

# Neurologic Bases of Motor Speech and Its Disorders

*“The student looking over the political map of a continent may little realize the complexity of the populations and states so simply represented. We, looking at the brain chart of the text-book, may never forget the unspeakable complexity of the reactions thus rudely symbolized and spatially indicated.”<sup>61</sup>*

C. S. Sherrington (1906)

*“To understand how the brain gives rise to behavior and cognition is perhaps the greatest goal in Neuroscience.”<sup>35</sup>*

B. R. Kanter et al. (2022)

## OUTLINE

### Gross Neuroanatomy and Major Neurologic Systems

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- Coverings—The Meninges and Spaces Between Them
- Major Anatomic Levels of the Nervous System
- Major Functional Longitudinal Systems

### Primary Structural Elements of the Nervous System

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- Conceptualization
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- Motor Speech Planning and Programming

### Summary

Knowledge of neuroanatomy and neurophysiology forms the foundation for differential diagnosis and management of motor speech disorders (MSDs). An overview of that foundation and an introduction to broad categories of neurologic disease are the purposes of this chapter.

This clinically oriented overview will provide a basis for understanding information in later chapters on specific MSDs. The structures and functions emphasized are those that are (1) directly implicated in speech, (2) relevant to understanding the mechanisms through which MSDs may emerge, or (3) relevant to observable deficits that often accompany MSDs and are supportive of certain motor speech diagnoses.

Before the reader grapples with the content of this chapter, a caveat and a comfort are in order. The caveat is for those who are unfamiliar with the neurologic bases of speech or who are just beginning to integrate such information into

clinical practice. The sheer number of terms and the complexity of the concepts introduced here may be overwhelming. Even when the facts are grasped, their relevance to MSDs may not be immediately obvious. These reactions are natural when learning how to think about problems with which one has little experience. The reality is that this material will not and perhaps cannot be understood rapidly. The first encounter with it may be somewhat of a struggle.

The comfort is that, in time, much of this will make sense and be valuable, if not essential, to clinical practice or research dealing with MSDs. Understanding the material in this chapter may be enhanced by referring back to it when reading chapters on specific MSDs. It may be better still to refer to this chapter after examining people with MSDs. Taking advantage of the opportunity to integrate this didactic information with patients' medical histories, laboratory and neuroimaging findings, and,

most important, the sounds and sights of their disordered speech may be the best way to achieve depth of understanding. In fact, it can be argued that this information cannot be integrated as a foundation for clinical practice until clinical practice has begun.

## GROSS NEUROANATOMY AND MAJOR NEUROLOGIC SYSTEMS<sup>a</sup>

This section addresses the bony boundaries and coverings of the nervous system. The skull and spinal column represent the bony boundaries. The meninges and their associated spaces are the coverings. The major anatomic levels and functional longitudinal systems of the nervous system will then be reviewed.

### Bony Boundaries—The Skull and Spinal Column

The brain is housed in the skull, and the spinal cord is housed within the spinal column. Our primary focus is on the skull because it contains most of the central nervous system (CNS) structures that subserve speech as well as the nuclei (origin) of the cranial nerves that innervate all of the speech muscles except those of breathing.

The bones of the skull (Fig. 2.1) form a nonyielding covering for the adult brain. They serve a protective function against trauma. This protection is offset somewhat by the inability of the adult brain to expand in response to pressure from certain internal pathologic conditions (e.g., hemorrhage, hydrocephalus, tumor), a situation that can produce diffuse neurologic abnormalities due to mass effects and increased intracranial pressure.

<sup>a</sup>The organization and content of several portions of this chapter, most notably the discussion of the motor system, rely heavily on the conceptual and organizational approach to anatomy, physiology, and pathology used in *Mayo Clinic Medical Neurosciences: Organized by Neurologic Systems and Levels*, ed 6, by Benarroch, Cutsforth-Gregory, and Flemming.<sup>9</sup>

Viewed from above (Fig. 2.2), three distinct shallow cavities lie at the base of the skull: the anterior, middle, and posterior fossae. These fossae help define two of the major levels of the CNS: the posterior fossa level and the supratentorial level (anterior and middle fossae). The posterior and middle fossae have symmetrically oriented foramina (openings) through which the paired cranial nerves exit to innervate peripheral structures, including the speech muscles of the head and neck. Crude localization of neurologic disease often refers to lesions as supratentorial or posterior fossa in origin (Fig. 2.3).

### Coverings—The Meninges and Spaces Between Them

The meninges (coverings) of the CNS consist of three layers: the dura, arachnoid, and pia mater (see Fig. 2.3).

The *dura mater*, the outermost membrane, consists of two layers of fused tissues that separate in certain regions to form the intracranial venous sinuses, areas where blood drains from the brain. The folds of the dura in the cranial cavity form two barriers: the falx cerebri, located between the two hemispheres, and the tentorium cerebelli, which separates the cerebellum from the cerebral hemispheres.

The *arachnoid* lies beneath the dura, loosely applied to the surface of the brain. The *pia mater*, the thin innermost layer, is closely attached to the brain's surface. The pia mater and arachnoid are collectively known as the *leptomeninges*.

The spaces around the meninges are functionally important and relevant to certain disorders. The epidural space is located between the inner bone of the skull and the dura. The subdural space is beneath the dura. Blood and pus from injury or infection can accumulate in the epidural and subdural spaces. The subarachnoid space, beneath the arachnoid, surrounds the brain and spinal cord and is filled with cerebrospinal fluid (CSF); it is connected to the interior of the brain through the ventricular system (Fig. 2.4).

Most conditions capable of producing MSDs that involve the meninges or meningeal spaces stem from infection, venous

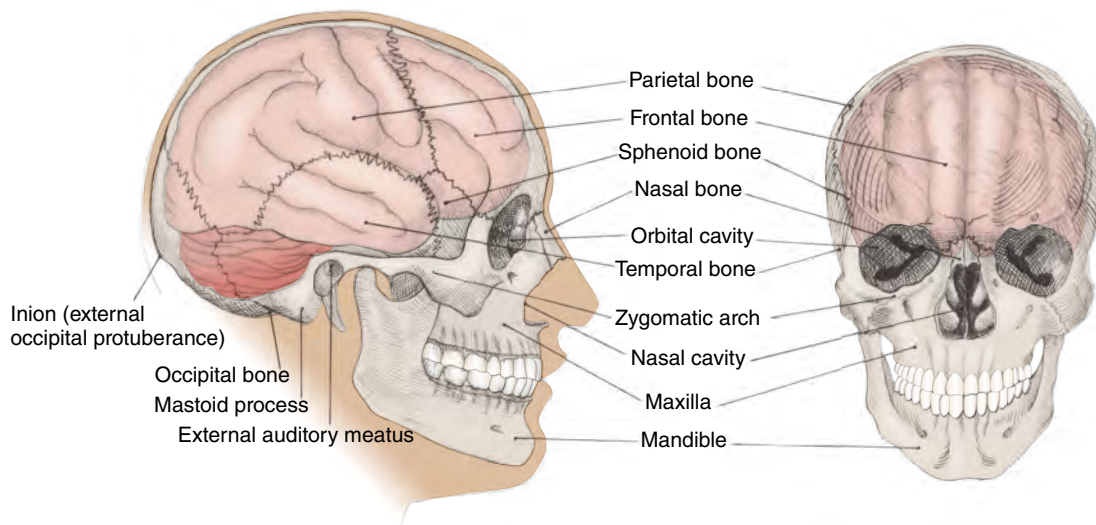
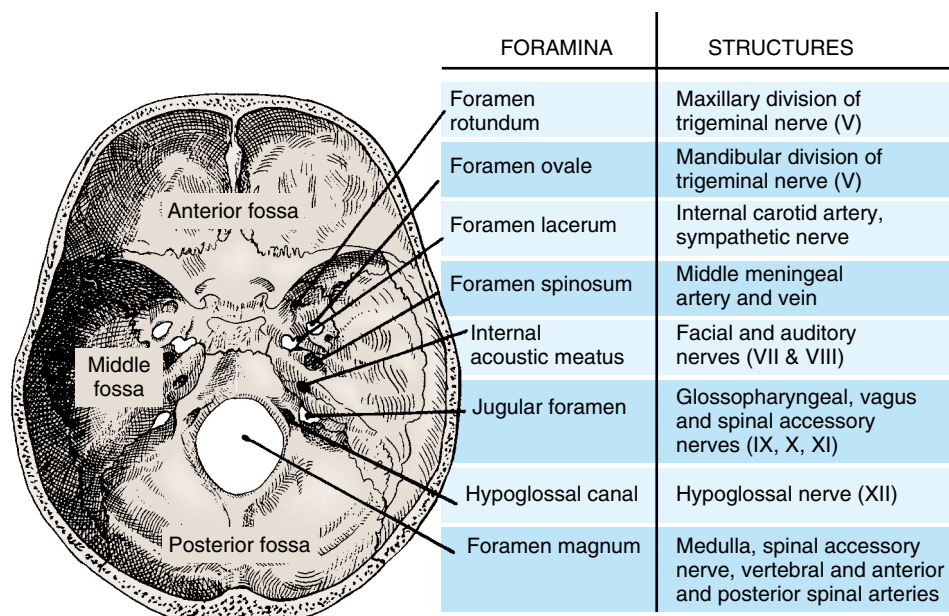
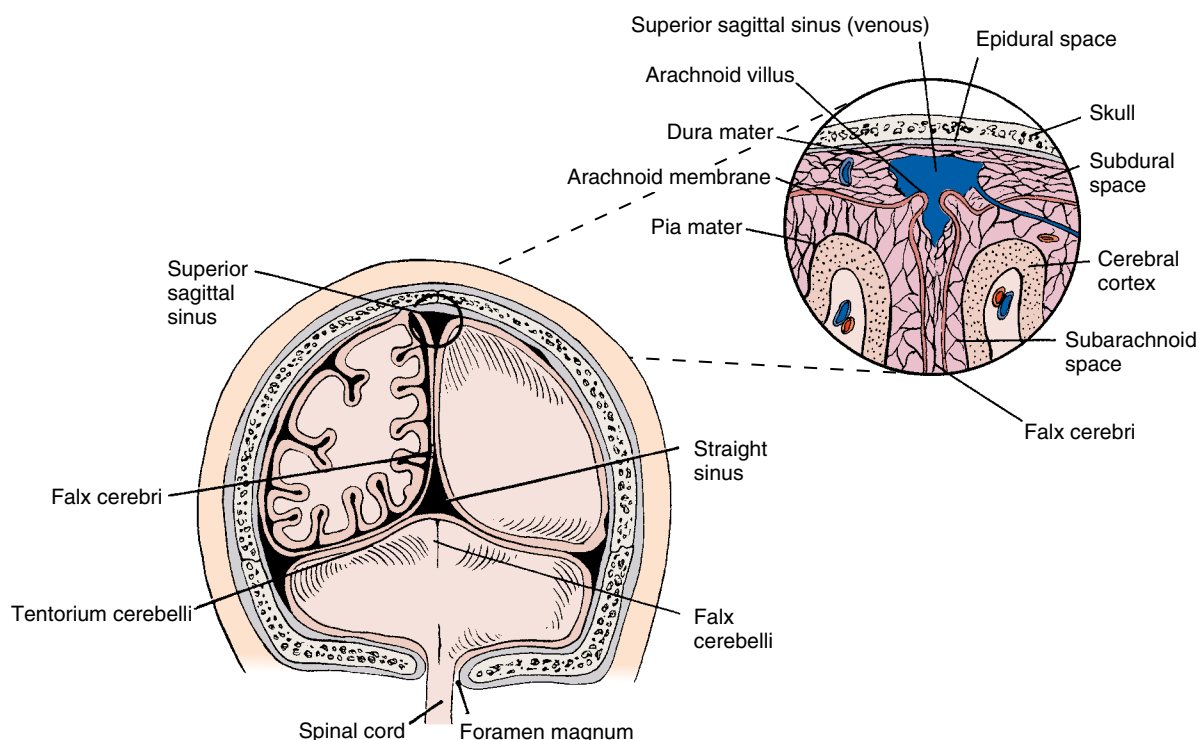


Fig. 2.1 The major bones of the skull.



**Fig. 2.2** Base of the skull, viewed from above, illustrating the major cranial fossae and foramina through which some vascular structures and the cranial nerves supplying speech muscles enter and exit.



**Fig. 2.3** Coronal view of the supratentorial and posterior fossa levels and their major boundaries. Also shown are the meninges and their associated spaces (*inset*).

vascular disorders, hydrocephalus, or trauma with associated hemorrhage and edema.

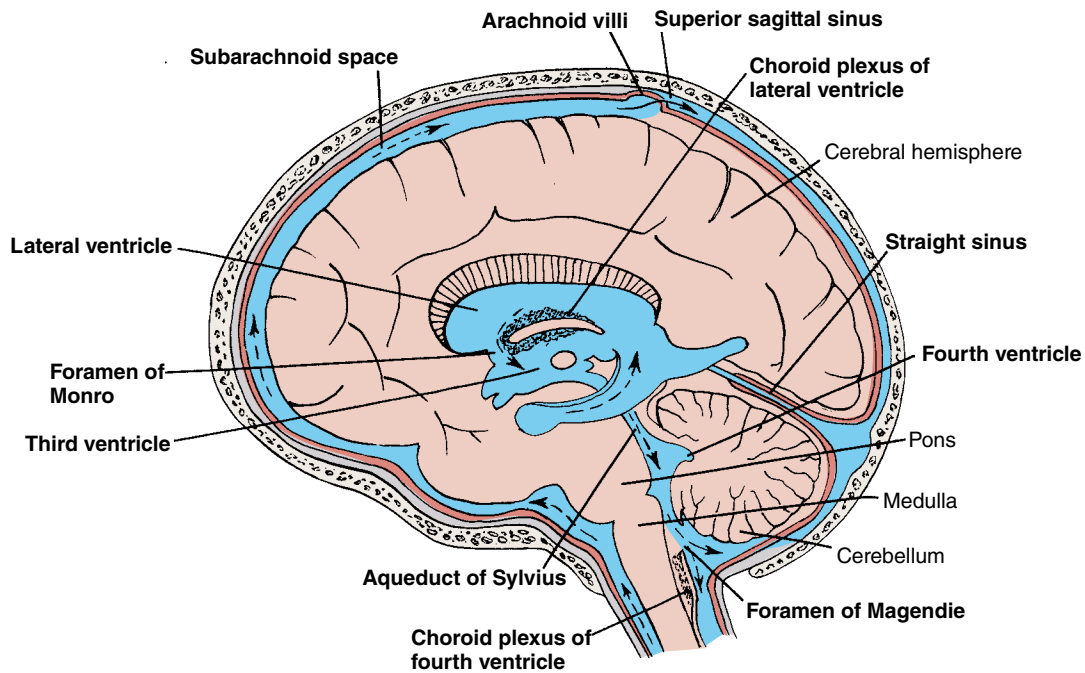
### Major Anatomic Levels of the Nervous System

The major anatomic levels of the nervous system can be related to the boundaries of the skull and spinal column. They are also roughly demarcated by the meninges and portions of the ventricular/cerebrospinal and vascular systems, which are

discussed later. The major anatomic levels and their skeletal, meningeal, ventricular, and vascular characteristics, as well as their relationship to the major types of MSDs, are summarized in [Table 2.1](#).

#### Supratentorial Level

The supratentorial level lies above the tentorium cerebelli (see [Fig. 2.3](#)), a nearly horizontal membrane that forms the



**Fig. 2.4** The subarachnoid space and ventricular system in which cerebrospinal fluid is produced and circulates.

**TABLE 2.1 Relationships Among the Major Anatomic Levels of the Nervous System, Skeleton, Meninges, Ventricular System, Vascular System, and Major Motor Speech Disorder Types**

| Anatomic Level                                                                                | Skeleton                                         | Meninges                                             | Ventricular System                                 | Vascular System                                                                                                                                                   | Motor Speech Disorder                                                                        |
|-----------------------------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------|----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| <b>Supratentorial</b><br>Hemispheres, lobes, basal ganglia, thalamus, cranial nerves I and II | Skull (anterior and middle fossa)                | Above tentorium cerebelli<br>Lateral to falx cerebri | Lateral and third ventricles<br>Subarachnoid space | Carotid arterial system<br>Ophthalmic arteries<br>Middle cerebral arteries<br>Anterior cerebral arteries<br>Vertebrobasilar system<br>Posterior cerebral arteries | Apraxia of speech<br>Dysarthrias<br>Spastic<br>Unilateral UMN<br>Hypokinetic<br>Hyperkinetic |
| <b>Posterior Fossa</b><br>Brainstem (pons, medulla, midbrain) and cerebellum                  | Skull<br>Posterior fossa                         | Below tentorium cerebelli                            | Fourth ventricle<br>Subarachnoid space             | Vertebrobasilar system<br>Vertebral arteries<br>Basilar artery                                                                                                    | Dysarthrias<br>Spastic<br>Unilateral UMN<br>Hyperkinetic<br>Ataxic<br>Flaccid                |
| <b>Spinal</b>                                                                                 | Vertebral column                                 | Spinal meninges                                      | Spinal<br>Subarachnoid space                       | Anterior spinal artery<br>Posterior spinal arteries                                                                                                               | Dysarthria<br>Flaccid                                                                        |
| <b>Peripheral</b><br>Cranial and spinal nerves                                                | Face and skull<br>Noncranial and nonspinal bones | None                                                 | None                                               | Branches of major extremity vessels                                                                                                                               | Dysarthria<br>Flaccid                                                                        |

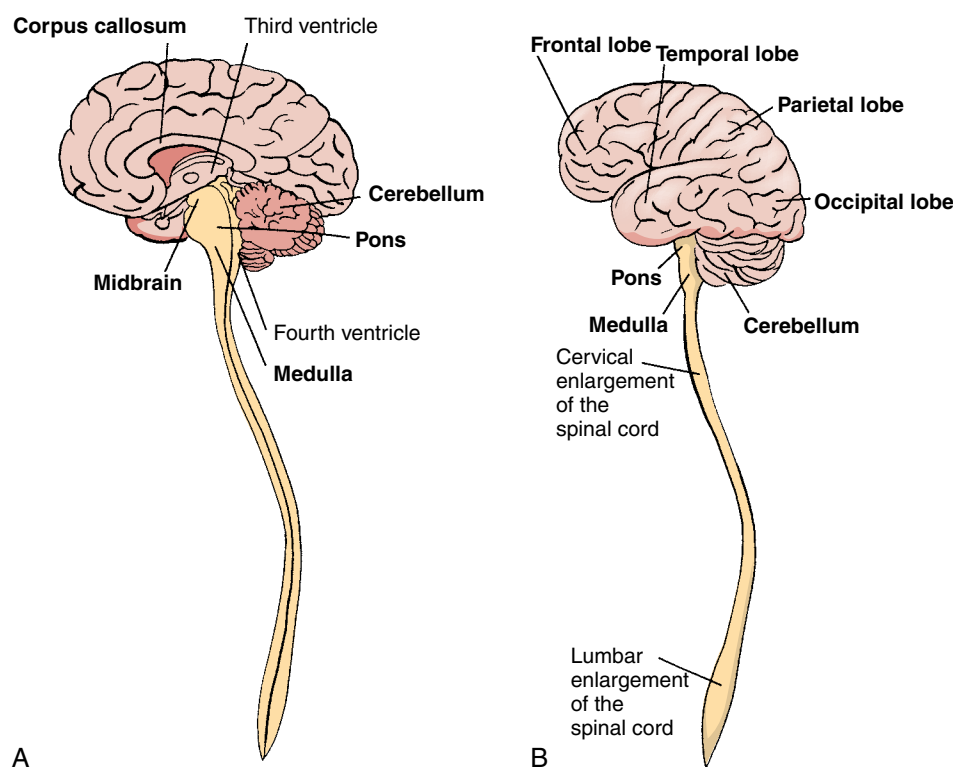
UMN, Upper motor neuron.

upper border of the posterior fossa, covers the upper surface of the cerebellum, and separates the anterior and middle fossae from the posterior fossa. The supratentorial level includes the paired frontal, temporal, parietal, and occipital lobes of the cerebral hemispheres (Fig. 2.5). It also includes the basal ganglia, thalamus, hypothalamus, and cranial nerves I (olfactory) and II (optic).

### Posterior Fossa Level

The major structures of the posterior fossa are the brainstem (pons, medulla, and midbrain), the cerebellum, and the origins of cranial nerves III through XII (see Fig. 2.5).

The area of the posterior fossa dorsal to the aqueduct of Sylvius (see Fig. 2.4) includes the inferior and superior colliculi (known collectively as the *corpora quadrigemina*), midbrain



**Fig. 2.5** Mesial (A) and lateral (B) aspects of the brain and spinal cord.

structures that are major relay stations for the auditory and visual systems, respectively. The area ventral to the aqueduct of Sylvius and fourth ventricle contains white matter pathways and many nuclei, including the *reticular formation*; large cerebral and cerebellar pathways in the most ventral region below this area form the base region of the midbrain and pons. The cerebellum lies dorsal to the fourth ventricle, pons, and medulla. It includes a right and left hemisphere and a midline vermis.

Of the 12 paired cranial nerves, 10 (all but I and II) have their origin in and exit from the brainstem. Several of them represent the last neural link, or *final common pathway (FCP)*, from the nervous system to the speech muscles. Their names, origins, and general functions are summarized in Table 2.2.

### KEY POINTS 2.1

- Although they originate in the brainstem, the cranial nerves serving speech are lower motor neurons (part of the FCP).
- This distinction is crucial to understanding the pathophysiology of flaccid dysarthria. All other dysarthria types result from CNS dysfunction.

### Spinal Level

The adult spinal cord begins at the *foramen magnum*, the large, central opening in the posterior fossa at the lower end of the medulla (see Figs. 2.2 and 2.3). The spinal cord is surrounded by the bony vertebral column, which includes 7 cervical, 12 thoracic, and 5 lumbar vertebrae. It ends at the level of the

**TABLE 2.2** Location and General Functions of the Cranial Nerves

|      | Nerve                         | Anatomic Origin      | Function                                                                                      |
|------|-------------------------------|----------------------|-----------------------------------------------------------------------------------------------|
| I    | Olfactory                     | Cerebral hemispheres | Smell                                                                                         |
| II   | Optic                         | Diencephalon         | Vision                                                                                        |
| III  | Oculomotor                    | Midbrain             | Eye movement; pupil constriction                                                              |
| IV   | Trochlear                     | Midbrain             | Eye movement                                                                                  |
| V    | Trigeminal <sup>a</sup>       | Pons                 | Jaw movement; face, mouth, jaw sensation                                                      |
| VI   | Abducens                      | Pons                 | Eye movement                                                                                  |
| VII  | Facial <sup>a</sup>           | Pons                 | Facial movement; hyoid elevation; stapedius reflex; salivation; lacrimation; taste            |
| VIII | Cochleovestibular             | Pons, medulla        | Hearing; balance                                                                              |
| IX   | Glossopharyngeal <sup>a</sup> | Medulla              | Pharyngeal movement; pharynx and tongue sensation; taste                                      |
| X    | Vagus <sup>a</sup>            | Medulla              | Pharyngeal, palatal, and laryngeal movement; pharyngeal sensation; control of visceral organs |
| XI   | Accessory <sup>a</sup>        | Medulla, spinal cord | Shoulder and neck movement                                                                    |
| XII  | Hypoglossal <sup>a</sup>      | Medulla              | Tongue movement                                                                               |

<sup>a</sup>Involvement in speech production.

first lumbar vertebra. Thirty-one pairs of spinal nerves are attached to it by dorsal (posterior) and ventral (anterior) nerve roots. The dorsal roots are sensory in function; the ventral roots are motor.

### Peripheral Level

The peripheral nervous system (PNS) consists of the cranial and spinal nerves. As already noted, most cranial nerves originate in the brainstem, exit the skull through paired foramina, and travel to their muscle destinations. The spinal nerves, which contain the joined dorsal and ventral roots, enter the peripheral level as they emerge from the vertebral column to travel to their muscle destinations. The course, innervation, and function of the cranial and spinal nerves subserving speech are discussed later in this chapter.

### Major Functional Longitudinal Systems

Neurologic diagnosis often begins by linking clinical signs and symptoms to one or more of the major longitudinal systems of the nervous system. These systems contain groups of structures that have specific functions. They are called longitudinal because, for the most part, their components span the length of the nervous system (i.e., from the supratentorial to the peripheral level). The relationships between each of these systems and speech production and MSDs range from indirect to direct.

#### KEY POINT 2.2

- Localizing disease requires knowledge about the affected functional system and its location in the nervous system.

### The Consciousness System

The consciousness system is represented only at the supratentorial and posterior fossa levels. It includes the reticular formation and its ascending projection pathways, portions of the thalamus, pathways to widespread areas of the cerebral cortex, and portions of all lobes of the cerebral cortex. It is crucial to maintaining wakefulness, consciousness, awareness of the environment, and, on a higher level, selective and sustained attention. Malfunctions within it can affect cognitive functions, including language and communication, and can indirectly affect motor functions, including speech.

### The Autonomic Nervous System

The autonomic nervous system is an internal regulation system that is represented at all major anatomic levels of the nervous system. Its components include the hypothalamus and parts of the limbic lobe supratentorially, the reticular formation and portions of some cranial nerves in the posterior fossa, longitudinal pathways in the brainstem and spinal cord, and ganglia, receptors, and effectors at the periphery. Its components interact to maintain a balanced internal environment (*homeostasis*) by regulating visceral glands (e.g., salivary) and organ functions (cardiac, respiratory, vascular, gastrointestinal, sexual/reproductive). Its supratentorial components integrate input from visceral organs and environmental stimuli and drive autonomic responses associated with emotional and adaptive responses.

### The Emotion System

The emotion system is represented at the supratentorial and posterior fossa levels, and its core components overlap with the autonomic and consciousness systems. Its supratentorial components—the limbic system—include the amygdala, insular cortex, orbitofrontal cortex, anterior cingulate cortex, nucleus accumbens, and hypothalamus. Posterior fossa components include the periaqueductal gray and dopaminergic neurons in the midbrain. Among its important functions are pain perception and modulation, responses to stress, emotional processing and expression, and reward-based and goal-driven motor behavior. Of note, its circuitry interacts with the sensory and motor systems, consistent with the fact that emotions have physical as well as psychological manifestations.

### The Ventricular and Cerebrospinal Fluid System

The ventricular system lies in the depths of the brain (see Fig. 2.4). The ventricles are cavities that contain CSF, which is produced by choroid plexuses located in each ventricle. Each cerebral hemisphere contains a lateral ventricle that is connected by way of the foramen of Monro to the midline-located third ventricle. The third ventricle narrows into the aqueduct of Sylvius, which leads to the fourth ventricle between the brainstem and cerebellum. The foramen of Luschka and the foramen of Magendie in the fourth ventricle link the ventricular system to the subarachnoid space.

The ventricular system and subarachnoid space comprise the CSF system. CSF circulates throughout the ventricles and subarachnoid space and is absorbed in the arachnoid villi in the brain or in the leptomeninges in the spinal cord subarachnoid space. CSF thus can be found in several of the major anatomic levels of the nervous system, including the supratentorial, posterior fossa, and spinal levels. Its primary functions are to cushion the CNS against physical trauma and to help support a stable environment for neural activity.

### The Vascular System

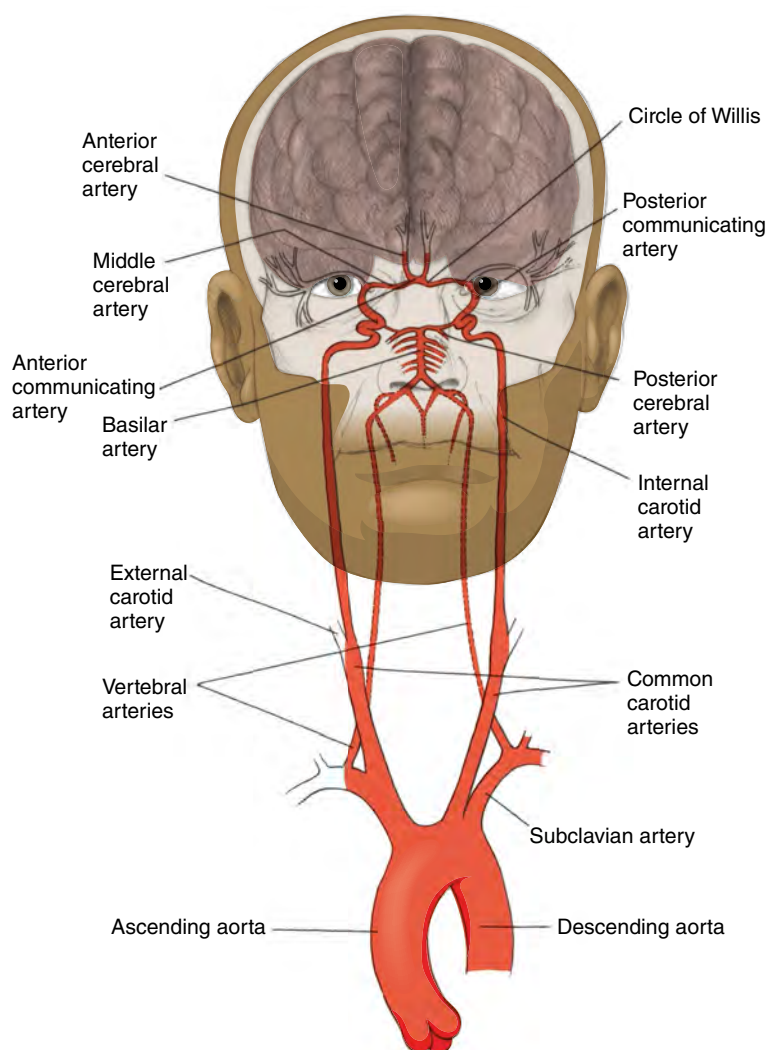
The vascular system (Figs. 2.6 to 2.8) is the literal lifeblood of the nervous system. It is found within all major anatomic levels, where it supplies oxygen and other nutrients to neural structures and removes metabolic wastes from them.

#### KEY POINT 2.3

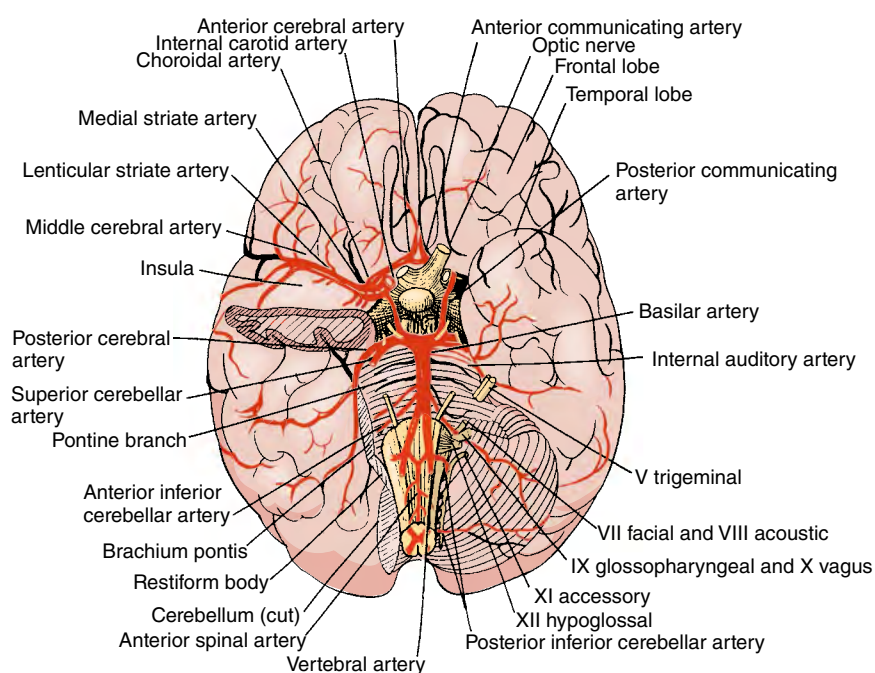
- The vascular system is a major locus of abnormalities that can lead to dysarthrias and apraxia of speech.

All blood vessels supplying the brainstem and cerebral hemispheres arise from the aortic arch in the chest. Blood enters the brain by way of the *carotid system* and the *vertebrobasilar system*. These two systems can communicate with each other through connecting channels in the brainstem known as the *circle of Willis* (see Fig. 2.6).

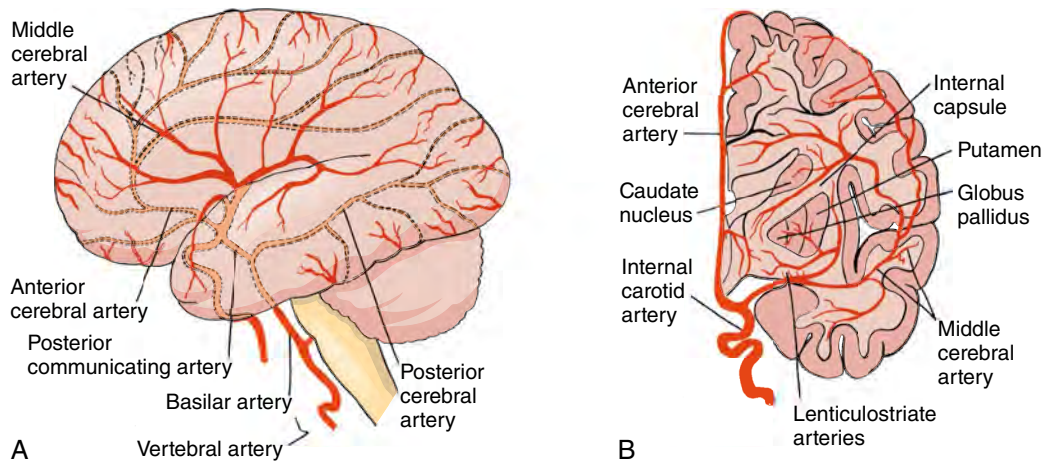
The carotid system originates with the paired internal carotid arteries that arise from the common carotid arteries in the neck at the level of the thyroid cartilage (see Fig. 2.6). The carotid arteries enter the skull through the carotid canal in the petrous



**Fig. 2.6** Major arteries supplying the brain.



**Fig. 2.7** Inferior view of the carotid, vertebral, and basilar arteries; some of their major branches; and their relationship to major brainstem and cerebral structures.



**Fig. 2.8** Lateral (A) and anteroposterior (B) views of the major cerebral arteries and some of their penetrating branches to subcortical structures.

portion of each temporal bone. They pass through the cavernous sinus lateral to the sphenoid bone and eventually to the circle of Willis.

Each internal carotid artery separates at the circle of Willis into two of the three major paired cerebral arteries, the anterior cerebral arteries and the middle cerebral arteries. The anterior cerebral arteries are connected to each other by the anterior communicating artery; they course upward in the midline and supply the medial surface of the cerebral hemispheres and the superior portion of the frontal and parietal lobes. The middle cerebral arteries course laterally, and their branches supply most of the lateral surfaces of the cerebral hemispheres and the deep structures of the frontal and parietal lobes (see Fig. 2.7).

The vertebrobasilar system begins with the paired vertebral arteries that enter the brainstem through the foramen magnum and join at the lower border of the pons to form the basilar artery. Branches from these arteries supply the midbrain, pons, medulla, cerebellum, and portions of the cervical spinal cord. The posterior cerebral arteries—the third of the major cerebral arteries—are branches of the vertebrobasilar system. They supply the occipital lobe, the thalamus, and the inferior and medial portions of the temporal lobe in each hemisphere (see Figs. 2.7 and 2.8). Table 2.3 summarizes the brain's vascular supply, the anatomic regions supplied by its components, and some neurologic signs, including MSDs, associated with vascular disturbances of each component.

#### KEY POINTS 2.4

- Vascular disturbances in the left or right carotid artery, and in the left or right anterior and middle cerebral arteries, can lead to dysarthria.
- Left middle cerebral artery disturbances are a common cause of apraxia of speech and aphasia.
- Vascular disturbances in the vertebrobasilar system often lead to dysarthria.

### The Sensory System

The sensory system is found at all major anatomic levels of the nervous system. It includes peripheral receptor organs; afferent fibers in cranial, spinal, and peripheral nerves; dorsal root

ganglia (spinal level); ascending pathways in the spinal cord and brainstem; portions of the thalamus; and thalamocortical connections, primarily to sensory cortex in the temporal, parietal, and occipital lobes. Special sensory systems, such as hearing and vision, are also found at the peripheral, posterior fossa, and supratentorial levels.

### The Motor System

The motor system is present at all major anatomic levels of the nervous system and is directly responsible for all motor activity involving striated muscle. It includes efferent connections of the cortex, especially the frontal lobes; the basal ganglia, cerebellum, and related CNS pathways; descending pathways to motor nuclei of cranial and spinal nerves; efferent fibers within cranial and spinal nerves; and striated muscle. It is essential to normal reflexes, to maintaining normal muscle tone and posture, and to the planning, control, and execution of voluntary movement, including speech.

#### KEY POINT 2.5

- Lesions in nonmotor functional longitudinal systems can alter speech indirectly through their effects on the motor system. For example, when a stroke (vascular system) leads to an MSD, it is because of the damage the stroke has done to portions of the motor system involved in speech production.

## PRIMARY STRUCTURAL ELEMENTS OF THE NERVOUS SYSTEM

The nervous system is composed of *neurons*, or nerve cells, and considerably more numerous supporting *glial cells* (Table 2.4). The brevity of the summary of their structure and functions provided here reflects the more global focus of this book plus an assumption that the reader already has some understanding of this relatively molecular topic.

### The Neuron and Neurotransmitters

Neurons are the most important cellular elements of the nervous system because their electrochemical activities drive the

**TABLE 2.3 Vascular Supply to the Brain, Some of the Major Anatomic Regions Supplied, and Some of the Primary Neurologic and Motor Speech Deficits that Result from Vascular Disturbances**

| Main Vessels                           | Anatomic Region Supplied                                                                                                                                                                                                                                                                                                                                        | Signs <sup>a</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
|----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>I. Carotid System</b>               |                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| A. Branches of internal carotid artery | Most of cerebral hemispheres                                                                                                                                                                                                                                                                                                                                    | Contralateral hemiplegia<br>Contralateral hemianesthesia<br>Hemianopsia or ipsilateral blindness<br>Aphasia (left)<br>Apraxia of speech (left)<br>Unilateral UMN dysarthria<br>Spastic dysarthria (usually bilateral)<br>Hypokinetic dysarthria<br>Hyperkinetic dysarthria                                                                                                                                                                                                                                                             |
| 1. Anterior choroidal                  | Optic tract; cerebral peduncle; lateral geniculate body; portions of internal capsule                                                                                                                                                                                                                                                                           | Hemianopsia or upper quadrant defect<br>Contralateral hemiplegia<br>Thalamic sensory changes<br>Unilateral UMN dysarthria?<br>Spastic dysarthria (if bilateral)?                                                                                                                                                                                                                                                                                                                                                                       |
| 2. Ophthalmic                          | Orbit and surrounding tissue; muscles and bulb of the eye                                                                                                                                                                                                                                                                                                       | Unilateral blindness<br>Optic atrophy                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 3. Anterior cerebral                   | <i>Cortical branches</i><br>Anterior $\frac{3}{4}$ of medial surface of cerebral hemispheres; frontal lobe, medial-orbital surface; frontal pole; superior lateral border of hemispheres; anterior $\frac{1}{5}$ of corpus callosum<br><br><i>Deep branches</i><br>Internal capsule, anterior limb; part of head of caudate nucleus                             | Contralateral lower extremity weakness<br>Paraplegia (if bilateral)<br>Cortical sensory defects, foot and leg<br>Contralateral forced grasping and groping<br>Sucking reflex<br>Incontinence<br>Gait and limb apraxia<br>Aphasia?<br>Abulia, akinetic mutism, cognitive impairments<br>Apraxia of speech (left)?<br>Unilateral UMN dysarthria?<br>Spastic dysarthria (if bilateral)?<br>Hypokinetic dysarthria?<br>Hyperkinetic dysarthria?                                                                                            |
| 4. Middle cerebral                     | <i>Cortical branches</i><br>Cortex and white matter of parietal lobe and lateral and inferior frontal lobe; superior parts of temporal lobe and insula<br><br><br><br><br><br><br><br><br><br><i>Penetrating branches</i><br>Putamen; part of head and body of caudate nucleus; outer part of globus pallidus; internal capsule; posterior limb; corona radiata | Contralateral hemiplegia<br>Contralateral cortical sensory deficit<br>Homonymous hemianopsia<br>Paralysis of conjugate gaze to side opposite lesion<br>Aphasia (left)<br>Apraxia of speech (left)<br>Unilateral UMN dysarthria<br>Spastic dysarthria (usually bilateral)<br>Limb apraxia<br><br>Contralateral hemiplegia or hemiparesis<br>Contralateral hemisensory deficits<br>Contralateral movement disorders<br>Aphasia (left)<br>Apraxia of speech (left)<br>Unilateral UMN dysarthria<br>Spastic dysarthria (usually bilateral) |

**TABLE 2.3 Vascular Supply to the Brain, Some of the Major Anatomic Regions Supplied, and Some of the Primary Neurologic and Motor Speech Deficits that Result from Vascular Disturbances—cont'd**

| Main Vessels                      | Anatomic Region Supplied                                                                                                                                                                                              | Signs <sup>a</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|-----------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>II. Vertebrobasilar System</b> |                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| A. Posterior cerebral             | Red nucleus; substantia nigra; cerebral peduncles; reticular formation; oculomotor and trochlear nuclei; superior cerebellar peduncles; hippocampus; portions of thalamus; inferomedial temporal lobe; occipital lobe | Contralateral hemiparesis<br>Oculomotor palsy<br>Ataxia and tremor<br>Memory and attention deficits<br>Unilateral sensory loss<br>Homonymous hemianopsia<br>Movement disorders<br>Various visual deficits<br>Alexia without agraphia<br>Aphasia (left)<br>Unilateral UMN dysarthria<br>Spastic dysarthria (usually bilateral)<br>Ataxic dysarthria<br>Hyperkinetic dysarthria                                                                              |
| B. Basilar artery                 | Pons; middle and superior cerebellar peduncles; cerebellar hemispheres; upper midbrain and subthalamus                                                                                                                | Quadriplegia (if bilateral)<br>Hemiplegia<br>Coma (if bilateral)<br>Somnolence<br>Oculomotor deficits<br>Visual defects<br>Nystagmus<br>Ipsilateral cerebellar ataxia<br>Nausea and vomiting<br>Cranial nerve involvement (III–XII)<br>Spastic dysarthria (if bilateral)<br>Anarthria (if bilateral)<br>“Locked-in” syndrome (if bilateral)<br>Ataxic dysarthria<br>Unilateral UMN dysarthria<br>Flaccid dysarthria<br>Palatal-pharyngeal-laryngeal tremor |
| C. Vertebral artery               | Medulla; cerebellum (posterior inferior)                                                                                                                                                                              | Contralateral hemiplegia and sensory loss<br>Ptosis<br>Ipsilateral weakness of cranial nerves IX–XII<br>Nystagmus, vertigo<br>Ipsilateral ataxia<br>Ipsilateral loss of facial sensation<br>Cranial nerve V and taste<br>Hiccups<br>Nausea and vomiting<br>Spastic dysarthria (usually bilateral)<br>Ataxic dysarthria<br>Unilateral UMN dysarthria<br>Flaccid dysarthria                                                                                  |

UMN, Upper motor neuron.

<sup>a</sup>Signs occur with vascular disturbance on the right or left unless otherwise specified in parentheses.

Motor Speech Disorders and other Disorders Affecting Spoken Communication are Highlighted in Green.

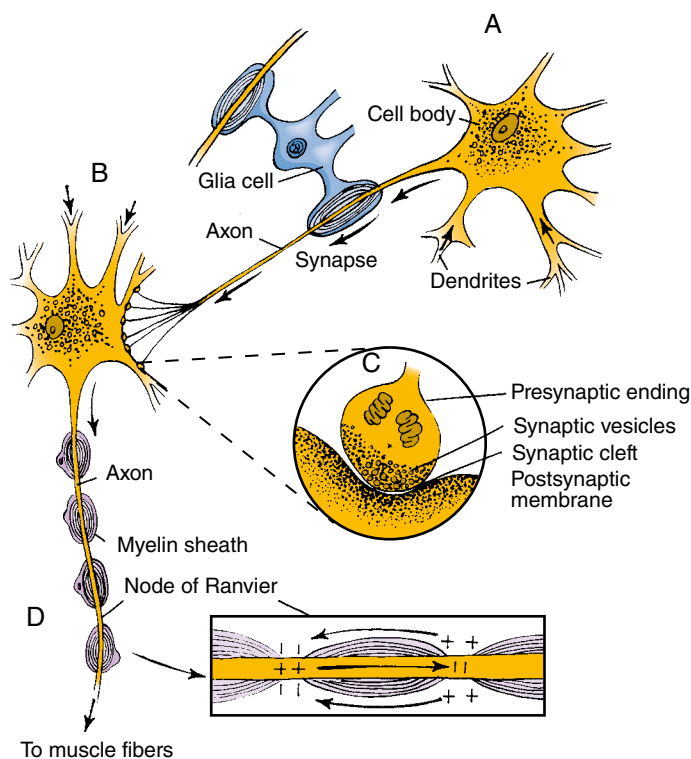
receipt, processing, and transmission of information. Their estimated number in humans is an astounding 86 billion.<sup>40</sup> Many diseases affecting neurons result in their malfunction, degeneration, or loss, while others prevent normal development of neurons.

Neurons in different parts of the nervous system vary in size and shape, but they all have a cell body, dendrites, and an axon (Fig. 2.9). The cell body is the central processing unit and is responsible for neuronal metabolic functions. Dendrites and an axon extend from the cell body into surrounding tissue; their

**TABLE 2.4 Structural Elements of the Nervous System**

| Structure               | Locus                                                                       | Function                                                                  |
|-------------------------|-----------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Neurons                 | CNS and PNS                                                                 | Drive all neurologic functions                                            |
| Nerves                  | PNS (brainstem or spinal cord to end organs)                                | PNS motor and sensory functions                                           |
| Tracts or pathways      | CNS                                                                         | Communication among groups of neurons                                     |
| Commissural             | Between cerebral hemispheres                                                |                                                                           |
| Association             | Within cerebral hemispheres                                                 |                                                                           |
| Projection              | To and from higher and lower centers within CNS (e.g., cortex and thalamus) |                                                                           |
| <b>Supporting Cells</b> |                                                                             |                                                                           |
| Oligodendroglia         | Surround CNS axons (myelin)                                                 | Insulation: speed transmission                                            |
| Schwann cells           | Surround PNS axons (myelin)                                                 | Insulation: speed transmission                                            |
| Astrocytes              | Relate to CNS blood vessels and neurons                                     | Transport substances from blood vessels to neurons<br>Blood-brain barrier |
| Ependymal cells         | Lining of ventricles                                                        | Separate ventricles from parenchyma                                       |
|                         | Choroid plexuses                                                            | Produce CSF                                                               |
| Microglia               | Scattered in CNS                                                            |                                                                           |
|                         | Form microphages                                                            | Ingest or remove damaged tissue                                           |
| Connective tissue       | Form meninges                                                               | Covering of CNS                                                           |
|                         | Sheaths on PNS nerve fibers and nerves                                      | Cover and bind fibers together in PNS nerves                              |

CNS, Central nervous system; CSF, cerebrospinal fluid; PNS, peripheral nervous system.



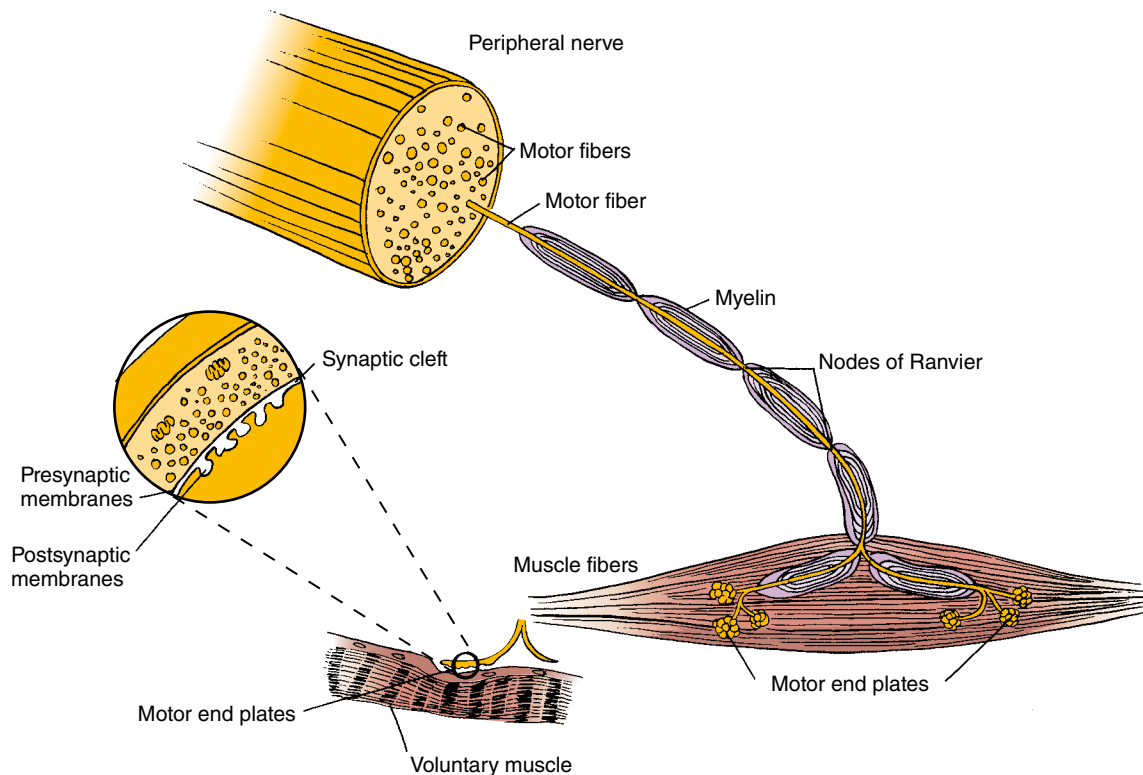
**Fig. 2.9** Neuron (A) and anatomy of neuron-to-neuron communication (B and C, inset). Dendrites receive information while the axon transmits information to other neurons. (D, inset) Action potential is moving through saltatory conduction in the direction of the arrows inside the axon.

length and structure vary greatly across different types of neurons. Dendrites are usually numerous but short, with many branches; they are responsible for gathering information transmitted from surrounding neurons. Neurons have a single axon that may extend from the cell body for a few millimeters or for

several feet; an axon's diameter generally varies with its length. Neurons with axons that travel extended distances are generally specialized for conducting information. Neurons with axons that terminate near their own dendrites and cell body are more involved in complex interactions within pools of neurons, interactions that can be thought of as information processing.

The axon conducts signals away from the cell body to other neurons or to muscle or glands. Most communication among neurons, or between neurons and muscles, takes place at regions known as *synapses* (Fig. 2.10; see also Fig. 2.9). In neuron-to-neuron synapses, the axon usually communicates with the cell body or dendrites of another neuron. In most instances, the axon and dendrite (or muscle fibers) are separated by a *synaptic cleft*. At the tip of the axon are tiny synaptic vesicles containing a chemical neurotransmitter that carries the axon's signal to neurotransmitter receptors that mediate excitatory, inhibitory, or modulatory effects on the receiving cell. Actions at synapses can be complex, varying as a function of the particular neurotransmitter and the type of neurotransmitter receptor. A given neurotransmitter may have different effects as a function of the receptor type, and different neurotransmitters may produce the same ultimate synaptic effect.

Despite the complexities just described, the message carried by a single axon to another neuron is, ultimately, simple; it either facilitates or inhibits the neuron receiving it from firing a message of its own. All that varies in the message of a single neuron is the rate at which it is sent. This "go" or "no go" form of communication leads to a limited set of simple, stereotypic outcomes in organisms with few neurons. In the human nervous system, however, axons branch repeatedly, forming 1000 to 10,000 synapses, and their cell bodies and dendrites receive information from about 1000 other neurons. The number of synapses in the brain may be about 100 trillion. As a result, the



**Fig. 2.10** Motor unit. A myelinated axon (motor fiber) carries an action potential that results in the release of acetylcholine from synaptic vesicles across the neuromuscular junction (*inset*) to trigger muscle fiber contraction. The final common pathways innervating muscles for speech have thousands of such motor units.

“decision” of a neuron to fire or not reflects a summation of the messages it receives from multiple sources.

Neurotransmitters are at work at all anatomic levels of the nervous system.<sup>b</sup> There are many different CNS neurotransmitters, and they play different roles. Some are responsible for rapid excitation or inhibition, others modulate the excitability of neurons, and still others produce long-term effects that influence neural development, learning, plasticity, and responses to injury. A few relevant examples illustrate some of their variable functions and complexity.

- **Glutamate** is the primary excitatory neurotransmitter for all CNS neurons. **Gamma-aminobutyric acid (GABA)** is a primary inhibitory neurotransmitter in the mature CNS. It plays a key role in the regulation of muscle tone; it is active in the cerebral cortex, thalamus, and sensory and motor nuclei; and it is important in motor control activities of the basal ganglia and cerebellum. Glutamate and GABA are widespread in the nervous system and are important for swift neuronal excitation and inhibition.
- **Dopamine** is a crucial neurotransmitter that originates in the substantia nigra and ventral tegmental area in the midbrain and projects to many areas of the brain. It has many functions in the CNS, playing a role in movement, motivation and

reward, cognition and learning, attention, mood, and sleep. Its modulatory actions in the basal ganglia, through several different dopamine receptors, aid the initiation and control of skilled motor acts, including speech.

- **Acetylcholine (ACh; the cholinergic system)** is the only neurotransmitter involved in the PNS control of skeletal muscle functions. It acts quickly and has excitatory effects. If released in sufficient quantity at the neuromuscular junction, it leads to movement by inducing muscle fiber contraction. ACh is also present in the CNS, including areas relevant to speech motor control and learning, where it has modulatory effects by influencing neuronal excitability.

#### KEY POINTS 2.6

- Neurochemical abnormalities are associated with numerous neurologic and psychiatric disorders and can lead to motor speech and other neurologic communication disorders.
- The use of medicinal drugs to influence neurochemical systems is crucial to the management of several diseases associated with MSDs.

It is important to bear in mind that the actions of neurotransmitters at a given point in time must end; that is, they must be turned off. The mechanisms that accomplish this generally depend on the type of neurotransmitter. They include uptake by astrocytes or presynaptic terminals, enzyme metabolism, or diffusion out of the synaptic cleft. Malfunction of these mechanisms can be a source of neurologic disease.

<sup>b</sup>The summary information in this section relies heavily on more detailed overviews of neurotransmitters and neurochemical transmission in Bennaroch<sup>8</sup> and Bennaroch et al.<sup>9</sup>

## Supporting (Glial) Cells

### Oligodendroglia and Schwann Cells

Oligodendroglia and Schwann cells form the insulation, or *myelin*, which surrounds axons in the CNS and PNS. Schwann cells in the PNS form myelin, which wraps around fibers in most peripheral nerves. Small gaps between each myelinated segment of peripheral nerve fibers are known as *nodes of Ranvier*. Electrical signals traveling down axons skip from node to node, with a resulting increased speed of transmission, a process known as saltatory conduction (see Figs. 2.9 and 2.10). In addition to speeding transmission, myelin appears to protect axons from injury. For example, in multiple sclerosis, in which demyelination occurs, the loss of myelin seems to predispose axons to later injury, which may contribute to the functional deficits associated with the disease.<sup>57</sup> Oligodendroglia cells are the source of myelin in the CNS.

### Astrocytes

Star-shaped astrocytes are widely distributed in the CNS, lying close to both neurons and capillaries. They assist neuronal migration during development; help regulate neuronal metabolism, the chemical microenvironment, and synaptic transmission; and contribute to mechanisms of repair in response to injury. They are an important part of the *blood-brain barrier*, a mechanism that prevents the passage of many metabolites from the blood into the brain, thereby protecting it from toxic compounds and variations in blood composition.

### Ependymal Cells

Ependymal cells line the ventricular system and form a barrier between ventricular fluid and the neuronal substance (parenchyma) of the brain. They also form the *choroid plexuses* that produce ventricular and cerebrospinal fluid.

### Microglia

Microglia are scattered throughout the nervous system. They respond to destructive CNS processes by proliferating and transforming into *macrophages* (scavenger cells), which ingest pathogens and remove damaged tissue.

### Connective Tissue

Connective tissues make up the meninges. In the PNS, connective tissues form thin layers on myelinated nerve fibers, help bind fibers together within nerves, and can be found covering areas at the trunks of nerves. They are analogous to the meninges that surround the CNS.

## Nerves, Tracts, and Pathways

The activity of a single neuron is of little consequence to observable human behavior. Only through the activity of many neurons does meaningful sensory, motor, and cognitive activity occur. For example, voluntary movement requires the integrated activity of many neurons conducting impulses within and among many levels of the CNS motor system, plus the final influence of impulses carried by many axons traveling in nerves to many muscle fibers. Because our focus here is on motor behavior, we are most interested in the combined activities of groups of neurons that join forces to accomplish motor goals.

The major PNS structural unit is the nerve (see Fig. 2.10), a collection of axons (nerve fibers) bound together by connective tissue. Peripheral nerves (cranial and spinal nerves) travel between the CNS (where their cell bodies reside) and peripheral *end organs*, which are the sensory, motor, and visceral structures that nerves innervate.

A nerve contains up to thousands of nerve fibers of varying sizes. Fibers relevant to sensorimotor speech functions are generally relatively large and myelinated. They conduct impulses relatively quickly.

The term *nerve* is reserved for groups of axons that travel together to a common destination in the PNS. A *tract* (or *pathway*) is a group of axons that travel together to a common destination in the CNS.

### KEY POINTS 2.7

- In the CNS, tracts are often referred to as *white matter* because of the whitish appearance of their myelin sheaths. In contrast, the cell bodies of neurons covering the cerebral and cerebellar cortex are *gray matter*, as are groups of cell bodies (nuclei) in various parts of the brain (e.g., the caudate nucleus in the basal ganglia; the dentate nucleus in the cerebellum).
- A major distinction between PNS nerves and CNS tracts is that CNS tracts send impulses to other neurons, while PNS nerves send impulses from nerves to end organs, such as muscle.

Fiber tracts in the CNS are categorized according to the areas they connect. *Commissural tracts* connect homologous areas in the two cerebral hemispheres. *Association tracts* connect cortical areas within a hemisphere. *Projection tracts* contain fibers that connect higher and lower centers in the CNS. The specific names of projection tracts reflect the areas they connect. For example, afferent fibers from the thalamus to the cortex are known as *thalamocortical fibers*; efferent fibers from the cortex to the cranial nerves are known as *corticobulbar fibers*; efferent fibers from the cortex to the red nucleus in the midbrain are known as *corticorubral fibers* (*rubral*, meaning “red,” refers to the red nucleus). Afferent and efferent projection fibers are crucial components of circuits and networks involved in motor activities.

## Pathologic Reactions of Structural Elements

Nervous system cells respond to neurologic disease. In some disorders, the response is physiologic. In others, structural changes reflect specific effects of damage or a response to the pathologic process. Some structural responses are nonspecific, while others are specific to a particular disease.

### Neuronal Reactions

Neuronal loss occurs in many neurologic diseases. After as little as 2 to 5 minutes of *ischemia* (deprivation of oxygen and cessation of oxidative metabolism, as occurs in stroke), acute swelling of neurons, followed by shrinkage and eventual cell loss, may occur.

When axons are severely injured, cell bodies may swell and lose some of their internal components, a process known as *central chromatolysis* or *axonal reaction*. These changes can be seen a few days after injury and peak at 2 to 3 weeks. Unlike