28th Edition

CLINICAL NEUROANATOMY

Stephen G. Waxman

Mc Graw Hill Education

LANGE®

a LANGE medical book

Clinical Neuroanatomy

Twenty-Eighth Edition

Stephen G. Waxman, MD, PhD
Bridget Marie Flaherty Professor of Neurology, Neurobiology, & Pharmacology
Director, Center for Neuroscience & Regeneration Research
Yale University School of Medicine
New Haven, Connecticut

Mc Graw Hill Education

New York Chicago San Francisco Lisbon London Madrid Mexico City
Milan New Delhi San Juan Seoul Singapore Sydney Toronto

Clinical Neuroanatomy, Twenty-Eighth Edition

1 2 3 4 5 6 7 8 9 DSS 21 20 19 18 17 16

ISBN 978-0-07-184770-4
MHID 0-07-184770-7
ISSN 0892-1237

Notice

Medicine is an ever-changing science. As new research and clinical experience broaden our knowledge, changes in treatment and drug therapy are required. The author and the publisher of this work have checked with sources believed to be reliable in their efforts to provide information that is complete and generally in accord with the standards accepted at the time of publication. However, in view of the possibility of human error or changes in medical sciences, neither the author nor the publisher nor any other party who has been involved in the preparation or publication of this work warrants that the information contained herein is in every respect accurate or complete, and they disclaim all responsibility for any errors or omissions or for the results obtained from use of the information contained in this work. Readers are encouraged to confirm the information contained herein with other sources. For example and in particular, readers are advised to check the product information sheet included in the package of each drug they plan to administer to be certain that the information contained in this work is accurate and that changes have not been made in the recommended dose or in the contraindications for administration. This recommendation is of particular importance in connection with new or infrequently used drugs.

This book was set in Minion Pro by Aptara, Inc.
The editors were Michael Weitz and Brian Kearns.
The production supervisor was Richard Ruzycka.
Project management was provided by Amit Kashyap, Aptara, Inc.
The text designer was Elise Lansdon.
RR Donnelley Shenzhen was printer and binder.

International Edition ISBN 978-1-259-92161-2; MHID 1-259-92161-1.

For Jordanna and for Jonah

Key Features of this Edition!

- **300+ full-color illustrations**
- **Larger 8½ × 11 trim size** complements the new full-color art
- **Discussion of the latest advances in molecular and cellular biology** in the context of neuroanatomy
- **Coverage of the basic structure and function of the brain, spinal cord, and peripheral nerves** as well as clinical presentations of disease processes involving specific structures
- **Clinical Correlations and case studies** to help you interpret and remember essential neuroanatomic concepts in terms of function and clinical application

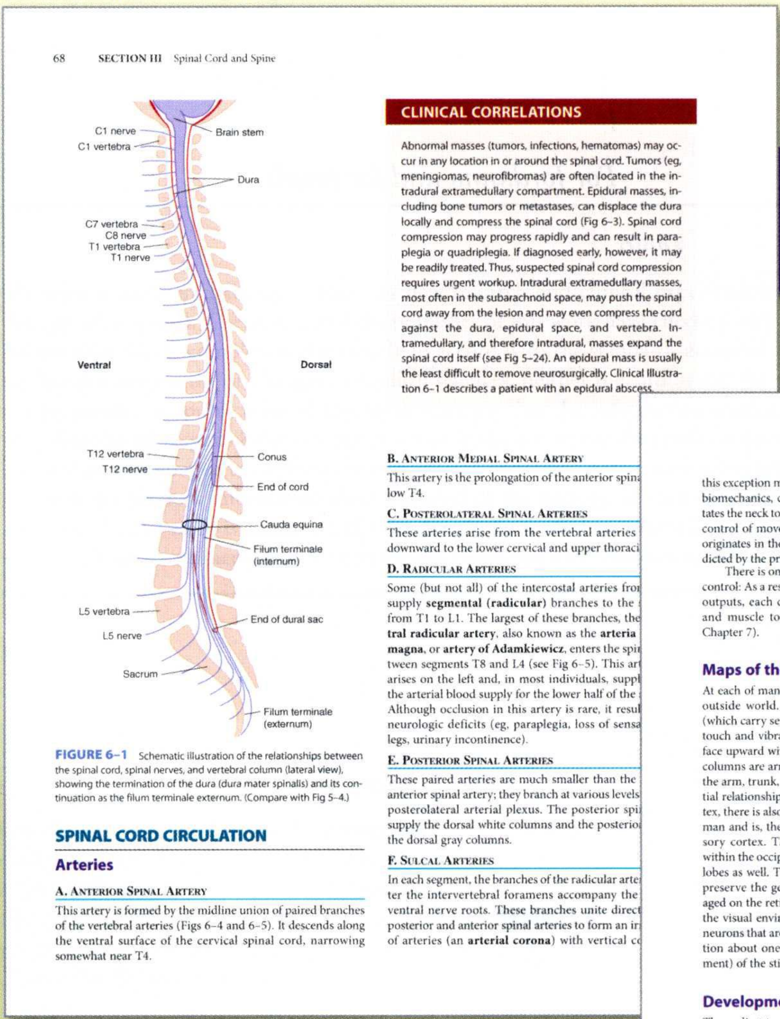

68 SECTION III Spinal Cord and Spine

FIGURE 6–1 Schematic illustration of the relationships between the spinal cord, spinal nerves, and vertebral column (lateral view), showing the termination of the dura (dura mater spinalis) and its continuation as the filum terminale externum. (Compare with Fig 5–4.)

SPINAL CORD CIRCULATION

Arteries

A. ANTERIOR SPINAL ARTERY

This artery is formed by the midline union of paired branches of the vertebral arteries (Figs 6–4 and 6–5). It descends along the ventral surface of the cervical spinal cord, narrowing somewhat near T4.

CLINICAL CORRELATIONS

Abnormal masses (tumors, infections, hematomas) may occur in any location in or around the spinal cord. Tumors (eg, meningiomas, neurofibromas) are often located in the intradural extramedullary compartment. Epidural masses, including bone tumors or metastases, can displace the dura locally and compress the spinal cord (Fig 6–3). Spinal cord compression may progress rapidly and can result in paraplegia or quadriplegia. If diagnosed early, however, it may be readily treated. Thus, suspected spinal cord compression requires urgent workup. Intradural extramedullary masses, most often in the subarachnoid space, may push the spinal cord away from the lesion and may even compress the cord against the dura, epidural space, and vertebra. Intramedullary, and therefore intradural, masses expand the spinal cord itself (see Fig 5–24). An epidural mass is usually the least difficult to remove neurosurgically. Clinical Illustration 6–1 describes a patient with an epidural abscess.

B. ANTERIOR MEDIAL SPINAL ARTERY

This artery is the prolongation of the anterior spina... low T4.

C. POSTEROLATERAL SPINAL ARTERIES

These arteries arise from the vertebral arteries ... downward to the lower cervical and upper thoraci...

D. RADICULAR ARTERIES

Some (but not all) of the intercostal arteries fro... supply **segmental (radicular)** branches to the ... from T1 to L1. The largest of these branches, the ... **tral radicular artery**, also known as the **arteria magna**, or **artery of Adamkiewicz**, enters the spi... tween segments T8 and L4 (see Fig 6–5). This ar... arises on the left and, in most individuals, suppl... the arterial blood supply for the lower half of the ... Although occlusion in this artery is rare, it resul... neurologic deficits (eg, paraplegia, loss of sensa... legs, urinary incontinence).

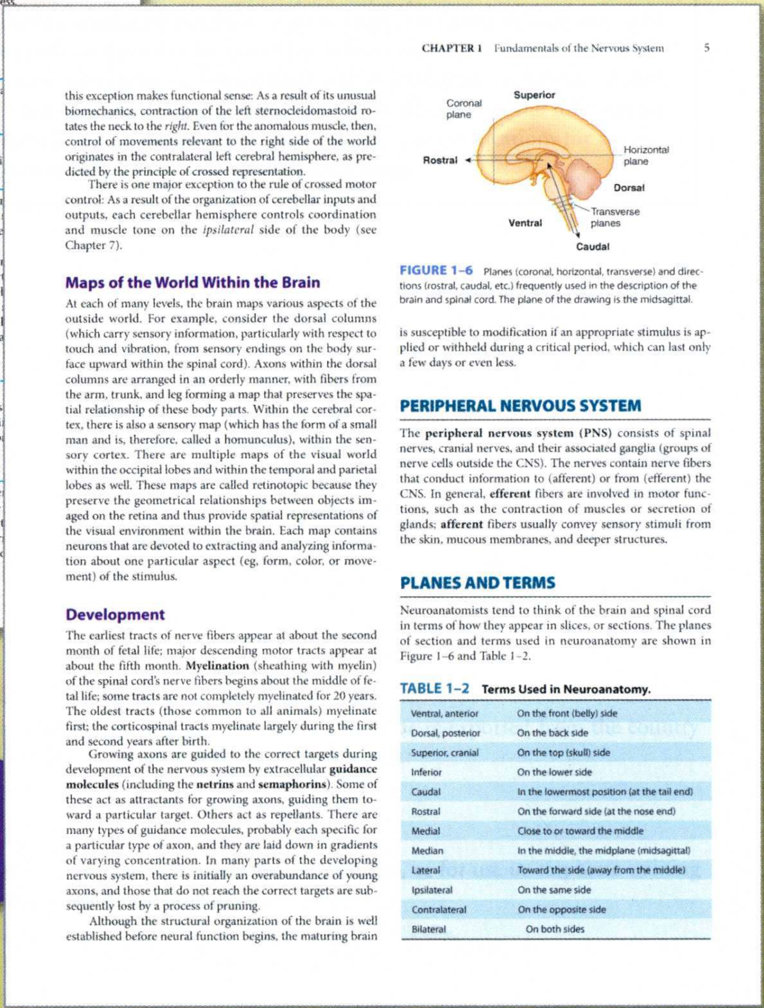
E. POSTERIOR SPINAL ARTERIES

These paired arteries are much smaller than the ... anterior spinal artery; they branch at various levels ... posterolateral arterial plexus. The posterior spi... supply the dorsal white columns and the posterio... the dorsal gray columns.

F. SULCAL ARTERIES

In each segment, the branches of the radicular arte... ter the intervertebral foramens accompany the ... ventral nerve roots. These branches unite direct... posterior and anterior spinal arteries to form an ir... of arteries (an **arterial corona**) with vertical c...

Clinical Correlations help you learn neuroanatomic concepts in the context of real world examples


CHAPTER 1 Fundamentals of the Nervous System 5

this exception makes functional sense: As a result of its unusual biomechanics, contraction of the left sternocleidomastoid rotates the neck to the *right*. Even for the anomalous muscle, then, control of movements relevant to the right side of the world originates in the contralateral left cerebral hemisphere, as predicted by the principle of crossed representation.

There is one major exception to the rule of crossed motor control: As a result of the organization of cerebellar inputs and outputs, each cerebellar hemisphere controls coordination and muscle tone on the *ipsilateral* side of the body (see Chapter 7).

Maps of the World Within the Brain

At each of many levels, the brain maps various aspects of the outside world. For example, consider the dorsal columns (which carry sensory information, particularly with respect to touch and vibration, from sensory endings on the body surface upward within the spinal cord). Axons within the dorsal columns are arranged in an orderly manner, with fibers from the arm, trunk, and leg forming a map that preserves the spatial relationship of these body parts. Within the cerebral cortex, there is also a sensory map (which has the form of a small man and is, therefore, called a homunculus), within the sensory cortex. There are multiple maps of the visual world within the occipital lobes and within the temporal and parietal lobes as well. These maps are called retinotopic because they preserve the geometrical relationships between objects imaged on the retina and thus provide spatial representations of the visual environment within the brain. Each map contains neurons that are devoted to extracting and analyzing information about one particular aspect (eg, form, color, or movement) of the stimulus.

Development

The earliest tracts of nerve fibers appear at about the second month of fetal life; major descending motor tracts appear at about the fifth month. **Myelination** (sheathing with myelin) of the spinal cord's nerve fibers begins about the middle of fetal life; some tracts are not completely myelinated for 20 years. The oldest tracts (those common to all animals) myelinate first; the corticospinal tracts myelinate largely during the first and second years after birth.

Growing axons are guided to the correct targets during development of the nervous system by extracellular **guidance molecules** (including the **netrins** and **semaphorins**). Some of these act as attractants for growing axons, guiding them toward a particular target. Others act as repellants. There are many types of guidance molecules, probably each specific for a particular type of axon, and they are laid down in gradients of varying concentration. In many parts of the developing nervous system, there is initially an overabundance of young axons, and those that do not reach the correct targets are subsequently lost by a process of pruning.

Although the structural organization of the brain is well established before neural function begins, the maturing brain

FIGURE 1–6 Planes (coronal, horizontal, transverse) and directions (rostral, caudal, etc.) frequently used in the description of the brain and spinal cord. The plane of the drawing is the midsagittal.

is susceptible to modification if an appropriate stimulus is applied or withheld during a critical period, which can last only a few days or even less.

PERIPHERAL NERVOUS SYSTEM

The **peripheral nervous system (PNS)** consists of spinal nerves, cranial nerves, and their associated ganglia (groups of nerve cells outside the CNS). The nerves contain nerve fibers that conduct information to (afferent) or from (efferent) the CNS. In general, **efferent** fibers are involved in motor functions, such as the contraction of muscles or secretion of glands; **afferent** fibers usually convey sensory stimuli from the skin, mucous membranes, and deeper structures.

PLANES AND TERMS

Neuroanatomists tend to think of the brain and spinal cord in terms of how they appear in slices, or sections. The planes of section and terms used in neuroanatomy are shown in Figure 1–6 and Table 1–2.

TABLE 1–2 Terms Used in Neuroanatomy.

Ventral, anterior	On the front (belly) side
Dorsal, posterior	On the back side
Superior, cranial	On the top (skull) side
Inferior	On the lower side
Caudal	In the lowermost position (at the tail end)
Rostral	On the forward side (at the nose end)
Medial	Close to or toward the middle
Median	In the middle, the midplane (midsagittal)
Lateral	Toward the side (away from the middle)
Ipsilateral	On the same side
Contralateral	On the opposite side
Bilateral	On both sides

Tables encapsulate important information

- **Summary listing** "Essentials for the clinical neuroanatomist" at end of each chapter
- **Numerous computed tomography (CT) and magnetic resonance images (MRIs)** of the normal brain and spinal cord; functional magnetic resonance images that provide a noninvasive window on brain function; and neuroimaging studies that illustrate common pathological entities that affect the nervous system, including stroke, intracerebral hemorrhage, and tumors of the brain and spinal cord
- **Introduction to Clinical Thinking** section explains how to use neuroanatomy as a basis for analyzing the disordered nervous sytem
- **Numerous tables** that make information clear and easy to remember
- **A complete practice exam** to test your knowledge

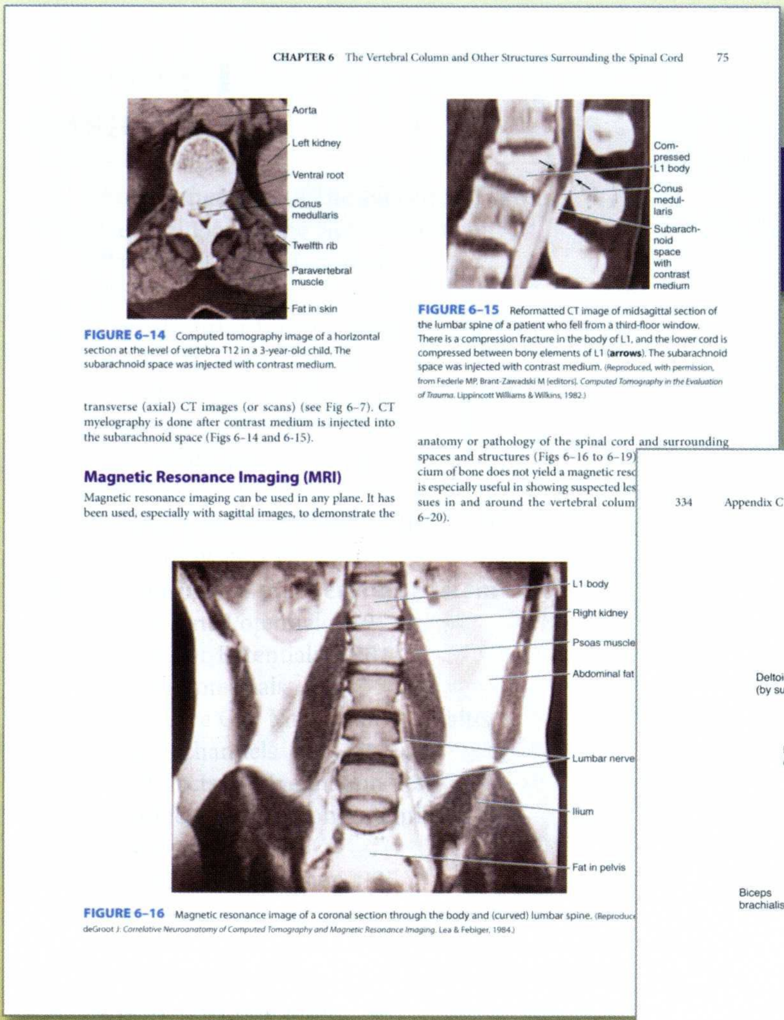

CHAPTER 6 The Vertebral Column and Other Structures Surrounding the Spinal Cord 75

FIGURE 6–14 Computed tomography image of a horizontal section at the level of vertebra T12 in a 3-year-old child. The subarachnoid space was injected with contrast medium.

FIGURE 6–15 Reformatted CT image of midsagittal section of the lumbar spine of a patient who fell from a third-floor window. There is a compression fracture in the body of L1, and the lower cord is compressed between bony elements of L1 (**arrows**). The subarachnoid space was injected with contrast medium. (Reproduced, with permission, from Federle MP, Brant-Zawadski M [editors]. *Computed Tomography in the Evaluation of Trauma*. Lippincott Williams & Wilkins, 1982.)

transverse (axial) CT images (or scans) (see Fig 6–7). CT myelography is done after contrast medium is injected into the subarachnoid space (Figs 6–14 and 6–15).

Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging can be used in any plane. It has been used, especially with sagittal images, to demonstrate the anatomy or pathology of the spinal cord and surrounding spaces and structures (Figs 6–16 to 6–19) cium of bone does not yield a magnetic reso is especially useful in showing suspected les sues in and around the vertebral colum 6–20).

FIGURE 6–16 Magnetic resonance image of a coronal section through the body and (curved) lumbar spine. (Reproduc deGroot J: *Correlative Neuroanatomy of Computed Tomography and Magnetic Resonance Imaging*. Lea & Febiger, 1984.)

Numerous CT and MRI images illustrate pathological entities

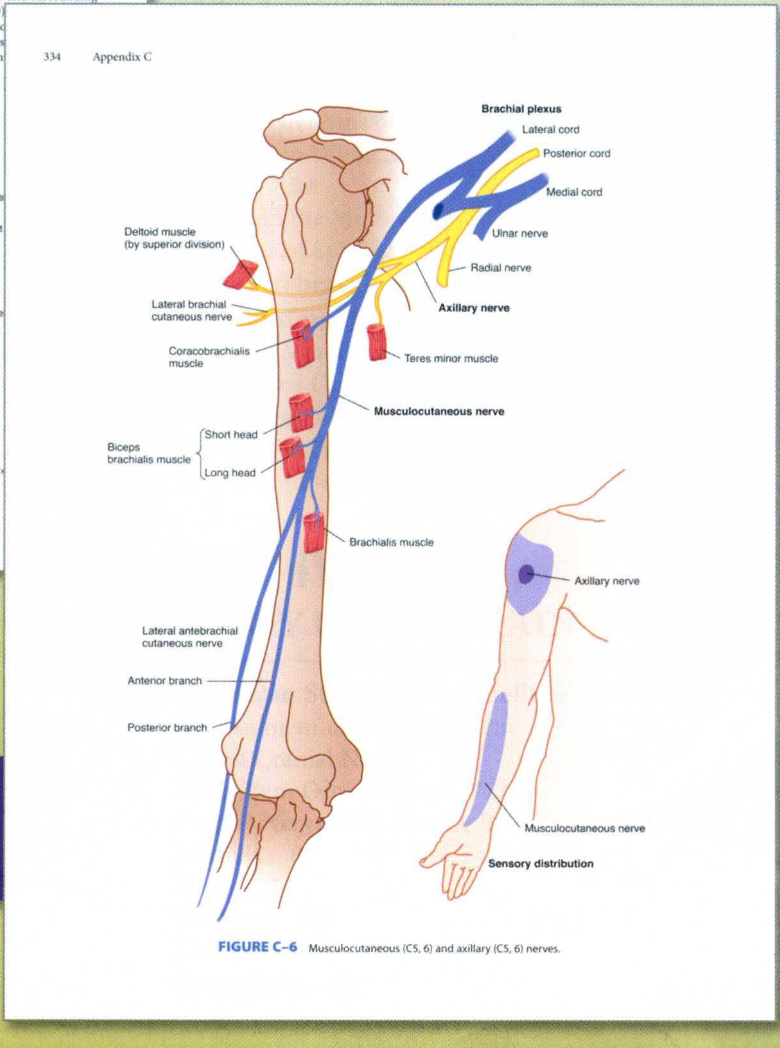

334 Appendix C

FIGURE C–6 Musculocutaneous (C5, 6) and axillary (C5, 6) nerves.

300+ full-color illustrations illuminate the text

Preface

No other organ system presents as fascinating an array of structures and mechanisms as the human brain and spinal cord. It is hard to think of any clinical field that does not encompass at least some aspect of the neurosciences, from molecular and cellular neurobiology through motor, sensory, and cognitive neuroscience, to human behavior and even social interactions. It is the brain, in fact, that makes us uniquely human. No surprise, then, that neuroscience has emerged as one of the most exciting fields of research and now occupies a central role as a substrate for clinical medicine.

The nervous system is unique in its exquisite nature. The nervous system contains more cell types than any other organ or organ system, and its constituent nerve cells—more than 100,000,000,000 of them—and an even larger number of supportive glial cells are arranged in a complex but orderly, and functionally crucial, way. Many disease processes affect, in a direct or indirect way, the nervous system. Thus, every clinician, and every basic scientist with an interest in clinical disease, needs an understanding of neuroanatomy. Stroke is the most frequent cause of death in most industrialized societies; mood disorders such as depression affect more than 1 person in 10; and clinical dysfunction of the nervous system occurs in 25% of patients in most general hospital settings at some time during their hospital stay. An understanding of neuroanatomy is crucial not only for neurologists, neurosurgeons, and psychiatrists but also for clinicians in all subspecialties, since patients of every stripe will present situations that require an understanding of the nervous system, its structure, and its function.

This new 28th edition has been designed to provide an accessible, easy-to-remember synopsis of neuroanatomy and its functional and clinical implications. A new section summarizes the most essential take-away lessons from each chapter. Since many of us learn and remember better when material is presented visually, this book is well illustrated not only with clinical material such as brain scans and pathological specimens but also with hundreds of diagrams and tables that are designed to be clear and memorable. The diagrams, which have been refined over 28 editions are uniquely explicative and clear, and the Appendices provide unique tools for the clinician. This book is not meant to supplant longer, comprehensive handbooks on neuroscience and neuroanatomy. On the contrary, it has been designed to provide a manageable and concise overview for busy medical students and residents, as well as trainees in health-related fields such as physical therapy; graduate students and postdoctoral fellows with an interest in neuroanatomy and its functional underpinnings; and clinicians in practice, for whom minutes are precious.

This book is unique in containing a section entitled "Introduction to Clinical Thinking," which introduces the reader, early in the text, to the logical processes involved in *using neuroanatomy as a basis for thinking about patients.* Since some trainees remember *patients* better than isolated facts, I have included discussions of clinical correlates and clinical illustrations that synthesize the most important characteristics of patients selected from an extensive clinical experience. Also included are illustrative clinical images including computer tomography (CT) and magnetic resonance imaging (MRI), both of normal brain and spinal cord, and of common clinical entities that trainees will likely encounter.

As with past editions, I owe a debt of gratitude to many colleagues and friends within the Department of Neurology at Yale Medical School and elsewhere. These colleagues and friends have helped to create an environment where learning is *fun*, a motif that I have woven into this book. I hope that readers will join me in finding that neuroanatomy, which provides much of the foundation for both neuroscience and clinical medicine, can be enjoyable, memorable, and easily learned.

Stephen G. Waxman, MD, PhD
New Haven, Connecticut

Contents

SECTION I BASIC PRINCIPLES

CHAPTER 1

Fundamentals of the Nervous System

More than any other organ, the nervous system makes human beings special. The human central nervous system (CNS) is the most complex and elegant computing device that exists. It receives and interprets an immense array of sensory information, controls a variety of simple and complex motor behaviors, and engages in deductive and inductive logic. The brain can make complex decisions, think creatively, and feel emotions. It can *generalize* and possesses an elegant ability to recognize that cannot be reproduced by even advanced computers. The human nervous system, for example, can immediately identify a familiar face regardless of the angle at which it is presented. It can carry out many of these demanding tasks in a nearly simultaneous manner.

The complexity of the nervous system's actions is reflected by a rich and complex structure—in a sense, the nervous system can be viewed as a complex and dynamic network of interlinked computers. Nevertheless, the anatomy of the nervous system *can* be readily understood. Since different parts of the brain and spinal cord subserve different functions, the astute clinician can often make relatively accurate predictions about the site(s) of dysfunction on the basis of the clinical history and careful neurological examination. Clinical neuroanatomy (i.e., the structure of the nervous system, considered in the context of disorders of the nervous system) can teach us important lessons about the structure and organization of the normal nervous system, and is essential for an understanding of disorders of the nervous system.

GENERAL PLAN OF THE NERVOUS SYSTEM

Main Divisions

A. Anatomy

The human nervous system is a complex of two subdivisions.

1. CNS**—**The CNS, comprising the brain and spinal cord, is enclosed in bone and wrapped in protective coverings (meninges) and fluid-filled spaces.

2. Peripheral nervous system (PNS)**—**The PNS is formed by the cranial and spinal nerves (Fig 1–1).

B. Physiology

Functionally, the nervous system is divided into two systems.

1. Somatic nervous system**—**This innervates the structures of the body wall (muscles, skin, and mucous membranes).

2. Autonomic (visceral) nervous system (ANS)**—**The ANS contains portions of the central and peripheral systems. It controls the activities of the smooth muscles and glands of the internal organs (viscera) and the blood vessels and returns sensory information to the brain.

Structural Units and Overall Organization

The central portion of the nervous system consists of the **brain** and the elongated **spinal cord** (Fig 1–2 and Table 1–1). The brain has a tiered structure and, from a gross point of view, can be subdivided into the cerebrum, the brain stem, and the cerebellum.

The most rostral part of the nervous system (cerebrum, or forebrain) is the most phylogenetically advanced and is responsible for the most complex functions (eg, cognition). The brain stem, medulla, and spinal cord serve less advanced, but essential, functions.

The **cerebrum (forebrain)** consists of the **telencephalon** and the **diencephalon**; the telencephalon includes the cerebral cortex (the most highly evolved part of the brain, sometimes called "gray matter"), subcortical white matter, and the basal ganglia, which are gray masses deep within the cerebral hemispheres. The **white matter** carries that name because, in a

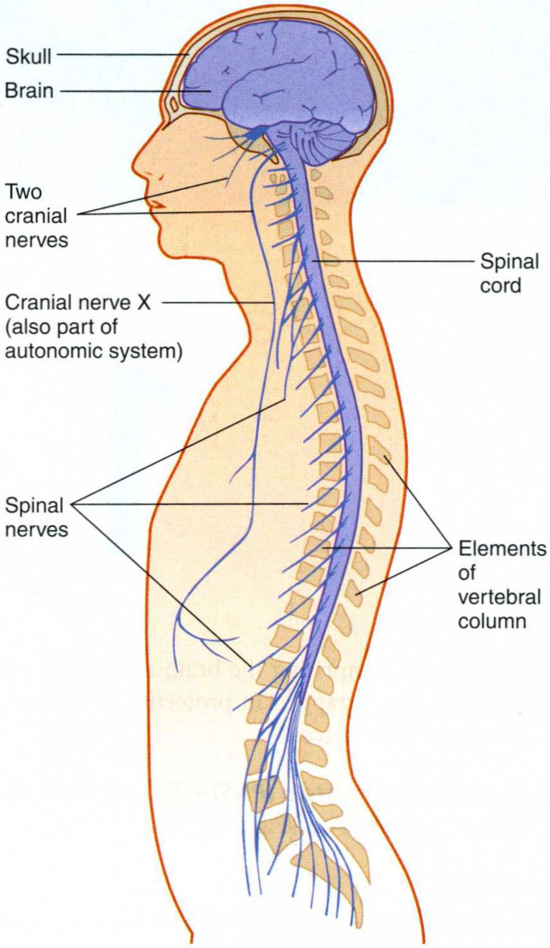


FIGURE 1–1 The structure of the central nervous system and the peripheral nervous system, showing the relationship between the central nervous system and its bony coverings.

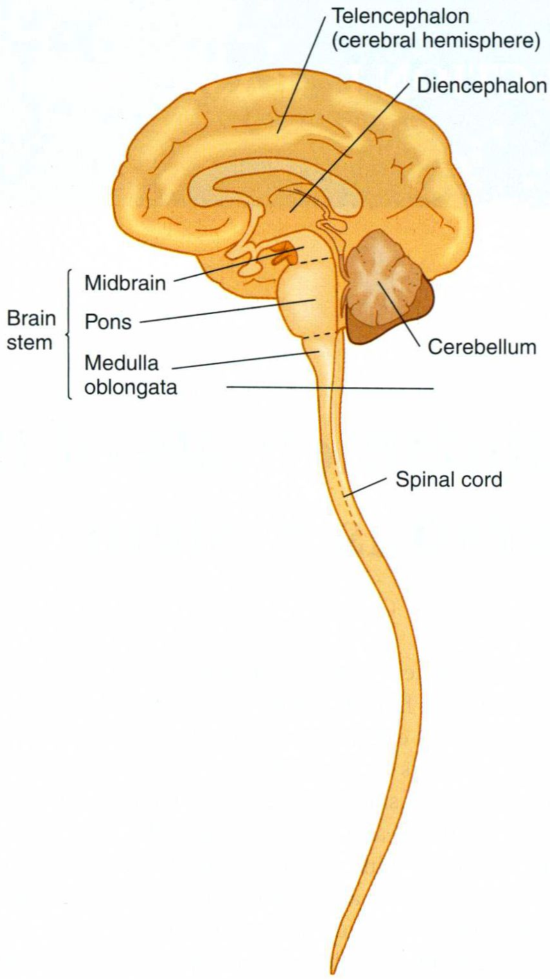


FIGURE 1–2 The two major divisions of the central nervous system, the brain, and the spinal cord, as seen in the midsagittal plane.

freshly sectioned brain, it has a glistening appearance as a result of its high lipid-rich myelin content; the white matter consists of myelinated fibers and does not contain neuronal cell bodies or synapses (Fig 1–3). The major subdivisions of the diencephalon are the thalamus and hypothalamus. The **brain stem** consists of the **midbrain (mesencephalon)**, **pons**, and **medulla oblongata**. The **cerebellum** includes the vermis and two lateral lobes. The brain, which is hollow, contains a system of spaces called **ventricles**; the spinal cord has a narrow central canal that is largely obliterated in adulthood. These spaces are filled with cerebrospinal fluid (CSF) (Figs 1–4 and 1–5; see also Chapter 11).

Functional Units

The brain, which accounts for about 2% of the body's weight, contains many billions (perhaps even a trillion) of neurons and glial cells (see Chapter 2). **Neurons**, or nerve cells, are specialized cells that receive and send signals to other cells through their extensions (nerve fibers, or **axons**). The information is processed and encoded in a sequence of electrical or chemical steps that occur, in most cases, very rapidly (in milliseconds). Many neurons have relatively large cell bodies and long axons that transmit impulses quickly over a considerable distance. Interneurons, on the other hand, have small cell bodies and short axons and transmit impulses locally. Nerve cells serving a common function, often with a common target, are frequently grouped together into **nuclei**. Nerve cells with common form, function, and connections that are grouped together outside the CNS are called **ganglia**.

Other cellular elements that support the activity of the neurons are the **glial cells**, of which there are several types. Glial cells within the brain and spinal cord outnumber neurons 10:1.

Computation in the Nervous System

Nerve cells convey signals to one another at **synapses** (see Chapters 2 and 3). Chemical transmitters are associated with the function of the synapse: excitation or inhibition.

TABLE 1–1 Major Divisions of the Central Nervous System.

Brain (en-cephalon)	Cerebrum (forebrain)	Telencephalon	Cerebral cortex
			Subcortical white matter
			Commissures
			Basal ganglia
		Diencephalon	Thalamus
			Hypothalamus
			Epithalamus
			Subthalamus
	Cerebellum	Cerebellar cortex	
		Cerebellar nuclei	
	Brain stem	Midbrain (mesencephalon)	
		Pons	
		Medulla oblongata	
Spinal cord	White matter	Dorsal columns	
		Lateral columns	
		Anterior columns	
	Gray matter		

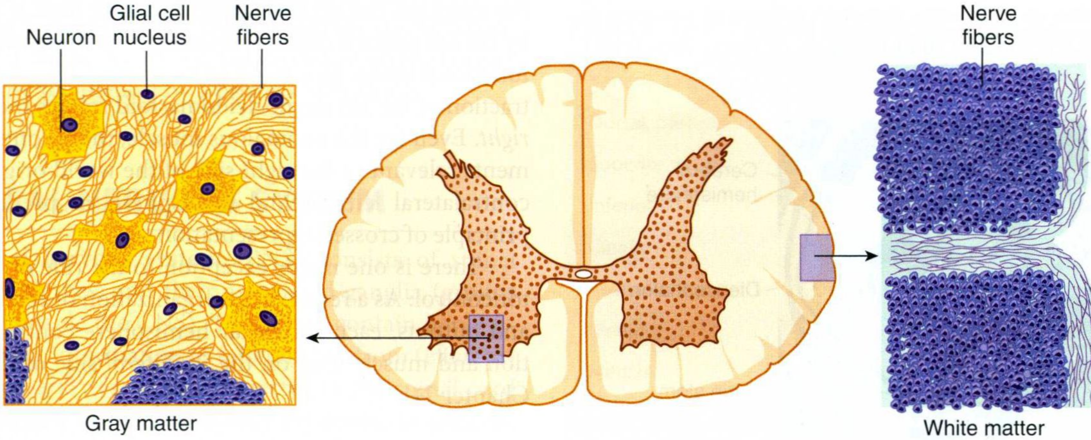


FIGURE 1–3 Cross section through the spinal cord, showing gray matter (which contains neuronal and glial cell bodies, axons, dendrites, and synapses) and white matter (which contains myelinated axons and associated glial cells). (Reproduced, with permission, from Junqueira LC, Carneiro J, Kelley RO: *Basic Histology: Text & Atlas*. 11th ed. McGraw-Hill, 2005.)

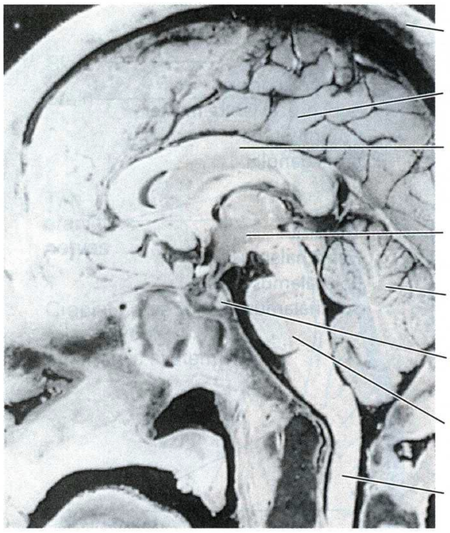


FIGURE 1–4 Photograph of a midsagittal section through the head and upper neck, showing the major divisions of the central nervous system. (Reproduced, with permission, from deGroot J: *Correlative Neuroanatomy of Computed Tomography and Magnetic Resonance Imagery*. 21st ed. Appleton & Lange, 1991.)

A neuron may receive thousands of synapses, which bring it information from many sources. By integrating the excitatory and inhibitory inputs from these diverse sources and producing its own message, each neuron acts as an information-processing device.

Some very primitive behaviors (eg, the reflex and unconscious contraction of the muscles around the knee in response to percussion of the patellar tendon) are mediated by a simple **monosynaptic** chain of two neurons connected by a **synapse**. More complex behaviors, however, require larger **polysynaptic** neural circuits in which many neurons, interconnected by synapses, are involved.

Tracts and Commissures

The connections, or pathways, between groups of neurons in the CNS are in the form of fiber bundles, or tracts (**fasciculi**).

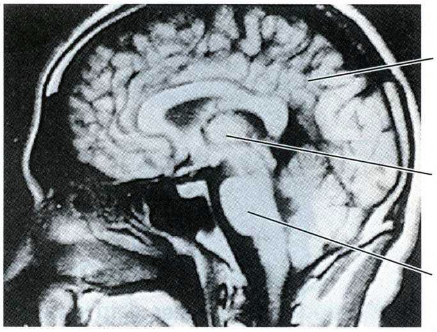


FIGURE 1–5 Magnetic resonance image of a midsagittal section through the head (short time sequence; see Chapter 22). Compare with Figure 1–2.

Aggregates of tracts, as seen in the spinal cord, are referred to as **columns (funiculi)**. Tracts may descend (eg, from the cerebrum to the brain stem or spinal cord) or ascend (eg, from the spinal cord to the cerebrum). These pathways are vertical connections that in their course may cross (**decussate**) from one side of the CNS to the other. Horizontal (lateral) connections are called **commissures**.

Symmetry of the Nervous System

A general theme in neuroanatomy is that, to a first approximation, the nervous system is constructed with **bilateral symmetry**. This is most apparent in the cerebrum and cerebellum, which are organized into right and left **hemispheres**. Some higher cortical functions such as language are represented more strongly in one hemisphere than in the other, but to gross inspection, the hemispheres have a similar structure. Even in more caudal structures, such as the brain stem and spinal cord, which are not organized into hemispheres, there is bilateral symmetry.

Crossed Representation

Another general theme in the construction of the nervous system is **decussation and crossed representation**: Neuroanatomists use the term "decussation" to describe the crossing of a fiber tract from one side of the nervous system (right or left) to the other. The right side of the brain receives information about, and controls motor function pertaining to, the left side of the world and vice versa. Visual information about the right side of the world is processed in the visual cortex on the left. Similarly, sensation of touch, sensation of heat or cold, and joint position sense from the body's right side are processed in the somatosensory cortex in the left cerebral hemisphere. In terms of motor control, the motor cortex in the left cerebral hemisphere controls body movements that pertain to the right side of the external world. This includes, of course, control of the muscles of the right arm and leg, such as the biceps, triceps, hand muscles, and gastrocnemius. There are occasional exceptions to this pattern of "crossed innervation": For example, the *left* sternocleidomastoid muscle is controlled by the *left* cerebral cortex. However, even this exception makes functional sense: As a result of its unusual biomechanics, contraction of the left sternocleidomastoid rotates the neck to the *right*. Even for the anomalous muscle, then, control of movements relevant to the right side of the world originates in the contralateral left cerebral hemisphere, as predicted by the principle of crossed representation.

There is one major exception to the rule of crossed motor control: As a result of the organization of cerebellar inputs and outputs, each cerebellar hemisphere controls coordination and muscle tone on the *ipsilateral* side of the body (see Chapter 7).

Maps of the World Within the Brain

At each of many levels, the brain maps (contain a representation of) various aspects of the outside world. For example, consider the dorsal columns (which carry sensory information, particularly with respect to touch and vibration, from sensory endings on the body surface upward within the spinal cord). Axons within the dorsal columns are arranged in an orderly manner, with fibers from the arm, trunk, and leg forming a map that preserves the spatial relationship of these body parts. Within the cerebral cortex, there is also a sensory map (which has the form of a small man and is, therefore, called a homunculus) within the sensory cortex. There are multiple maps of the visual world within the occipital lobes and within the temporal and parietal lobes. These maps are called retinotopic because they preserve the geometrical relationships between objects imaged on the retina and thus provide spatial representations of the visual environment within the brain.

The existence of these maps within the brain is important to clinicians. Focal lesions of the brain may interfere with function of only part of the map, thus producing signs and symptoms (such as loss of vision in only part of the visual world) that can help to localize the lesions.

Development

The earliest tracts of nerve fibers appear at about the second month of fetal life; major descending motor tracts appear at about the fifth month. **Myelination** (sheathing with myelin) of the spinal cord's nerve fibers begins about the middle of fetal life; some tracts are not completely myelinated for 20 years. The oldest tracts (those common to all animals) myelinate first; the corticospinal tracts myelinate largely during the first and second years after birth.

Growing axons are guided to the correct targets during development of the nervous system by extracellular **guidance molecules** (including the **netrins** and **semaphorins**). Some of these act as attractants for growing axons, guiding them toward a particular target. Others act as repellants. There are many types of guidance molecules, probably each specific for a particular type of axon, and they are laid down in gradients of varying concentration. In many parts of the developing nervous system, there is initially an overabundance of young axons, and those that do not reach the correct targets are subsequently lost by a process of pruning.

PERIPHERAL NERVOUS SYSTEM

The **peripheral nervous system (PNS)** consists of spinal nerves, cranial nerves, and their associated ganglia (groups of nerve cells outside the CNS). The nerves contain nerve fibers that conduct information to (afferent) or from (efferent) the CNS. Peripheral nerves are connected to the spinal cord via **dorsal** (sensory) and **ventral** (motor) **roots**. In general, **efferent** fibers are involved in motor functions, such as the contraction of muscles or secretion of glands; **afferent** fibers usually convey sensory stimuli from the skin, mucous membranes, and deeper structures.

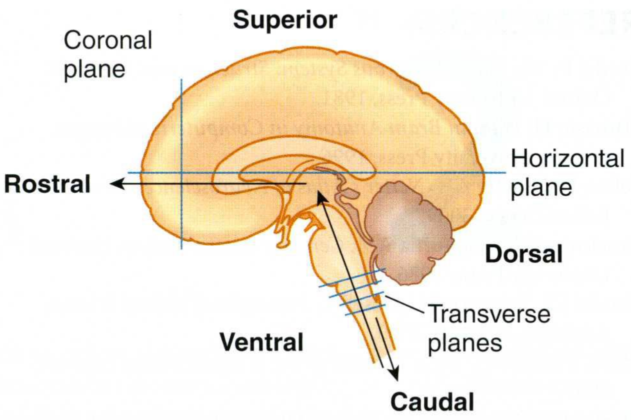


FIGURE 1–6 Planes (coronal, horizontal, transverse) and directions (rostral, caudal, etc.) frequently used in the description of the brain and spinal cord. The plane of the drawing is the midsagittal.

Individual nerves can be injured by compression or physical trauma, resulting in a motor and sensory deficit in the part of the body innervated by that particular nerve. Some systemic illnesses such as diabetes, or exposure to toxins or drugs that are neurotoxic can injure nerves throughout the body, producing a peripheral polyneuropathy; in these cases the longest nerves (those innervating the feet) are affected first.

Appendices B and C show the pattern of innervation of the body for each spinal root and for each peripheral nerve.

PLANES AND TERMS

Neuroanatomists tend to think of the brain and spinal cord in terms of how they appear in slices, or sections. The planes of section and terms used in neuroanatomy are shown in Figure 1–6 and Table 1–2.

TABLE 1–2 Terms Used in Neuroanatomy.

Ventral, anterior	On the front (belly) side
Dorsal, posterior	On the back side
Superior, cranial	On the top (skull) side
Inferior	On the lower side
Caudal	In the lowermost position (at the tail end)
Rostral	On the forward side (at the nose end)
Medial	Close to or toward the middle
Median	In the middle, the midplane (midsagittal)
Lateral	Toward the side (away from the middle)
Ipsilateral	On the same side
Contralateral	On the opposite side
Bilateral	On both sides

REFERENCES

Brodal P: *The Central Nervous System: Structure and Function.* Oxford University Press, 1981.

Damasio H: *Human Brain Anatomy in Computerized Images.* Oxford University Press, 1996.

Felten DL, Shetty AN. *Netter's Atlas of Neuroscience.* 2n ed. Netter Basic Science, 2009.

Geschwind N, Galaburda AM: *Cerebral Lateralization.* Harvard University Press, 1986.

Kandel ER, Schwartz JN, Jessell T: *Principles of Neural Science.* Appleton & Lange, 2000.

Mai J, Paxinos G, Voss T: *Atlas of the Human Brain.* Elsevier, 2007.

Martin JH: *Neuroanatomy Text & Atlas.* 2nd ed. Appleton & Lange, 1996.

Mazziotta J, Toga A, Frackowiak R: *Brain Mapping: The Disorders.* Elsevier, 2000.

Netter FH: *Nervous System (Atlas and Annotations).* Vol 1: The CIBA Collection of Medical Illustrations. CIBA Pharmaceutical Company, 1983.

Nicholls JG, Martin AR, Wallace BG: *From Neuron to Brain.* 3rd ed. Sinauer, 1992.

Parent A, Carpenter MC: *Carpenter's Human Neuroanatomy.* 8th ed. Williams & Wilkins, 1996.

Shepherd GM: *Synaptic Organization of the Brain.* 4th ed. Oxford University Press, 1997.

Toga A, Mazziotta J: *Brain Mapping: The Systems.* Elsevier, 2000.

BOX 1–1 Essentials for the Clinical Neuroanatomist

After reading and digesting this chapter, you should know and understand:

- The main divisions of the nervous system
- The functional (cellular) units of the nervous system; different functions of neurons and glial cells
- Principles of symmetry and crossed representation within the brain
- The principle of decussations
- The principle of maps within the brain
- The meaning of "afferent" versus "efferent"
- The planes used by neuroanatomists and neuroimagers: coronal, horizontal, transverse (Fig. 1-6)
- Terminology, including "rostral" and "caudal," "dorsal" and "ventral"; see Table 1-2

Development and Cellular Constituents of the Nervous System

CHAPTER 2

CELLULAR ASPECTS OF NEURAL DEVELOPMENT

Early in the development of the nervous system, a hollow tube of ectodermal neural tissue forms at the embryo's dorsal midline. The cellular elements of the tube appear undifferentiated at first, but they later develop into various types of neurons and supporting glial cells.

Layers of the Neural Tube

The embryonic neural tube has three layers (Fig 2–1): the **ventricular zone**, later called the **ependyma**, around the lumen (central canal) of the tube; the **intermediate zone**, which is formed by the dividing cells of the ventricular zone (including the earliest radial glial cell type) and stretches between the ventricular surface and the outer (pial) layer; and the external **marginal zone**, which is formed later by processes of the nerve cells in the intermediate zone (Fig 2–1B).

The intermediate zone, or mantle layer, increases in cellularity and becomes gray matter. The nerve cell processes in the marginal zone, as well as other cell processes, become white matter when myelinated.

Differentiation and Migration

The largest neurons, which are mostly motor neurons, differentiate first. Sensory and small neurons, and most of the glial cells, appear later, up to the time of birth. Newly formed neurons may migrate extensively through regions of previously formed neurons. When glial cells appear, they can act as a framework that guides growing neurons to the correct target areas. Because the axonal process of a neuron may begin growing toward its target during migration, nerve processes in the adult brain are often curved rather than straight.

NEURONS

Neurons vary in size and complexity. Motor neurons are usually larger than sensory neurons. Nerve cells with long processes (eg, dorsal root ganglion cells) are larger than those with short processes (Figs 2–2 and 2–3).

Some neurons project from the cerebral cortex to the lower spinal cord, a distance of 4 ft or more in adults; others have very short processes, reaching, for example, only from cell to cell in the cerebral cortex. These small neurons, with short axons that terminate locally, are called **interneurons**.

Extending from the nerve cell body are usually a number of processes called the **axon** and **dendrites**. Most neurons give rise to a single axon (which branches along its course) and to many dendrites (which also divide and subdivide, like the branches of a tree). The receptive part of the neuron is the **dendritic zone** (see Dendrites section). The conducting (propagating or transmitting) part is the axon, which may have one or more collateral branches. The downstream end of the axon is called the **synaptic terminal**, or **arborization**. The neuron's cell body is called the **soma**, or **perikaryon**.

Cell Bodies

The cell body is the metabolic and genetic center of a neuron (see Fig 2–3). Although its size varies greatly in different neuron types, the cell body makes up only a small part of the neuron's total volume.

The cell body and dendrites constitute the receptive pole of the neuron. Synapses from other cells or glial processes tend to cover the surface of a cell body (Fig 2–4).

Dendrites

Dendrites are branches of neurons that extend from the cell body; they receive incoming synaptic information and thus, together with the cell body, provide the receptive pole of the neuron. Most neurons have many dendrites (see Figs 2–2, 2–3, and 2–5). Because most dendrites are long and thin, they act as resistors, isolating electrical events, such as postsynaptic potentials, from one another (see Chapter 3). The branching pattern of the dendrites can be complex and determines how the neuron integrates synaptic inputs from various sources. Some dendrites give rise to **dendritic spines**, which are small mushroom-shaped projections that act as fine dendritic branches and receive synaptic inputs (Fig 2–5). Dendritic spines are currently of great interest to researchers. The shape of a spine regulates the strength of the synaptic signal that it receives. A synapse onto the tip of a spine with a thin "neck" will have a smaller influence than a synapse onto a spine with a thick neck. Dendritic spines are dynamic, and their shape can change. Changes in dendritic spine shape can strengthen synaptic connections so as to contribute to learning and memory. Maladaptive changes in spines may contribute to altered function of the nervous system after injury.