cycles (Figure 7.15b). Damage to this area can result in permanent unconsciousness (coma).

Cerebellum

The large, cauliflowerlike **cerebellum** (ser″e-bel′um) projects dorsally from under the occipital lobe of the cerebrum. Like the cerebrum, it has two hemispheres and a convoluted surface. The cerebellum also has an outer cortex made up of gray matter and an inner region of white matter.

The cerebellum provides the precise timing for skeletal muscle activity and controls our balance and equilibrium. Because of its activity, body movements are smooth and coordinated. Fibers reach the cerebellum from the equilibrium apparatus of the inner ear, the eye, the proprioceptors of the skeletal muscles and tendons, and many other areas. The cerebellum can be compared to an automatic pilot, continuously comparing the brain's "intentions" with actual body performance by monitoring body position and amount of tension in various body parts. When needed, it sends messages to initiate the appropriate corrective measures.

Homeostatic Imbalance

If the cerebellum is damaged (for example, by a blow to the head, a tumor, or a stroke), movements become clumsy and disorganized—a condition called *ataxia.* Victims cannot keep their balance and may appear to be drunk because of the loss of muscle coordination. They are no longer able to touch their finger to their nose with eyes closed—a feat that normal individuals accomplish easily. ▲

Protection of the Central Nervous System

Nervous tissue is very soft and delicate, and the irreplaceable neurons are injured by even the slightest pressure. Nature has tried to protect the brain and spinal cord by enclosing them within bone (the skull and vertebral column), membranes (the meninges), and a watery cushion (cerebrospinal fluid). Protection from harmful substances in the blood is provided by the so-called blood-brain barrier. Since we have already considered the bony enclosures (Chapter 5), we will focus on the other protective devices here.

Meninges

The three connective tissue membranes covering and protecting the CNS structures are **meninges** (mě-nin′jēz) (Figure 7.16). The outermost layer, the leathery dura mater (du′rah ma′ter), meaning "tough or hard mother," is a double-layered membrane where it surrounds the brain. One of its layers is attached to the inner surface of the skull, forming the periosteum (*periosteal layer*). The other, called the *meningeal layer,* forms the outermost covering of the brain and continues as the dura mater of the spinal cord. The dural layers are fused together except in three areas where they separate to enclose *dural sinuses* that collect venous blood.

In several places, the inner dural membrane extends inward to form a fold that attaches the brain to the cranial cavity. One of these folds, the **falx** (falks) **cerebri,** is shown in Figure 7.16a. Another such fold, the **tentorium cerebelli** separating the cerebellum from the cerebrum, is shown in Figures 7.16b and 7.17c.

The middle meningeal layer is the weblike **arachnoid** (ah-rak′noid) **mater** (see Fig. 7.16). *Arachnida* means "spider," and some think the arachnoid membrane looks like a cobweb. Its threadlike extensions span the **subarachnoid space** to attach it to the innermost membrane, the **pia** (pi′ah) **mater** ("gentle mother"). The delicate pia mater clings tightly to the surface of the brain and spinal cord, following every fold.

The subarachnoid space is filled with cerebrospinal fluid. Specialized projections of the arachnoid membrane, **arachnoid villi** (vih′li), protrude through the dura mater. The cerebrospinal fluid is absorbed into the venous blood in the dural sinuses through the arachnoid villi.

Homeostatic Imbalance

Meningitis, an inflammation of the meninges, is a serious threat to the brain because bacterial or viral meningitis may spread into the nervous tissue of the CNS. This condition of brain inflammation is called *encephalitis* (en-sef-ah-li′tis). Meningitis is usually diagnosed by taking a sample of cerebrospinal fluid from the subarachnoid space. ▲
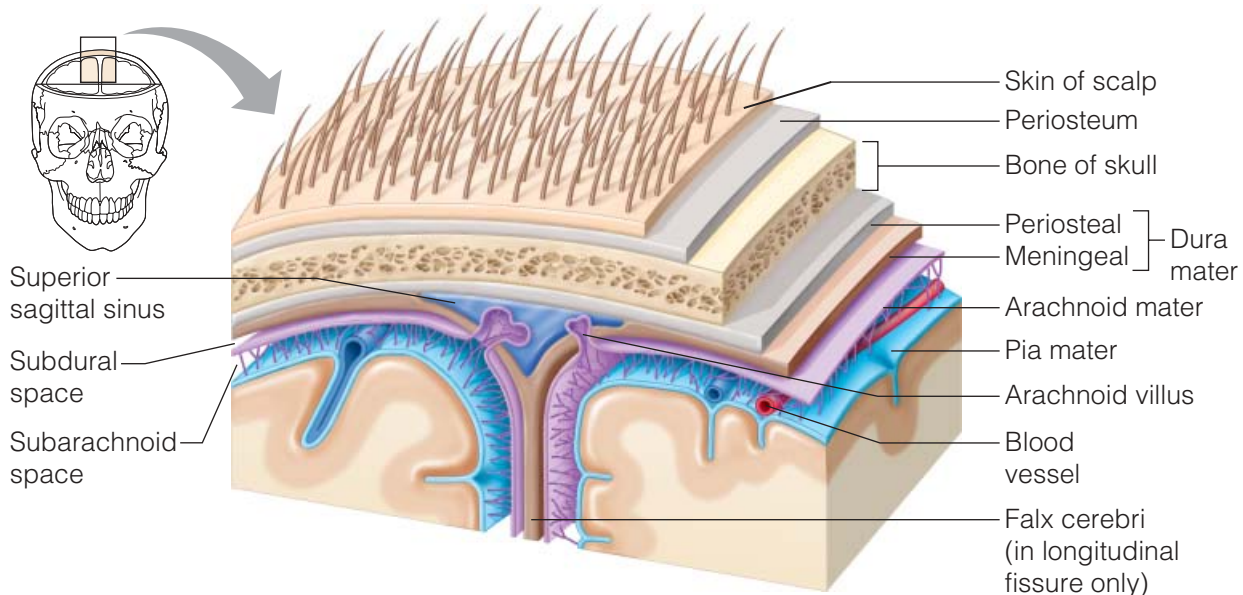
Cerebrospinal Fluid

Cerebrospinal (ser″e-bro-spi′nal) **fluid (CSF)** is a watery "broth" similar in its makeup to blood plasma, from which it forms. However, it contains less protein, more vitamin C, and its ion composition is different.
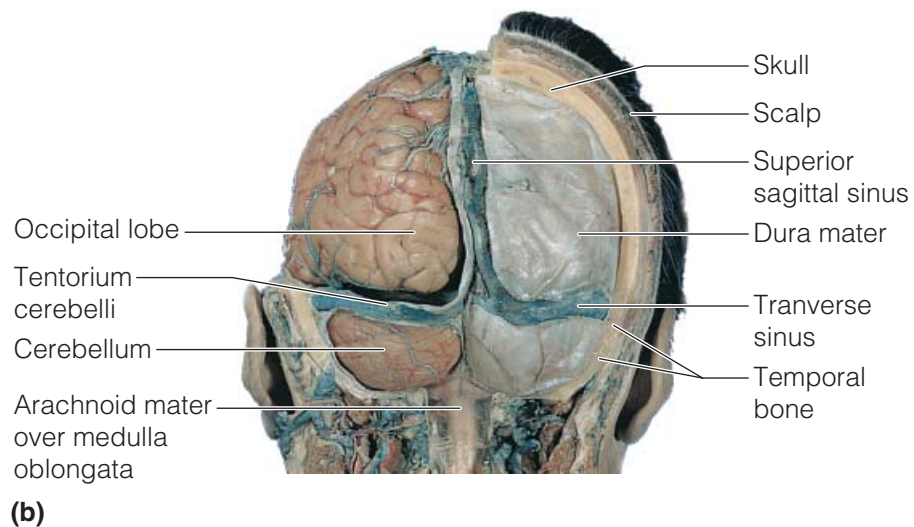
CSF is continually formed from blood by the choroid plexuses. Choroid plexuses are clusters of

Q *What would be the consequence of blocked arachnoid villi?*

- Skin of scalp
- Periosteum
- Bone of skull
- Periosteal ⎤ Dura
- Meningeal ⎦ mater
- Arachnoid mater
- Pia mater
- Arachnoid villus
- Blood vessel
- Falx cerebri (in longitudinal fissure only)

Superior sagittal sinus

Subdural space

Subarachnoid space

(a)

Occipital lobe

Tentorium cerebelli

Cerebellum

Arachnoid mater over medulla oblongata

- Skull
- Scalp
- Superior sagittal sinus
- Dura mater
- Tranverse sinus
- Temporal bone

(b)

FIGURE 7.16   Meninges of the brain. (a) Three-dimensional frontal section showing the meninges—the dura mater, arachnoid mater, and pia mater—that surround and protect the brain. The relationship of the dura mater to the falx cerebri and the superior sagittal (dural) sinus is also shown. **(b)** Posterior view of the brain in place surrounded by the dura mater.
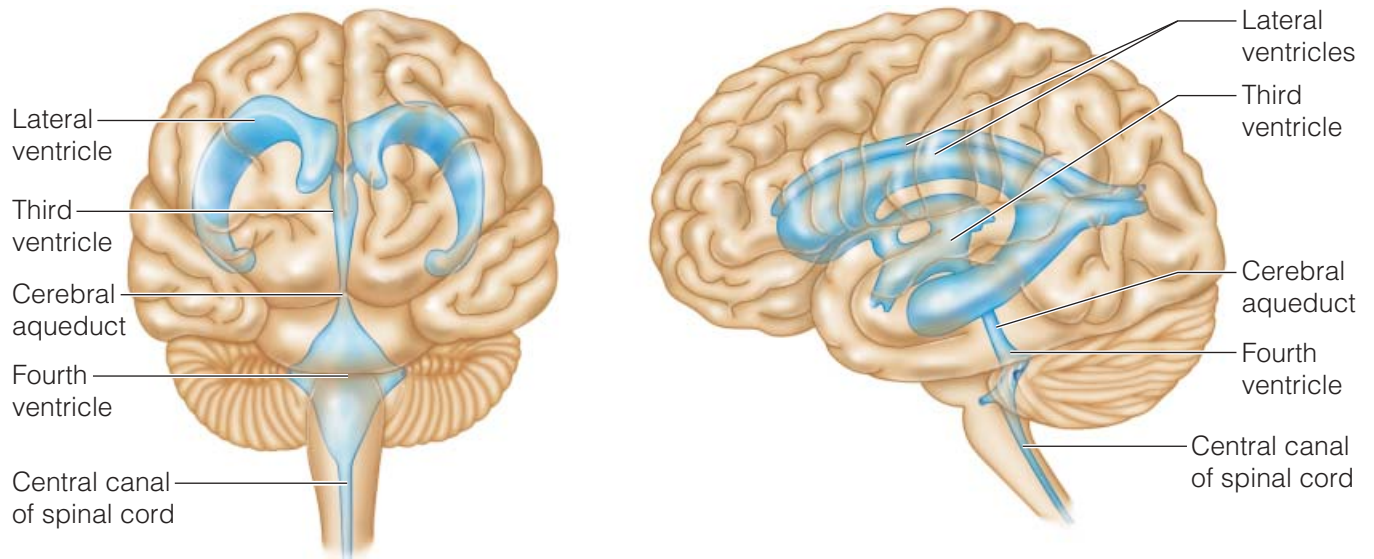
capillaries hanging from the "roof" in each of the brain's ventricles. The CSF in and around the brain and cord forms a watery cushion that protects the fragile nervous tissue from blows and other trauma.

A *Hydrocephalus ("water on the brain"). The ventricles would expand as cerebrospinal fluid (unable to drain into the dural sinus) accumulated.*
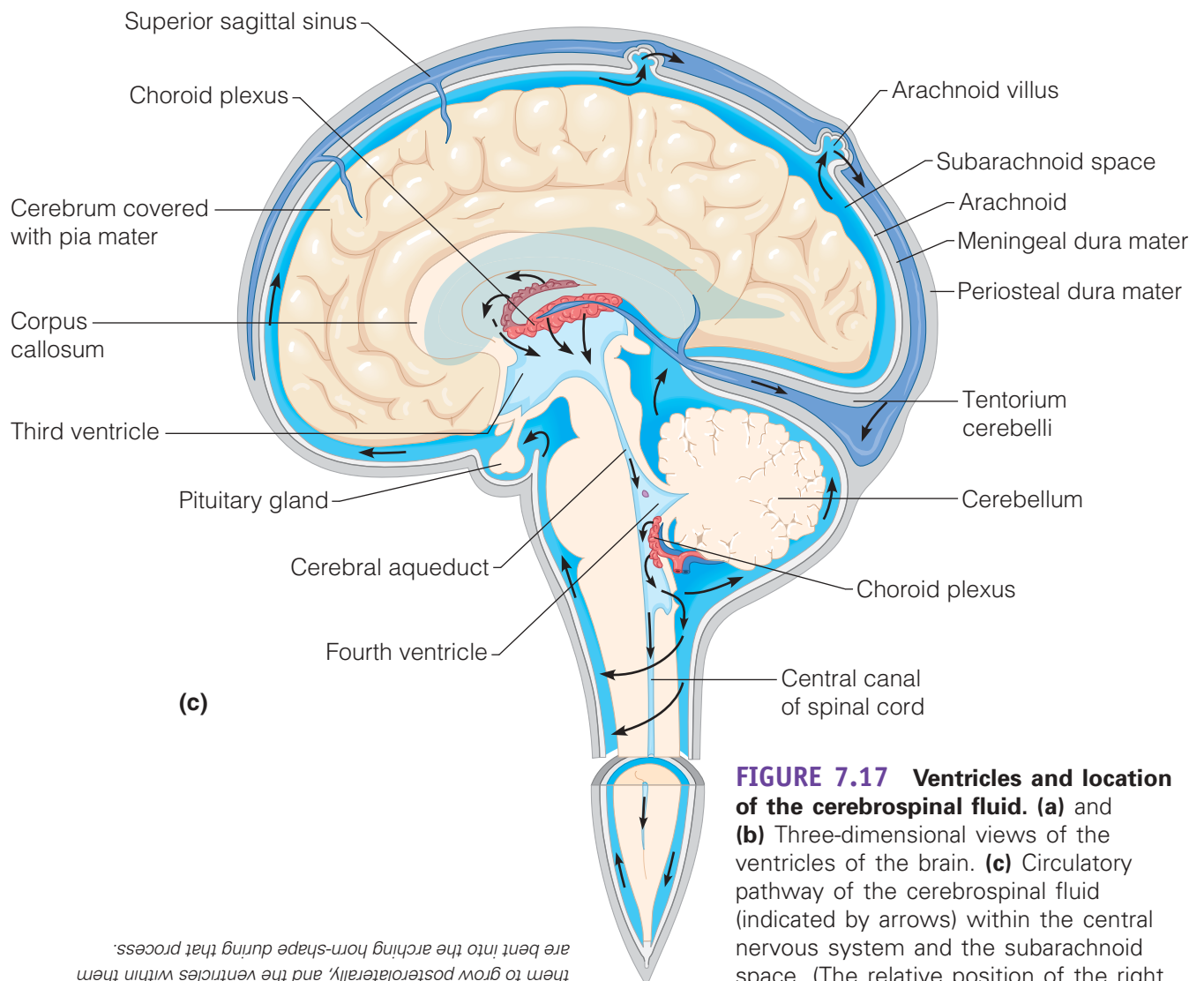
Inside the brain, CSF is continually moving (see Figure 7.17c). It circulates from the two lateral ventricles (in the cerebral hemispheres) into the third ventricle (in the diencephalon), and then through the cerebral aqueduct of the midbrain into the fourth ventricle dorsal to the pons and medulla oblongata. Some of the fluid reaching the fourth ventricle continues down the **central canal** of the

Q *Why are the lateral ventricles horn-shaped rather than oriented vertically like the third and fourth ventricles?*

Lateral ventricle

Third ventricle

Cerebral aqueduct

Fourth ventricle

Central canal of spinal cord

(a) Anterior view

Lateral ventricles

Third ventricle

Cerebral aqueduct

Fourth ventricle

Central canal of spinal cord

(b) Left lateral view

Superior sagittal sinus

Choroid plexus

Cerebrum covered with pia mater

Corpus callosum

Third ventricle

Pituitary gland

Cerebral aqueduct

Fourth ventricle

(c)

Arachnoid villus

Subarachnoid space

Arachnoid

Meningeal dura mater

Periosteal dura mater

Tentorium cerebelli

Cerebellum

Choroid plexus

Central canal of spinal cord

FIGURE 7.17 Ventricles and location of the cerebrospinal fluid. (a) and **(b)** Three-dimensional views of the ventricles of the brain. **(c)** Circulatory pathway of the cerebrospinal fluid (indicated by arrows) within the central nervous system and the subarachnoid space. (The relative position of the right lateral ventricle is indicated by the pale blue area deep to the corpus callosum.)

A *The bones of the skull restrict superior growth of the cerebral hemispheres (and their ventricles) during development, forcing them to grow posterolaterally, and the ventricles within them are bent into the arching horn-shape during that process.*

spinal cord, but most of it circulates into the **subarachnoid space** through three openings in the walls of the fourth ventricle. The fluid returns to the blood in the dural sinuses through the arachnoid villi. Ordinarily, CSF forms and drains at a constant rate so that its normal pressure and volume (150 ml—about half a cup) are maintained. Any significant changes in CSF composition (or the appearance of blood cells in it) may be a sign of meningitis or certain other brain pathologies (such as tumors and multiple sclerosis). The CSF sample for testing is obtained by a procedure called a *lumbar (spinal) tap.* Since the withdrawal of fluid for testing decreases CSF fluid pressure, the patient must remain in a horizontal position (lying down) for 6 to 12 hours after the procedure to prevent an agonizingly painful "spinal headache."

▲ Homeostatic Imbalance

If something obstructs its drainage (for example, a tumor), CSF begins to accumulate and exert pressure on the brain. This condition is *hydrocephalus* (hi-dro-sef'ah-lus), literally, "water on the brain." Hydrocephalus in a newborn baby causes the head to enlarge as the brain increases in size. This is possible in an infant because the skull bones have not yet fused. However, in an adult this condition is likely to result in brain damage because the skull is hard, and the accumulating fluid crushes soft nervous tissue. Today hydrocephalus is treated surgically by inserting a shunt (a plastic tube) to direct the excess fluid into a vein in the neck. ▲

The Blood-Brain Barrier

No other body organ is so absolutely dependent on a constant internal environment as is the brain. Other body tissues can withstand the rather small fluctuations in the concentrations of hormones, ions, and nutrients that continually occur, particularly after eating or exercising. If the brain were exposed to such chemical changes, uncontrolled neural activity might result—remember that certain ions (sodium and potassium) are involved in initiating nerve impulses, and some amino acids serve as neurotransmitters. Consequently, neurons are kept separated from bloodborne substances by a so-called **blood-brain barrier,** composed of the *least* permeable capillaries in the whole body. Of water-soluble substances, only water, glucose, and essential amino acids pass easily through the walls of these capillaries. Metabolic wastes, such as urea, toxins, proteins, and most drugs are prevented from

entering the brain tissue. Nonessential amino acids and potassium ions are not only prevented from entering the brain, but also are actively pumped from the brain into the blood across capillary walls. Although the bulbous "feet" of the astrocytes that cling to the capillaries may contribute to the barrier, the relative impermeability of the brain capillaries is most responsible for providing this protection.

The blood-brain barrier is virtually useless against fats, respiratory gases, and other fat-soluble molecules that diffuse easily through all plasma membranes. This explains why bloodborne alcohol, nicotine, and anesthetics can affect the brain.

Brain Dysfunctions

▲ Homeostatic Imbalance

Brain dysfunctions are unbelievably varied. We mention some of them (the "terrible three" in the "A Closer Look" box on pages 245–246), and we will discuss developmental problems in the final section of this chapter. Here, we will focus on traumatic brain injuries and cerebrovascular accidents. Techniques used to diagnose many brain disorders are described in the "A Closer Look" box on pages 262–263.

Traumatic Brain Injuries

Head injuries are a leading cause of accidental death in the United States. Consider, for example, what happens when you forget to fasten your seat belt and then crash into the rear end of another car. Your head is moving and then is suddenly stopped as it hits the windshield. Brain damage is caused not only by injury at the site of the blow, but also by the effect of the ricocheting brain hitting the opposite end of the skull.

A *concussion* occurs when brain injury is slight. The victim may be dizzy, "see stars," or lose consciousness briefly, but no permanent brain damage occurs. A brain *contusion* is the result of marked tissue destruction. If the cerebral cortex is injured, the individual may remain conscious, but severe brain stem contusions always result in a coma lasting from hours to a lifetime because of injury to the reticular activating system.

After head blows, death may result from *intracranial hemorrhage* (bleeding from ruptured vessels) or *cerebral edema* (swelling of the brain due to inflammatory response to injury). Individuals who are initially alert and lucid following head trauma and then begin to deteriorate neurologically later are most

likely hemorrhaging or suffering the consequences of edema, both of which compress vital brain tissue.

Cerebrovascular Accident   Commonly called *strokes,* **cerebrovascular** (ser"e-bro-vas'ku-lar) **accidents (CVAs)** are the third leading cause of death in the United States. CVAs occur when blood circulation to a brain area is blocked, as by a blood clot or a ruptured blood vessel, and vital brain tissue dies. After a CVA, it is often possible to determine the area of brain damage by observing the patient's symptoms. For example, if the patient has left-sided paralysis, the right motor cortex of the frontal lobe is most likely involved. *Aphasias* (ah-fa'ze-ahz) are a common result of damage to the left cerebral hemisphere, where the language areas are located. There are many types of aphasias, but the most common are *motor aphasia,* which involves damage to Broca's area and a loss of ability to speak, and *sensory aphasia,* in which a person loses the ability to understand written or spoken language. Aphasias are maddening to the victims because, as a rule, their intellect is unimpaired. Brain lesions can also cause marked changes in a person's disposition (for example, a change from a sunny to a foul personality). In such cases, a tumor as well as a CVA might be suspected.

Fewer than a third of those surviving a CVA are alive three years later. Even so, the picture is not hopeless. Some patients recover at least part of their lost faculties because undamaged neurons spread into areas where neurons have died and take over some lost functions. Indeed, most of the recovery seen after brain injury is due to this phenomenon.

Not all strokes are "completed." Temporary brain ischemia, or restriction of blood flow, is called a *transient ischemic attack (TIA).* TIAs last from 5 to 50 minutes and are characterized by symptoms such as numbness, temporary paralysis, and impaired speech. Although these defects are not permanent, they do constitute "red flags" that warn of impending, more serious CVAs. ▲

Spinal Cord

The cylindrical **spinal cord,** which is approximately 17 inches (42 cm) long, is a glistening white continuation of the brain stem. The spinal cord provides a two-way conduction pathway to and from the brain, and it is a major reflex center (the spinal reflexes are completed at this level). Enclosed within the vertebral column, the spinal cord extends from the foramen magnum of the skull to the first or second lumbar vertebra, where it ends just below the ribs (Figure 7.18). Like the brain, the spinal cord
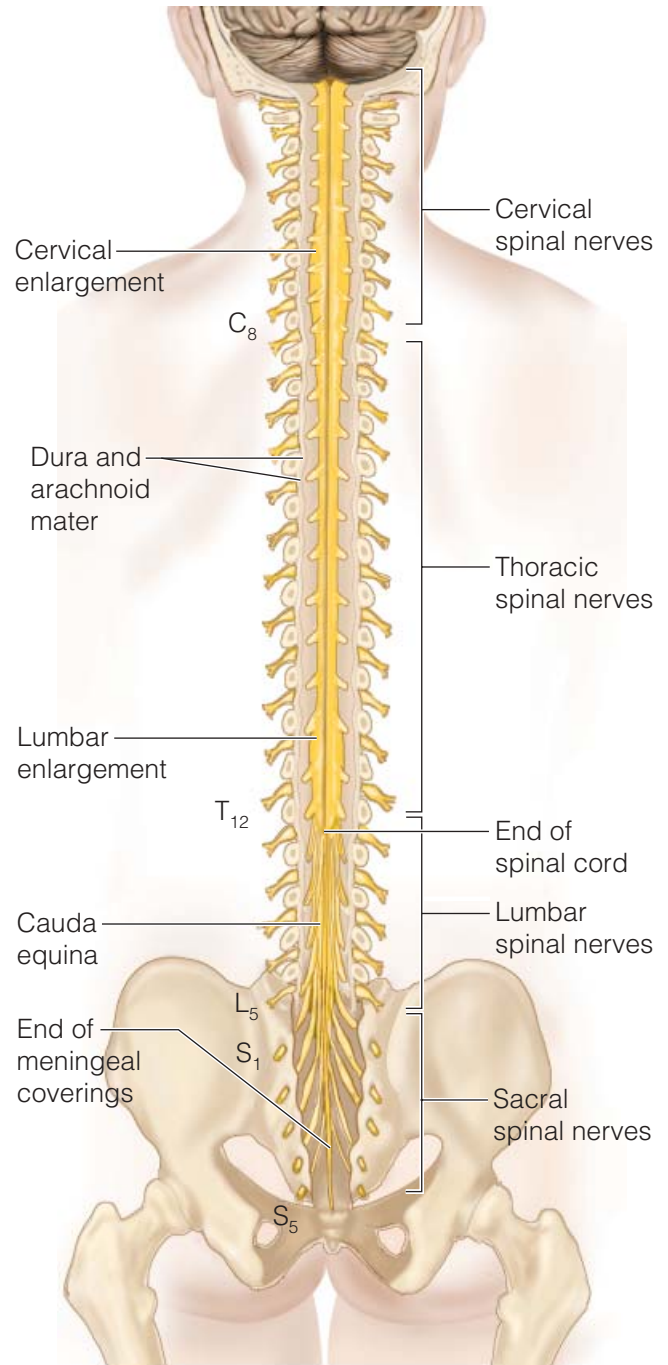

FIGURE 7.18   Anatomy of the spinal cord, posterior view.

is cushioned and protected by meninges. Meningeal coverings do not end at the second lumbar vertebra (L_2), but instead extend well beyond the end of the spinal cord in the vertebral canal. Because there is no possibility of damaging the cord beyond L_3, the meningeal sac inferior to that point provides a nearly ideal spot for removing CSF for testing.
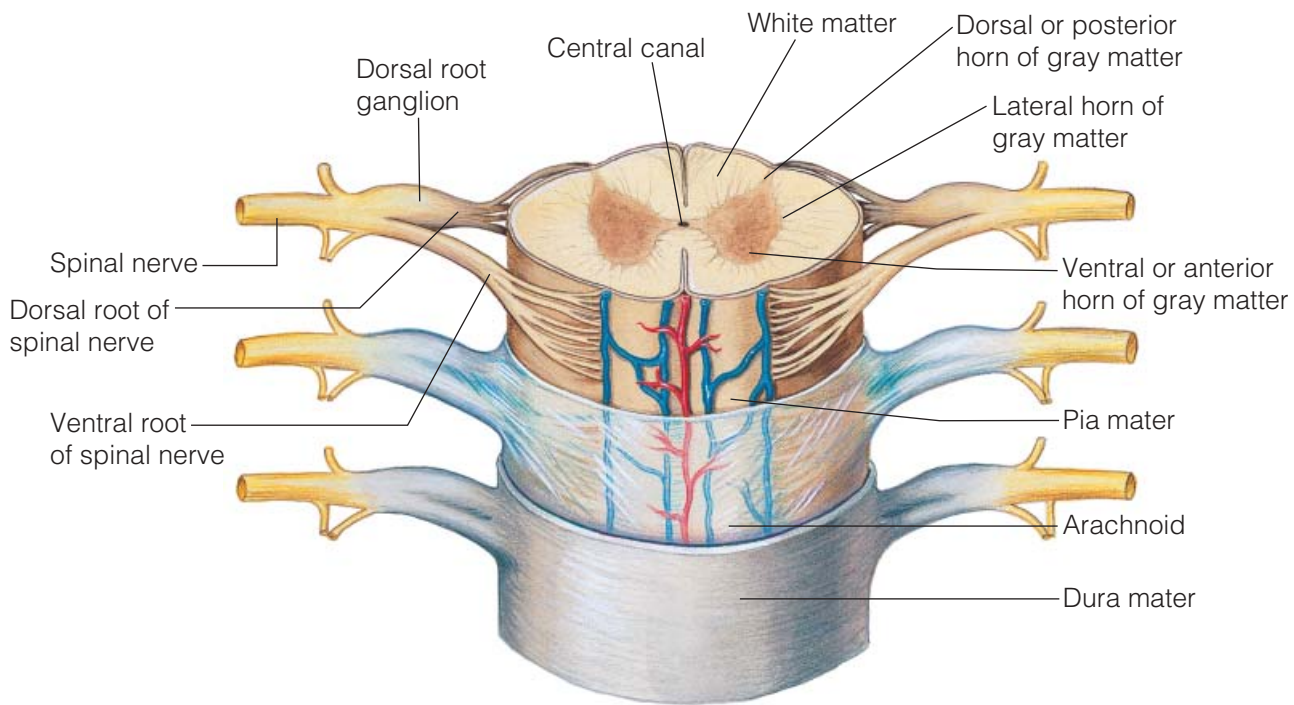
FIGURE 7.19 **Spinal cord with meninges (three-dimensional view).**

In humans, 31 pairs of spinal nerves arise from the cord and exit from the vertebral column to serve the body area close by. The spinal cord is about the size of a thumb for most of its length, but it is obviously enlarged in the cervical and lumbar regions where the nerves serving the upper and lower limbs arise and leave the cord. Because the vertebral column grows faster than the spinal cord, the spinal cord does not reach the end of the vertebral column and the spinal nerves leaving its inferior end must travel through the vertebral canal for some distance before exiting. This collection of spinal nerves at the inferior end of the vertebral canal is called the **cauda equina** (kaw′da e-kwi′nah) because it looks so much like a horse's tail (the literal translation of *cauda equina*).

Gray Matter of the Spinal Cord and Spinal Roots

The gray matter of the spinal cord looks like a butterfly or the letter H in cross section (Figure 7.19). The two posterior projections are the **dorsal,** or **posterior, horns;** the two anterior projections are the **ventral,** or **anterior, horns.** The gray matter surrounds the **central canal** of the cord, which contains CSF.

Neurons with specific functions can be located in the gray matter. The dorsal horns contain association neurons, or interneurons. The cell bodies of the sen-

sory neurons, whose fibers enter the cord by the **dorsal root,** are found in an enlarged area called the **dorsal root ganglion.** If the dorsal root or its ganglion is damaged, sensation from the body area served will be lost. The ventral horns of the gray matter contain cell bodies of motor neurons of the somatic (voluntary) nervous system, which send their axons out the **ventral root** of the cord. The dorsal and ventral roots fuse to form the **spinal nerves.**

Homeostatic Imbalance

Damage to the ventral root results in a *flaccid paralysis* of the muscles served. In flaccid paralysis, nerve impulses do not reach the muscles affected; thus, no voluntary movement of those muscles is possible. The muscles begin to atrophy because they are no longer stimulated. ▲

White Matter of the Spinal Cord

White matter of the spinal cord is composed of myelinated fiber tracts—some running to higher centers, some traveling from the brain to the cord, and some conducting impulses from one side of the spinal cord to the other.

Because of the irregular shape of gray matter, the white matter on each side of the cord is divided into three regions—the **posterior, lateral,** and

anterior columns. Each of the columns contains a number of fiber tracts made up of axons with the same destination and function. Tracts conducting sensory impulses to the brain are *sensory,* or *afferent, tracts.* Those carrying impulses from the brain to skeletal muscles are *motor,* or *efferent, tracts.* All tracts in the posterior columns are ascending tracts that carry sensory input to the brain. The lateral and anterior tracts contain both ascending and descending (motor) tracts.

Homeostatic Imbalance

If the spinal cord is transected (cut crosswise) or crushed, *spastic paralysis* results. The affected muscles stay healthy because they are still stimulated by spinal reflex arcs, and movement of those muscles does occur. However, movements are involuntary and not controllable, and this can be as much of a problem as complete lack of mobility. In addition, because the spinal cord carries both sensory and motor impulses, a loss of feeling or sensory input occurs in the body areas below the point of cord destruction. Physicians often use a pin to see if a person can feel pain after spinal cord injury—to find out if regeneration is occurring. Pain is a hopeful sign in such cases. If the spinal cord injury occurs high in the cord, so that all four limbs are affected, the individual is a *quadriplegic* (kwod″rĭ-ple′jik). If only the legs are paralyzed, the individual is a *paraplegic* (par″ă-ple′jik). ▲

Peripheral Nervous System

The **peripheral nervous system (PNS)** consists of nerves and scattered groups of neuronal cell bodies (ganglia) found outside the CNS. One type of ganglion has already been considered—the dorsal root ganglion of the spinal cord. Others will be covered in the discussion of the autonomic nervous system. Here, we will concern ourselves only with nerves.

Structure of a Nerve

A **nerve** is a bundle of neuron fibers found outside the CNS. Within a nerve, neuron fibers, or processes, are wrapped in protective connective tissue coverings. Each fiber is surrounded by a delicate connective tissue sheath, an **endoneurium** (en″do-nu′re-um). Groups of fibers are bound by a coarser connective tissue wrapping, the **perineurium** (per″ĭ-nu′re-um), to form fiber bundles, or **fascicles.** Finally, all the fascicles are bound together by a tough fibrous sheath, the **epineurium,** to form the cordlike nerve (Figure 7.20).
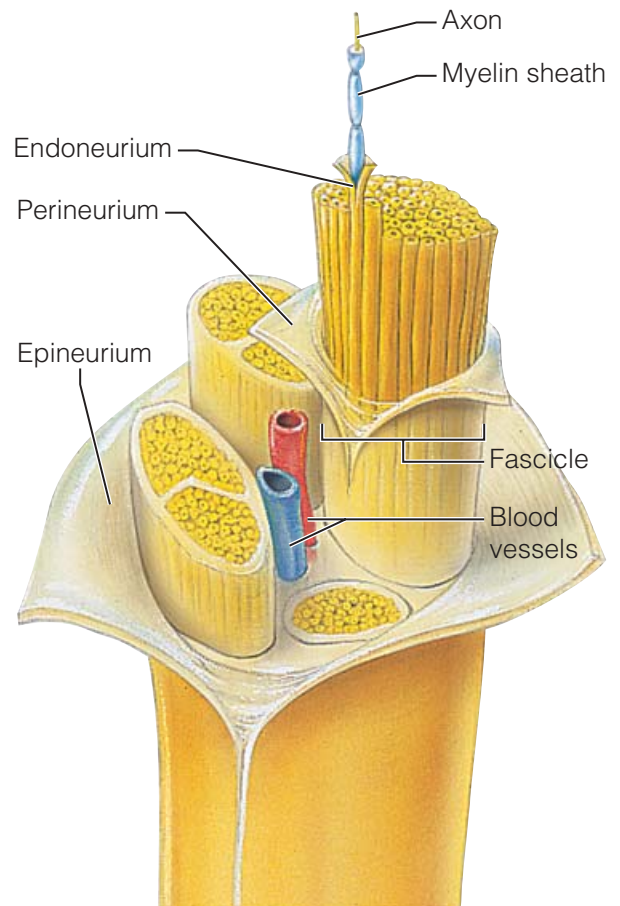

FIGURE 7.20   Structure of a nerve. Three-dimensional view of a portion of a nerve, showing its connective tissue wrappings.

Like neurons, nerves are classified according to the direction in which they transmit impulses. Nerves carrying both sensory and motor fibers are called **mixed nerves;** all spinal nerves are mixed nerves. Nerves that carry impulses toward the CNS only are called **sensory,** or **afferent, nerves,** whereas those that carry only motor fibers are **motor,** or **efferent, nerves.**

Cranial Nerves

The 12 pairs of **cranial nerves** primarily serve the head and neck. Only one pair (the vagus nerves) extends to the thoracic and abdominal cavities.

The cranial nerves are numbered in order, and in most cases their names reveal the most important structures they control. The cranial nerves are described by name, number, course, and major function in Table 7.1. The last column