and the smooth muscles of many blood vessels are stimulated to contract. The smooth muscles of the bronchioles and of some blood vessels, however, are inhibited from contracting; adrenergic chemicals, therefore, cause these structures to dilate.

cholinergic: Gk. chole, bile; ergon, work
Responses to Cholinergic Stimulation

Somatic motor neurons, postganglionic parasympathetic neurons, and all preganglionic autonomic neurons are cholinergic—they use acetylcholine as a neurotransmitter. The cholinergic effects of somatic motor neurons and preganglionic autonomic neurons are always excitatory. The cholinergic effects of postganglionic parasympathetic neurons are usually excitatory, with some notable exceptions; the parasympathetic neurons innervating the heart, for example, cause slowing of the heart rate.

The drug muscarine (məsˈka-rən), a poison derived from certain mushrooms, mimics the cholinergic effects of parasympathetic nerves in the heart, smooth muscles, and glands by stimulating the acetylcholine receptors located in these organs. This drug, however, does not affect the cholinergic receptors of skeletal muscle or those of autonomic ganglia. The acetylcholine receptors of visceral organs are therefore said to be muscarinic.

The muscarinic effects of ACh are specifically inhibited by the drug atropine, derived from the deadly nightshade plant (Atropa belladonna). Indeed, extracts of this plant were used by women during the Middle Ages to dilate their pupils (atropine inhibits parasympathetic stimulation of the iris). This was thought to enhance their beauty (in Italian, bella = beautiful, donna = woman). Atropine is used clinically today to dilate pupils during eye examinations, to reduce secretions of the respiratory tract prior to general anesthesia, and to inhibit spasmodic contractions of the lower GI tract.
Organs with Dual Innervation

Many organs receive dual innervation—they are innervated by both sympathetic and parasympathetic neurons. When this occurs, the effects of these two divisions may be antagonistic, complementary, or cooperative.

Antagonistic Effects

The effects of sympathetic and parasympathetic innervation on the sinoatrial (SA) node (“pacemaker”) of the heart (see fig. 16.11) is the best example of the antagonism of these two systems. In this case, sympathetic and parasympathetic neurons innervate the SA node. Adrenergic stimulation from sympathetic neurons increases the heart rate, whereas cholinergic stimulation from parasympathetic neurons inhibits the SA node, which decreases the heart rate. Antagonism is also seen in the GI tract, where sympathetic nerves inhibit and parasympathetic nerves stimulate intestinal movements and secretions.

The effects of sympathetic and parasympathetic stimulation on the diameter of the pupil of the eye are analogous to the reciprocal innervation of flexor and extensor skeletal muscles by somatic motor neurons. This is because the iris contains antagonistic muscle layers. Contraction of the pupillary dilator muscle, which is stimulated by impulses through sympathetic nerve endings, causes dilation; contraction of the pupillary constrictor muscle, which is innervated by parasympathetic nerve endings, causes constriction of the pupil (fig. 13.8).

Complementary Effects

The effects of sympathetic and parasympathetic stimulation on salivary gland secretion are complementary. The secretion of watery saliva is stimulated by impulses through parasympathetic nerves, which also stimulate the secretion of other exocrine glands in the GI tract. Impulses through sympathetic nerves stimulate the constriction of blood vessels throughout the GI tract. The resultant decrease in blood flow to the salivary glands causes the production of a thicker, more viscous saliva.

Cooperative Effects

The effects of sympathetic and parasympathetic stimulation on the urinary and reproductive systems are cooperative. Erection of the penis, for example, is due to vasodilation resulting from action potentials through parasympathetic nerves; ejaculation is due to action potentials through sympathetic nerves. Although the contraction of the urinary bladder is myogenic (independent of nerve stimulation),
it is promoted in part by the action potentials through parasympathetic nerves. This micturition (mik’tur-i-sh’un) or urination, urge and reflex is also enhanced by action potentials through sympathetic nerves, which increases the tone of the urinary bladder muscles. Emotional states that are accompanied by high sympathetic nerve activity may thus result in reflex urination at urinary bladder volumes that are normally too low to trigger this reflex.

**Organs without Dual Innervation**

Although most organs are innervated by both sympathetic and parasympathetic nerves, some—including the adrenal medulla, arrector pili muscles, sweat glands, and most blood vessels—receive only sympathetic innervation. In these cases, regulation is achieved by increases or decreases in the “tone” (firing rate) of the sympathetic neurons. Constriction of blood vessels, for example, is produced by increased sympathetic activity, which stimulates adrenergic receptors, and vasodilation results from decreased sympathetic nerve activity.

Sympathetic activity is required for proper thermoregulatory responses to heat. In a hot room, for example, decreased sympathetic activity produces dilation of the blood vessels in the surface of the skin, which increases cutaneous blood flow and provides better heat radiation. During exercise, on the other hand, there is increased sympathetic activity, which causes constriction of the blood vessels in the skin of the limbs and stimulation of sweat glands in the trunk.

The eccrine sweat glands in the trunk secrete a watery fluid in response to sympathetic stimulation. Evaporation of this dilute sweat helps to cool the body. The eccrine sweat glands also secrete a chemical called bradykinin (brad’i-kin’in) in response to sympathetic stimulation. Bradykinin stimulates dilation of the surface blood vessels near the sweat glands, helping to radiate heat. At the conclusion of exercise, sympathetic activity is reduced and blood flow to the surface of the limbs is increased, which aids in the elimination of metabolic heat. Notice that all of these thermoregulatory responses are achieved without the direct involvement of the parasympathetic division.
Table 13.7  Some Vagal Reflexes Involving Peripheral Receptors and Nuclei in the Medulla Oblongata

<table>
<thead>
<tr>
<th>Organs</th>
<th>Receptors</th>
<th>Reflex Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lungs</td>
<td>Stretch receptors</td>
<td>Further inhalation inhibited; increase in cardiac rate and vasodilation</td>
</tr>
<tr>
<td></td>
<td>Type J receptors</td>
<td>Stimulated by pulmonary congestion—produces feelings of breathlessness and causes a reflex fall in cardiac rate and blood pressure</td>
</tr>
<tr>
<td>Aorta</td>
<td>Chemoreceptors</td>
<td>Stimulated by rise in CO₂ and fall in O₂—produces increased rate of breathing, rise in heart rate, and vasoconstriction</td>
</tr>
<tr>
<td>Aorta (cont.)</td>
<td>Baroreceptors</td>
<td>Stimulated by increased blood pressure—produces a reflex decrease in heart rate</td>
</tr>
<tr>
<td>Heart</td>
<td>Atrial stretch receptors</td>
<td>Antidiuretic hormone secretion thus increasing the volume of urine excreted</td>
</tr>
<tr>
<td></td>
<td>Stretch receptors in ventricles</td>
<td>Produces a reflex decrease in heart rate and vasodilation</td>
</tr>
<tr>
<td>GI tract</td>
<td>Stretch receptors</td>
<td>Feelings of satiety, discomfort, and pain</td>
</tr>
</tbody>
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Objective 13  Explain how autonomic functions can be affected by emotions.

Medulla Oblongata

The medulla oblongata of the brain stem is the structure that most directly controls the activity of the ANS. Almost all autonomic responses can be elicited by experimental stimulation of the medulla oblongata, which contains centers for the control of the circulatory, respiratory, urinary, reproductive, and digestive systems. Much of the sensory input to these centers travels through the sensory neurons of the vagus nerves. The reflexes that result are listed in table 13.7.

Hypothalamus

The hypothalamus (fig. 13.9 and 11.24), located just above the pituitary gland, is the overall control and integration center of the ANS. By means of motor fibers to the brain stem and posterior pituitary, and also by means of hormones that regulate the anterior pituitary, the hypothalamus serves to orchestrate somatic, autonomic, and endocrine responses during various behavioral states.

Experimental stimulation of different areas of the hypothalamus can evoke the autonomic responses characteristic of aggression, sexual behavior, eating, or satiety. Chronic stimulation of the lateral hypothalamus, for example, can make an animal eat and become obese, whereas stimulation of the medial hypothalamus inhibits eating. Other areas contain osmoreceptors that stimulate thirst and the secretion of antidiuretic hormone (ADH) from the posterior pituitary.
The hypothalamus is also where the body’s thermostat is located. Experimental cooling of the preoptic-anterior hypothalamus causes shivering (a somatic response) and nonshivering thermogenesis (a sympathetic response). Experimental heating of this hypothalamic area results in hyperventilation (stimulated by somatic motor nerves), vasodilation, salivation, and sweat gland secretion (stimulated by autonomic nerves).

The coordination of sympathetic and parasympathetic reflexes by the medulla oblongata is thus integrated with the control of somatic and endocrine responses by the hypothalamus. The activities of the hypothalamus are in turn influenced by higher brain centers.

Limbic System, Cerebellum, and Cerebrum

The limbic system is a group of fiber tracts and nuclei that form a ring (limbus) around the brain stem. It includes the cingulate gyrus of the cerebral cortex, the hypothalamus, the fornix (a fiber tract), the hippocampus, and the amygdaloid nucleus (fig. 13.10). These structures, which were derived early in the course of vertebrate evolution, were once called the rhinencephalon (rhin-encephalon) or “smell brain,” because of their importance in the central processing of olfactory information.

In primates, these structures are autonomic nervous system centers involved in such basic emotional drives as anger, fear, sex, and hunger, and in short-term memory. Complex circuits between the hypothalamus and other parts of the limbic system (illustrated in fig. 13.10) contribute visceral responses to emotions, including blushing, pallor, fainting, and “butterflies in the stomach.”

Experimental and clinical observations have demonstrated that the autonomic correlates of motion sickness—nausea, sweating, and cardiovascular changes—are eliminated by cutting the motor tracts of the cerebellum. This confirms that impulses from the cerebellum to the medulla oblongata influence activity of the ANS. In addition, the frontal and temporal lobes of the cerebral cortex influence lower brain areas as part of their involvement in emotion and personality.
One of the most dramatic examples of the role of higher brain areas in personality and emotion is the famous crowbar accident of 1848. A 25-year-old railroad foreman, Phineas P. Gage, was tamping gunpowder into a hole in a rock with a metal rod, when the gunpowder suddenly exploded. The rod—3 feet, 7 inches long and 1 1/4 inches thick—was driven through his left eye and through his brain, finally emerging through the back of his skull.

After a few minutes of convulsions, Gage got up, rode a horse three-quarters of a mile into town, and walked up a long flight of stairs to see a doctor. He recovered well, with no noticeable sensory or motor deficits. His associates, however, noted striking personality changes. Before the accident Gage was a responsible, capable, and financially prudent man. Afterward, he was much less inhibited socially, engaging for example, in gross profanity which he had never done previously. He also seemed to be tossed about by chance whims. Eventually, Gage was fired from his job, and his old friends remarked that he was “no longer Gage.”

Knowledge Check

13. Describe the role of the medulla oblongata in the regulation of the ANS.
14. Describe the role of the hypothalamus in the regulation of the autonomic nervous system and endocrine system.
15. What mechanisms are involved when a person blushes? What structures are involved in this response?

CLINICAL CONSIDERATIONS

Autonomic Dysreflexia

Autonomic dysreflexia, a serious condition producing rapid elevations in blood pressure that can lead to stroke (cerebrovascular accident), occurs in 85% of people with quadriplegia and others with spinal cord lesions above the sixth thoracic level. Lesions to the spinal cord first produce the symptoms of spinal shock, characterized by the loss of both skeletal muscle and autonomic reflexes. After a period of time, both types of reflexes return in an exaggerated state; the skeletal muscles may become spastic because of the absence of higher inhibitory influences, and the visceral organs experience denervation hypersensitivity. Patients in this state have difficulty emptying their urinary bladders and must often be catheterized.

Noxious stimuli, such as overdistension of the urinary bladder, can result in reflex activation of the sympathetic nerves below the spinal cord lesion. This produces goose bumps, cold skin, and vasoconstriction in the regions served by the spinal cord below the level of the lesion. The rise in blood pressure resulting from this vasoconstriction activates pressure receptors that transmit impulses along sensory neurons to the medulla ob-
longata. In response to this sensory input, the medulla oblongata directs a reflex slowing of the heart and vasodilation. Because descending impulses are blocked by the spinal lesion, however, the skin above the lesion is warm and moist (because of vasodilation and sweat gland secretion), whereas it is cold below the level of spinal cord damage.

Clinical Case Study Answer
The syndrome of organophosphate toxicity consists of symptoms of dangerously enhanced parasympathetic activity. Death may result from suffocation if the victim is unable to clear his airway secretions. Therapy includes the parasympathetic-receptor antagonist atropine and pralidoxime, which reactivates the enzyme cholinesterase.

CLINICAL PRACTICUM 13.1
A 70-year-old World War II veteran comes to your office complaining that his left arm has been hurting for about 10 days, and his forearm and hand seem to be a bit weak. He can’t recall injuring it, and it seems to be getting worse. You ask about his health in general and learn he has lost 15 pounds in the last year, and he has a long-standing cough that he can’t seem to get rid of. You also learn he has smoked most of his life.

During the physical exam you confirm the muscle weakness in his arm. You also notice his left eyelid droops, and his left pupil is constricted. He tells you his eyelid just started doing that the other day.

You tell him you think you know what’s causing the pain in his arm. He’s surprised when you order a chest X-ray to confirm a problem that seems to be in his arm.

QUESTIONS:
1. Given this man’s history, what is the most likely cause of the indicated lung density indicated with an arrow on the accompanying radiograph?
2. How can a lung lesion cause symptoms in the arm?
3. How do you explain the drooping eyelid and the constructed pupil? (Consider the autonomic activities of these structures.)

Chapter Summary

Introduction to the Autonomic Nervous System (pp. 435–438)
1. The autonomic nervous system (ANS) is a functional division of the nervous system; it is composed of portions of the central nervous system (CNS) and portions of the peripheral nervous system (PNS).
2. Preganglionic autonomic neurons originate in the brain or spinal cord; postganglionic neurons originate in ganglia outside the CNS.
3. Smooth muscle, cardiac muscle, and glands receive autonomic innervation.
   a. The involuntary effectors are somewhat independent of their innervation and become hypersensitive when their innervation is removed.
   b. Myocardial cells are interconnected by electrical synapses, or gap junctions, to form a functional syncytium with independent SA node activity.
   c. Single-unit smooth muscles are characterized by gap junctions and SA node activity; multunit smooth muscles have few, if any, gap junctions, and thus their individual cells must be stimulated separately by neurons.

Structure of the Autonomic Nervous System (pp. 438–443)
1. Preganglionic neurons of the sympathetic (thoracolumbar) division originate in the spinal cord (T1–L2).
   a. Many of these neurons synapse with postganglionic neurons, whose cell bodies are located in a trunk of sympathetic ganglia outside the spinal cord.
   b. Some preganglionic neurons synapse in peripheral ganglia; included in these are the celiac, superior mesenteric, and the inferior mesenteric ganglia.
CHAPTER 13

Objective Questions

1. Which of the following statements about the superior mesenteric ganglion is true?
   (a) It is a parasympathetic ganglion.
   (b) It is located in the head.
   (c) It contains postganglionic sympathetic neurons.
   (d) The sympathetic chain ganglia are located in a trunk parallel to the spinal cord.
   (b) in the posterior roots of spinal nerves.
   (c) next to or within the organs innervated.
   (d) in the brain.

2. The pterygopalatine, ciliary, submandibular, and otic ganglia are
   (a) collateral sympathetic ganglia.
   (b) cervical sympathetic ganglia.
   (c) parasympathetic ganglia that receive neurons from the vagus nerves.
   (d) parasympathetic ganglia that receive neurons from the third, seventh, and ninth cranial nerves.

3. Parasympathetic ganglia are located
   (a) in a trunk parallel to the spinal cord.
   (b) in the posterior roots of spinal nerves.
   (c) next to or within the organs innervated.
   (d) in the brain.

4. The neurotransmitter of preganglionic sympathetic neurons is
   (a) norepinephrine.
   (b) epinephrine.
   (c) acetylcholine.
   (d) dopamine.

5. The preganglionic neurons of the sympathetic division of the autonomic nervous system originate in
   (a) the medulla oblongata.
   (b) the entire spinal nerve complex.
   (c) the first cervical (C1) to the first lumbar (L1) vertebrae.
   (d) the first thoracic (T1) to the second lumbar (L2) vertebrae.

6. Which of the following neurons release norepinephrine?
   (a) preganglionic parasympathetic neurons
   (b) postganglionic parasympathetic neurons
   (c) postganglionic sympathetic neurons in the heart
   (d) postganglionic parasympathetic neurons in sweat glands
   (e) all of the above

Review Activities

Functions of the Autonomic Nervous System (pp. 444–448)

1. The effects of sympathetic and parasympathetic activity, together with those of hormones, help maintain homeostasis. The sympathetic division activates the body to “fight or flight” through adrenergic effects; the parasympathetic division conserves and restores the body’s energy through cholinergic effects.

2. All preganglionic autonomic neurons are cholinergic (use acetylcholine as a neurotransmitter).
   (a) All preganglionic parasympathetic neurons are cholinergic.
   (b) Most postganglionic sympathetic neurons are adrenergic (use norepinephrine at their synapses).
   (c) Sympathetic neurons that innervate sweat glands and those that innervate blood vessels in skeletal muscles are cholinergic.

3. Adrenergic effects include stimulation of the heart, vasosconstriction in the viscera and skin, bronchodilation, and glycogenolysis in the liver.

4. Cholinergic effects of parasympathetic nerves are promoted by the drug muscarine and inhibited by atropine.

5. In organs with dual innervation, the effects of the sympathetic and parasympathetic divisions can be antagonistic, complementary, or cooperative.
   (a) The effects are antagonistic in the heart and pupils.
   (b) The effects are complementary in the regulation of salivary gland secretion; they are cooperative in the regulation of the reproductive and urinary systems.

6. In organs without dual innervation (such as most blood vessels), regulation is achieved by increases or decreases in sympathetic nerve activity.

Control of the Autonomic Nervous System by Higher Brain Centers (pp. 448–450)

1. Visceral sensory input to the brain may result in the activity of the descending pathways to the preganglionic autonomic neurons. The centers in the brain that control autonomic activity are influenced by higher brain areas, as well as by sensory input.

2. The medulla oblongata is the structure that most directly controls the activity of the ANS.
   (a) The medulla oblongata is in turn influenced by sensory input and by input from the hypothalamus.
   (b) The hypothalamus orchestrates somatic, autonomic, and endocrine responses during various behavioral states.

3. The activity of the hypothalamus is influenced by input from the limbic system, cerebellum, and cerebrum; these interconnections provide an autonomic component to changes in body position, emotion, and various expressions of personality.
7. The actions of sympathetic and parasympathetic neurons are cooperative in
   (a) the heart.
   (b) the reproductive system.
   (c) the digestive system.
   (d) the eyes.
8. Which of the following is not a result of parasympathetic nerve stimulation?
   (a) increased movement of the GI tract
   (b) increased mucus secretion
   (c) constriction of the pupils
   (d) constriction of visceral blood vessels
9. Atropine blocks parasympathetic nerve effects. It would therefore result in
   (a) dilation of the pupils.
   (b) a decrease in mucus secretion.
   (c) a decrease in GI tract movement.
   (d) an increase in heart rate.
   (e) all of the above.
10. The area of the brain that is most directly involved in the reflex control of the autonomic system is
    (a) the hypothalamus.
    (b) the cerebral cortex.
    (c) the medulla oblongata.
    (d) the cerebellum.

**Essay Questions**
1. Compare the sympathetic and parasympathetic divisions in terms of ganglia location and nerve distribution.
2. Explain the structural and functional relationship between the sympathetic division of the ANS and the adrenal glands.
3. Compare the effects of adrenergic and cholinergic stimulation on the cardiovascular and digestive systems.
4. Explain how effectors that receive only sympathetic innervation are regulated by the ANS.
5. Explain why a person may sweat more profusely immediately after exercise than during exercise.

**Critical-Thinking Questions**
1. Shock is the medical condition that occurs when body tissues do not receive enough oxygen-carrying blood. It is characterized by low blood flow to the brain, leading to decreased levels of consciousness. Why would a patient with a cervical spinal cord injury be at risk of going into shock?
2. Imagine yourself at the starting block of the 100-meter dash of the Olympics. The gun is about to go off in the biggest race of your life. What is your autonomic nervous system doing at this point? How are your organs reacting?
3. Suppose you lift the wrist of a man who has fainted to feel for a pulse. How would you characterize his pulse? What specific role would the autonomic nervous system have in producing these effects?
4. Why would someone be given a prescription for atropine if they had gastritis? Why would the person’s mouth feel dry after taking this drug?
5. Most agents used in chemical warfare affect the autonomic nervous system. Nerve gas, for example, stimulates activity of the parasympathetic division of the ANS to such an extent that it causes rapid death. Based on your knowledge of the autonomic nervous system, can you predict the type of symptoms a nerve-gas victim might suffer?
6. Give evidence for the argument that the autonomic nervous system is somewhat misnamed.