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Neuroanatomy for the Neuroscientist

Third Edition

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*To Elliott M. Marcus, colleague,
friend, collaborator, superb neurologist,
and developer of neurosciences at Tufts
Medical School*

*To our wives: Avis Jacobson, Nuran Turksoy,
and Tricia Pugsley*

*To our children: Arthur Jacobson,
Robin Seidman, Erin Marcus, Robert Letson,
Gerard Pugsley, David Pugsley,
and Mark Pugsley*

*To our grandchildren: Ross Jacobson,
Jase Jacobson, Zachary Letson,
and Amelia Letson*

To our teachers, students, and colleagues

Preface

Elliott M. Marcus, M.D., was a friend and colleague for over 40 years, and he was the father of neurosciences at the Tufts University School of Medicine, and with his passing in 2011, we lost a dear friend, colleague, dynamic teacher, and an outstanding neurologist. This textbook is dedicated to his memory.

The purpose of this textbook is to enable a neuroscientist to discuss the structure and functions of the brain at a level appropriate for students at many levels of study including undergraduate, graduate, dental, or medical school level. It is truer in neurology than in any other system of medicine that a firm knowledge of basic science material, that is, the anatomy, physiology, and pathology of the nervous system, enables one to readily arrive at the diagnosis of where the disease process is located and to apply their knowledge at solving problems in clinical situations. The authors have a long experience in teaching neuroscience courses at the first- or second-year level to medical and dental students and to residents in which clinical information and clinical problem-solving are integral to the course.

Dr. Jacobson has taught neuroanatomy and gross anatomy for many years to medical and dental students at the Tufts University School of Medicine and an upper-level biology course on the central nervous system to undergraduates at Tufts University in Medford, MA, utilizing many of Dr. Marcus' cases to engage students. He also has used several movies on the brain developed in Hollywood to further involve students.

Dr. Marcus practiced neurology for 40 years, and he developed a case history of problem-solving sessions in the recent book *Integrated Neurosciences* by E.M. Marcus, S. Jacobson, and T. Sabin (Oxford University Press, 2014), and he also conducted a problem-solving seminar in which all medical students at the University of Massachusetts participate during their clinical neurology clerkship rotation. This provides students an opportunity to refresh their problem-solving skills and to review and update that basic science material essential for clinical neurology.

Dr. Pugsley is a senior neurosurgeon with extensive clinical and teaching experience. He trained in neurosurgery at the Tufts University School of Medicine. He observed that the inclusion of case history materials reinforces the basic science subject matter learned by markedly increasing the interest of students in both basic and clinical science material. He has added many new cases and a neurosurgeon's prospective to disease.

In this third edition, decisions had to be made so that the size of the textbook remained within reasonable limits. Throughout this book, we have utilized clinical illustration and integrated the anatomical, neurological, and neurosurgery managed in most of today's neuroscience courses, and we have responded to many of the very worthwhile suggestions from our colleagues. The book contains the core topics concerned with the central nervous system and all chapters have been updated. We have divided this edition into five parts: (I) Introduction to the Central Nervous System (Chaps. 1–10); (II) The Systems (Chaps. 11–17); (III) Neuropathology, (Chap. 18) Vascular Diseases and (Chap. 19) Nonvascular Diseases; (IV) The Nonnervous Elements, (Chap. 20) Meninges, Blood Supply, Ventricular System, (Chap. 21) General Case Histories, Problem-Solving, and (Chap. 22) Movies on the Brain; and (V) Descriptive Atlas of the Brain and Spinal Cord (Chap. 23).

We have added in several chapters, in Chap. 19, representative cases of trauma and infectious diseases within the CNS to aid students in understanding disease processes with the central nervous system and, in Chap. 20, the meninges, blood supply, and ventricular system. We have included an atlas at the end of the spinal cord (Chap. 3), brain stem (Chap. 6), and diencephalon chapters (Chap. 8). We have maintained the atlas chapter 23 and 24 with Chapter 23 Descriptive Atlas of Gross Brain and Chapter 24-Descriptive Atlas –Myelin stained sections.

In Chap. 22, Movies on the Brain, we have added in the film on Concussion which is an important discussion of the effects of contact sports. We have also used several of these movies as an adjunct to our teaching; (1) Young Frankenstein directed by Mel Brooks has a wonderful scene introducing the CNS and (2) Little Shop of Horrors directed by Frank Oz features Steve Martin as a dentist, and this is a great introduction to the trigeminal nerve). There are many movies in the science fiction genre that are also useful for discussion, and Star Trek and its many episodes and its medical manual are at the top of our list!

A number of other topics including cell biology, cell physiology, embryology, gross anatomy, nerve, and muscle are usually covered in other courses, and the student should examine these topics in those courses. The anatomy of the peripheral nervous system and autonomic nervous system has been touched on briefly here but should be reviewed in one of the standard gross anatomy texts.

Most of the case histories utilized in the chapters have been drawn from the files of Drs. Marcus and Pugsley. For a number of the cases, our associates at the Geisinger Medical Center in Danville, PA, Tufts Medical Center, St. Vincent Hospital, Fallon Clinic, and the University of Massachusetts School of Medicine either requested our opinion or brought a given case to our attention and provided information from their case files. These individual neurologists and neurosurgeons are identified in the specific case histories. We are also indebted to the many referring physicians of those institutions. Medical house officers at St Vincent Hospital presented some of the cases to Dr. Marcus during morning report. In particular, our thanks are due to our associates in Worcester: Drs. Bernard Stone, Alex Danylevich, Robin Davidson, Harold Wilkinson, and Gerry McGillicuddy. Drs. Sandra Horowitz, Tom Mullins, Steve Donhowe, Martha Fehr, and Carl Rosenberg provided clinical information from their files for some of the case histories. Our associates at the New England Medical Center Drs. John Sullivan, Sam Brendler, Peter Carney, John Hills, Huntington Porter, Thomas Sabin, Bertram Selverstone, Thomas Twitchell, C. W. Watson, and Robert Yuan likewise provided some of the clinical material. Dr. Milton Weiner at St Vincent Hospital was particularly helpful in providing many of the modern neuroradiological images. Dr. Sam Wolpert and Dr. Bertram Selverstone provided this material for the earlier version of the text. Dr. Val Runge from the Imaging Center at Texas A&M provided the normal MRIs. Dr. Anja Bergman (left-handed) had the patience to be our normal case, and the images from her brain form the normal MRIs in basic science chapters and atlas. Dr. Tom Smith and his associates in pathology provided much of the recent neuropathological material. Drs. John Hills and Jose Segarra provided access to neuropathological material for the earlier version of the text. Drs. Sandra Horowitz and David Chad provided critic of particular chapters.

Dr. Sarah B. Cairo, M.D., M.P.H., while still a medical student at Tufts Medical School developed the illustrated drawings that were used throughout the second edition of this book, and they will be used in this edition to illustrate the retina, pathways, levels of the spinal cord, levels of the brain stem, and levels of the thalamus.

Dr. Samuel Giles, MD, while a student at Tufts University School of Medicine, developed the Malaria and HIV/AIDS cases. He has continued to help us while he is training in Neurology at the University of Florida in Jacksonville.

Dr. Mary Gauthier Delaplane while a medical student at Boston University School of Medicine provided anatomical drawings illustrating the cranial nerves and the neuroembryology. Anne Que, Paul Ning, Tiffany Mellott, Elizabeth Haskins, and Tal Delman aided Dr. Delaplane. Dr. Marc Bard provided drawings for an earlier text, *An Introduction to the Neurosciences*, 1972, while a student at the Tufts University School of Medicine, and we have continued to utilize or have modified some of these illustrations. We have also borrowed with permission from other published illustrations. We have attempted to contact these original sources for continued permissions. We will acknowledge subsequently any sources that have been inadvertently overlooked. In many of the clinical chapters, various medications are recorded. Before utilizing these medications, the reader should check dosage and indications with other sources.

It is with great pleasure we extend our thanks to our publishers and particularly our editor Simina Calin for all her help. Special thanks to Michael J. Lukus, PA-C; Steven Toms, M.D.; and Michel Lacroix, M.D., for the advice and support in this endeavor. Any faults or errors are those of the authors, and we would therefore appreciate any suggestions or comments from our colleagues.

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Contents

Part I Introduction to the Central Nervous System

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Introduction to the Central Nervous System

Chapter 1
Introduction to the Central Nervous System

Abstract The brain and spinal cord form the central nervous system. The brain is the part of the central nervous system that is housed in the cranium/skull. It consists of the brain stem, diencephalon, cerebellum, and cerebrum. At the foramen magnum, the highest cervical segment of the spinal cord is continuous with the lowest level of the medulla of the brain stem. The spinal nerves from the sacral, lumbar, thoracic, and cervical levels of the spinal cord form the lower part of the peripheral nervous system and record general sensations of pain, temperature touch, and pressure. The 12 cranial nerves attached to the brain form the upper part of the peripheral nervous system and record general sensations of pain, temperature touch, and pressure, but in addition we now find the presence of the special senses of smell, vision, hearing, balance, and taste. The blood supply to the brain originates from the first major arterial branches from the heart insuring that over 20% of the entire supply of oxygenated blood flows directly into the brain.

Keywords Neuron • Glia • Spinal cord • Brain • Brain stem • Cerebellum • Diencephalon • Basal ganglia • Cerebrum • Lobes of the cerebrum • Cases

Homo sapiens evolved into the modern human in southern Africa for millions of years. About 100,000–60,000 years ago, they struck out and spread initially along the continental coast throughout Africa, into the Middle East, Europe, the Indian subcontinent, and the rest of Asia and finally crossed the land bridge from Asia into North America and then down into South America (the Out of Africa theory). The evidence for this comes partly from dating bones to specific periods, but also from genetics. As you move further away from Africa, across Asia, and then the Americas, the genetic diversity of indigenous populations drops. This implies that the source of these populations was in Africa and gradually lost diversity as it expanded.

Human beings enter the world naked but equipped with a nervous system that, with experience, is ready to function in almost any environment.

One word summarizes the function of the nervous system: "reaction." The central nervous system (brain and spinal cord) monitors and controls the entire body by its peripheral divisions, which are distributed to all the muscles, organs, and tissues. The brain has an advantageous site in the head and above the neck, which can move in about a 140° arc. Close to the brain are all of the specialized sense organs, which permit us to see, smell, taste, and hear our world. The central nervous system is protected by fluid-filled membranes, the meninges, and surrounded by the bony skull and vertebrae.

S. Jacobson et al., *Neuroanatomy for the Neuroscientist*,
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1.1 The Neuron

The basic conducting element in the nervous system is the nerve cell, or neuron (Fig. 1.1). A neuron has a cell body, dendrite, and axon. The cell body contains many of the organelles vital to maintain the cell structure and function, including the nucleus and nucleolus, and is considered the tropic center of the nerve cell. The dendrites extend from the cell body and increase the receptive surface of the neuron. The axon leaves the cell body and connects to other cells. Axons are covered by a lipoproteinaceous membrane called *myelin* that insulates the axons from the fluids in the central nervous system. The site of contact between the axon of one nerve cell and the dendrites and cell body of another neuron is the *synapse* (see Chap. 2). The cells in the nervous system are classified based on their shapes: unipolar, bipolar, and multipolar (Fig. 1.1; Table 1.1). In the central nervous system, the nerve cells are supported by glia and blood vessels; in the peripheral nervous system, they are supported by satellite cells, fibroblasts, Schwann cells, and blood vessels.

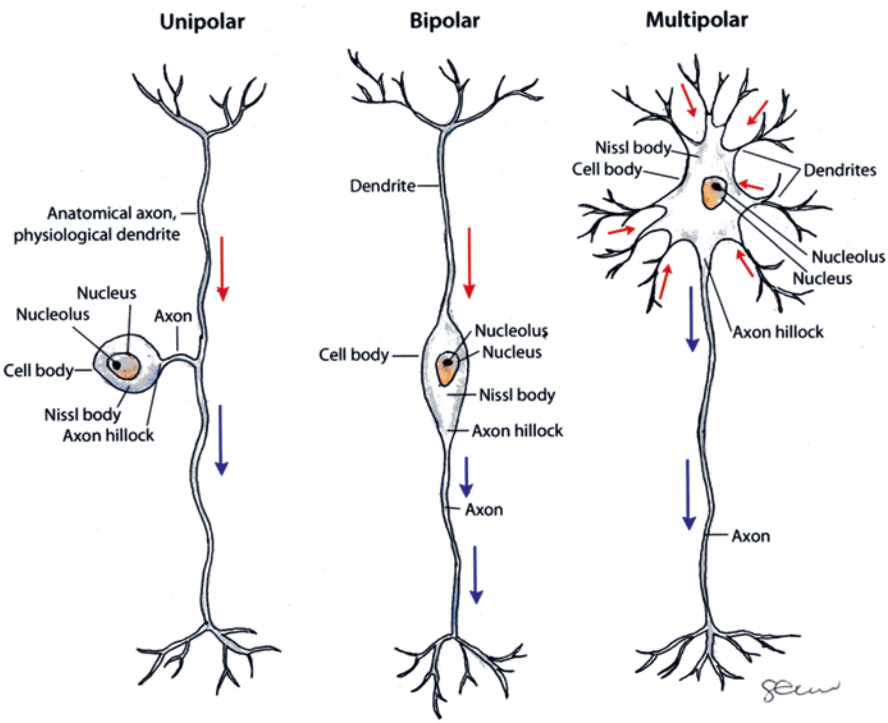


Fig. 1.1 Types of neurons in the central nervous system. The cells in the nervous system are classified based on their shapes: unipolar, bipolar, and multipolar. The input (*red*) reaches the dendrites of each cell and is then transported (*blue*) into the axon where it connects to the next neuron via a synaptic interruption

Table 1.1 Types of neurons in the nervous system

Neuronal type	% of neurons	Location
Unipolar 0.05	0.5	– Dorsal root ganglia of the spinal cord
		– Cranial nerve ganglia of the brain stem
		– Mesencephalic nucleus of CN V in the midbrain
Bipolar	0.05	Retina, inner ear, taste buds
Multipolar:		
– Peripheral	– 0.1	– Autonomic ganglia
– Central	– 99.8	– Brain and spinal cord

There are three basic categories of neurons:

1. Receptors. These neurons bring the information into the CNS, and these cells form either the ganglia of the spinal dorsal roots (at spinal cord levels C1–S5) and ganglia of the cranial nerves which have general sensory functions (CNs V, VII, IX, and X) or the ganglion cells associated with the special senses of olfaction (CN I), vision (CN II), hearing and balance (CN VIII), and taste (CNs VII, IX, and X).

   Ganglia. *Sensory ganglia* are found outside the central nervous system and contain the first-order neurons in the sensory systems, and they are the dorsal root ganglia on the 32 segments of the spinal cord and the sensory ganglia on cranial nerves, V, VII, VIII, IX, and X. They also form the primary cell bodies in the special senses associated with CN I (olfaction); II (vision); VII, IX, and X (taste); and VIII (hearing and balance).

   Motor/autonomic ganglia are found throughout the body, and they are either sympathetic or parasympathetic. The sympathetic ganglia originate from thoracolumbar levels T1–L2, while the parasympathetic ganglia originate from cranial nerves III, VII, IX, and X, which control many glands, smooth muscles, and cardiac muscles.

   The sympathetic ganglia (thoracolumbar locations) are located in paravertebral chains alongside the vertebrae at T1–L2.

   The parasympathetic ganglia (craniosacral – CN – III, VII, IX, and X; spinal cord sacral levels) are mostly terminal as they are located in close proximity to most of the structures they innervate with the exception of the maxillary glands that are distant from the ganglia.
2. Effectors. The ventral horn cells – the motor cranial nerve nuclei (CNs III–VII, IX, X, XI, and XII) – and motor division of the autonomic nervous system form the effectors which innervate the three types of muscles in our bodies: skeletal, smooth, and cardiac.
3. Interneurons. These are the vast majority of the neurons in the central nervous system. The areas in the central nervous system that contain high numbers of neuronal cell bodies are called *gray matter*, while the regions that contain primarily myelinated axons are called *white matter*. Neurons are organized into ganglia, nuclei, or layered cortices.

Table 1.2 Sensory receptors

Class of receptor	Function	Location
Chemoreceptors	– Taste	– Taste buds on the tongue
	– Smell	– Olfactory mucosa in the nose
Mechanoreceptors	– Balance	– Inner ear – semicircular canals
	– Sound	– Inner ear – cochlea
	– Tactile discrimination and pressure	– Skin, muscle, tendons, joints
Nociceptor	Pain	Free nerve endings in the skin and organs
Thermoreceptor	Temperature	Skin, tissues, and organs

Nuclei. Throughout the brain and spinal cord, there are groupings of neurons with a common function; these are the nuclei. They are found throughout the spinal cord (ventral and dorsal horn), brain stem (cranial nerve nuclei, reticular formation), diencephalon (nuclei of the thalamus, hypothalamus, subthalamus, and metathalamus), basal ganglia (caudate, putamen, globus pallidus, substantia nigra), and cerebral cortex (amygdaloid nuclei).

Lamina. In the cerebral cortex, cerebellar cortex, and superior colliculus, the gray matter is on the surface and organized anatomically into horizontal columns and physiologically into vertical columns permitting a nearly infinite number of interconnections.

The senses. Aristotle distinguished five senses: hearing, sight, smell, taste, and touch. Modern neuroscience, however, includes the *five special senses* (balance, vision, hearing, taste, and smell) and the *four general senses* (pain, temperature, touch, and pressure). Humans have evolved a series of specialized receptors for each of these different sensory functions (Table 1.2). The special sensory apparatuses are found in the head: the eye and its protective coverings and muscles, the membranous labyrinth in the temporal bone for hearing and balance, the nose with olfactory receptors, and the tongue with taste buds. The *receptors for general sensation* (mechanoreceptors, nociceptors, and thermoreceptors) are located primarily in the body's largest organ, the skin. Certain areas, e.g., the lips, fingers, feet, and genitalia, have a proliferation of the tactile mechanoreceptors. Everywhere except on the soles and palms we have hair, which is an important tactile receptor but is continually being depleted by our concern for grooming. The pain receptors, or free nerve endings in the skin, are located throughout the body, but probably more receptors are in the skin over the face, lips, hands, and feet and then over the rest of the body. As you review the receptors in Table 1.2, sense on your own body how the soles are especially good for feeling pressure and placing the body safely in light or darkness and the fingers and face are sensitive to touch and temperature. Remember that we have only discussed the skin receptors so far, which respond to external stimuli. However, there are also similar receptors within the respiratory, cardiovascular, endocrine, gastrointestinal, and urogenital systems that monitor our internal milieu.

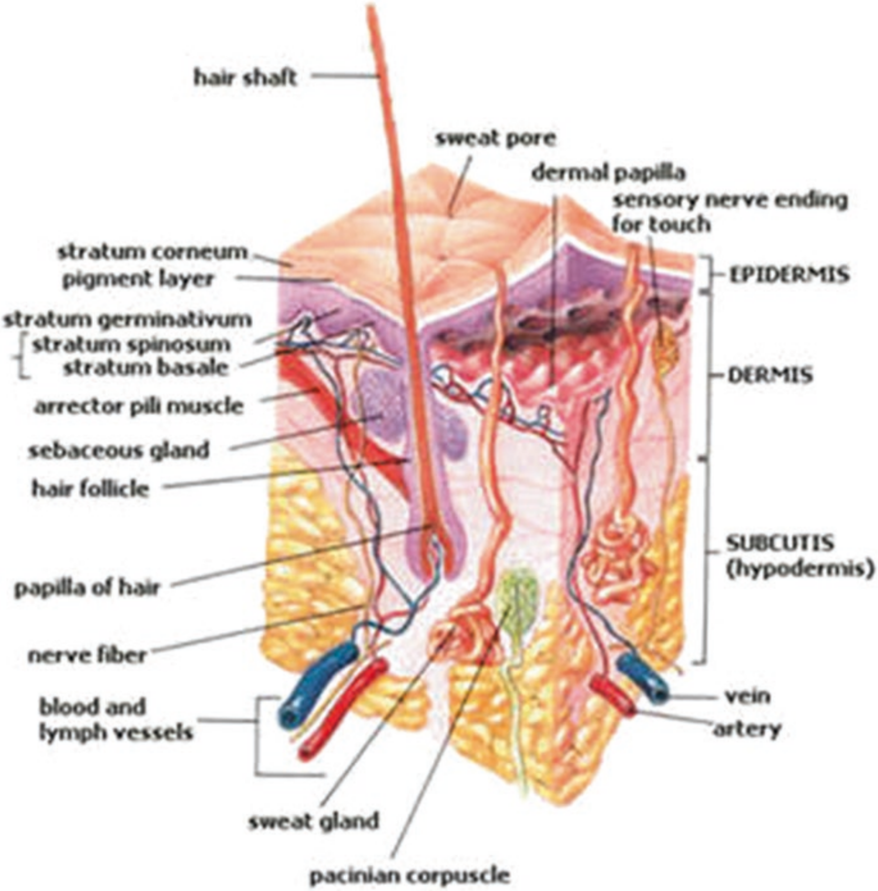


Fig. 1.2 Hairy skin showing the epidermis, dermis, and hypodermis. The blood vessels, lymph vessels, sweat glands, hair follicle, Pacinian tactile receptor, and free nerve endings (for pain) are also demonstrated (from Human free science.org)

Muscles. The 640± muscles in the body form the bulk of the body and consist of three different functional and histological entities: *skeletal*, *smooth*, and *cardiac*. Skeletal muscles are found in the head, neck, arms, legs, and trunk and permit us to undertake voluntary movements. Smooth, or unstriated, muscles are found in the viscera, blood vessels, and hair follicles. Cardiac muscles form the auricles and ventricles of the heart.

Each muscle group has a specialized nerve ending that permits the impulse carried down to the motor nerve via a peripheral nerve to stimulate the muscle through release of a specific chemical. Contraction of the three muscle groups in response to sensory information originates from the central nervous system via the efferent/motor peripheral nerves.

Sensory receptors. The general and special sensory receptors in the skin (Fig. 1.2) provide the *afferent* nerves that carry sensory information to the spinal cord and brain. The brain analyzes the sensory input before the muscles, which are controlled by the efferent nerves carrying information from the brain or spinal cord, and makes a response. These integrative functions of the central nervous system form the bulk of the discussion in this book.

1.2 The Nervous System

The nervous system consists of a peripheral and central division (Fig. 1.3). The central nervous system (brain and spinal cord, Fig. 1.3) is surrounded by fluid-filled membranes (meninges with CSF), and the brain is further protected in the bony

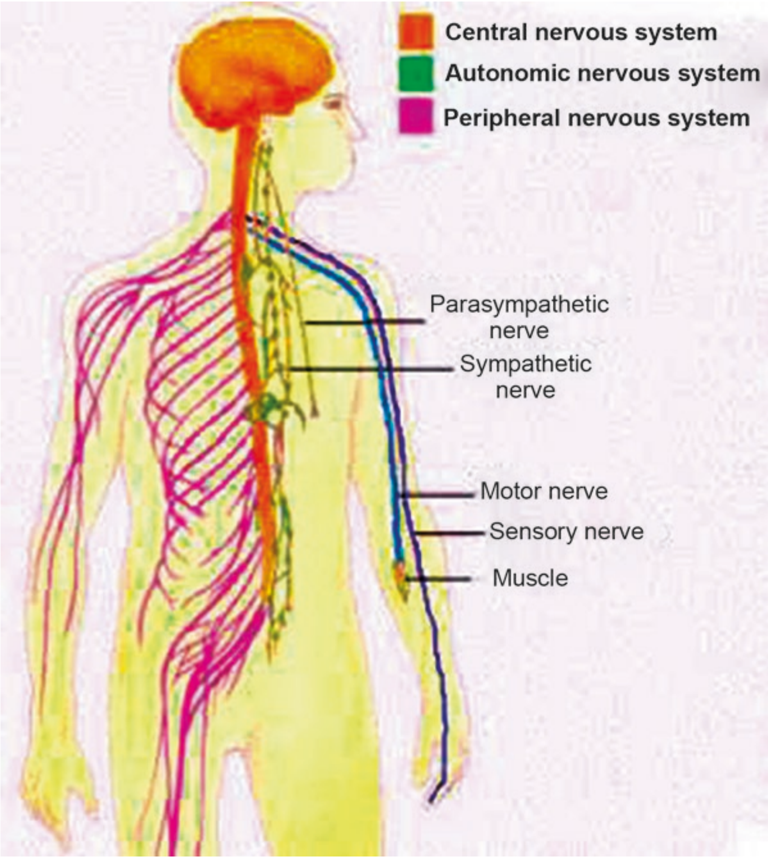


Fig. 1.3 Human nervous system (from Wikipedia 2016)

skull, while the spinal cord is housed in the bony vertebrae. In contrast, the peripheral nervous system that brings information from and to the central nervous system lacks a bony covering, but is protected by the fascia, skin, muscles, and organs where it distributes. Sensory information enters the central nervous system through the afferent divisions of the peripheral nerves.

1.2.1 Peripheral Nervous System (Fig. 1.3)

Peripheral nerves are found everywhere in the body: skin, muscles, organs, and glands. Peripheral nerves originate from either the spinal cord or the 12 cranial nerves associated with the brain. The peripheral nervous system is divided into a somatic and a visceral division. The s*omatic division* innervates the skin and skeletal muscles in the body. The visceral, or *autonomic division*, innervates the cardiac muscles of the heart and the smooth muscles and receptors in the blood vessels and gastrointestinal, respiratory, urogenital, and endocrine organs. The details of the peripheral nervous system are usually taught as part of gross anatomy, so the student may want to review an anatomy text.

1.2.2 Central Nervous System

The central nervous system consists of the spinal cord and brain. The spinal cord has 32 segments, while the brain consists of the brain stem, cerebellum, diencephalons, and cerebrum. In Fig. 1.3, we show an isolated entire human CNS, while in Fig. 1.4, we demonstrate the CNS in situ. Attached to all of the 32 segments of the spinal cord and the brain stem are the sensory ganglia that form the first link in the sensory system and bring the sensory information into the central nervous system. Motor axons exit from each of the 32 segments of the spinal cord and all levels of the brain stem and connect the central nervous system to all muscles and organs in the body. In the spinal cord, much of the brain stem, and diencephalon, the neurons are organized into nuclei, while in the superior colliculus of the brain stem, cerebellum, and cerebrum, the neurons are organized anatomically into layers and functionally into vertical columns.

1.2.2.1 Spinal Cord (Fig. 1.5)

The spinal cord, Chap. 4, is that portion of the central nervous system that lies in the vertebral canal from the upper border of the atlas (first cervical vertebrae) to the lower border of the first lumbar vertebrae in the adult (or third lumbar vertebrae in the neonate). The spinal cord has 32 segments divided into five regions – cervical, thoracic, lumbar, sacral, and coccygeal – and these regions innervate specific regions

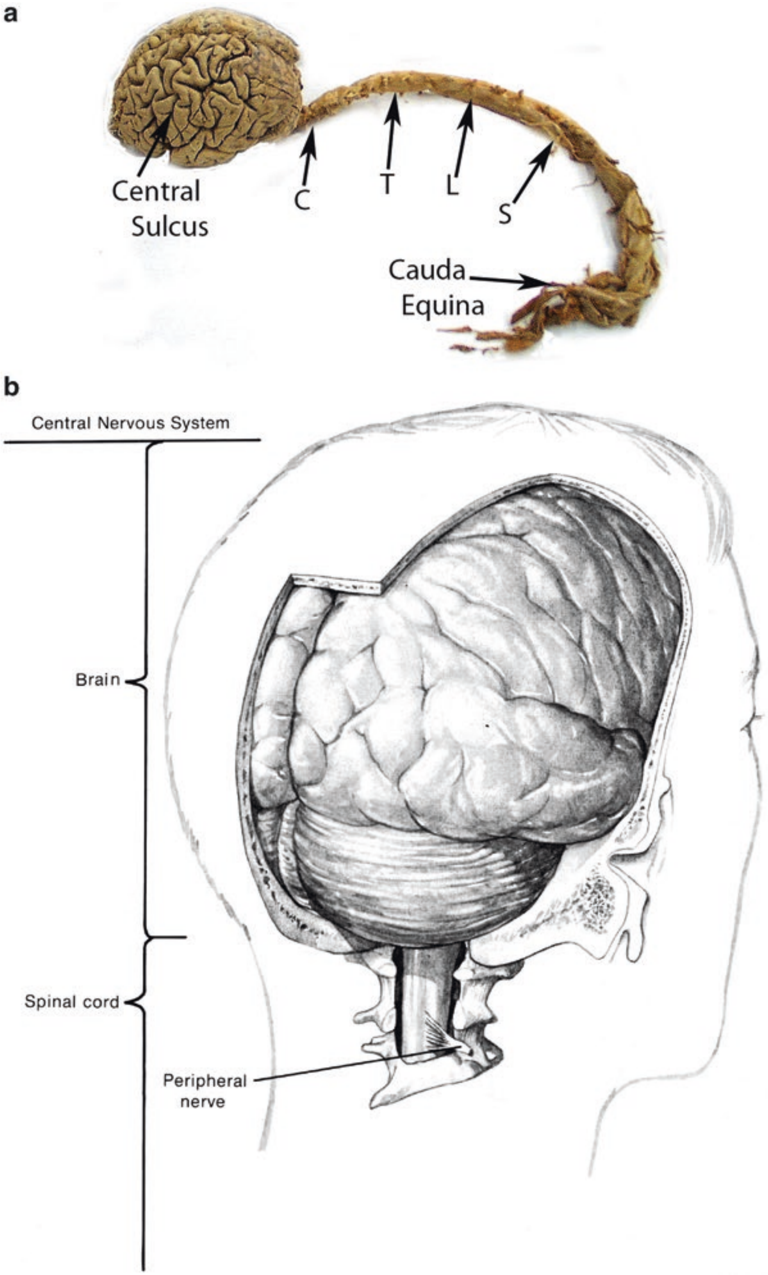
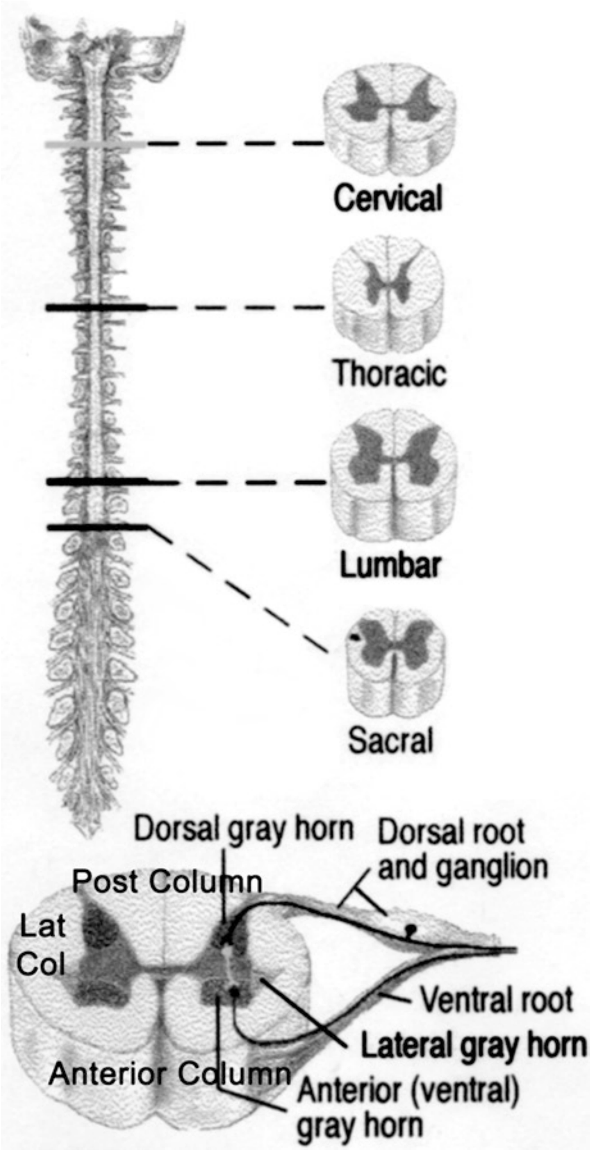


Fig. 1.4 Central nervous system. In (**a**) a human CNS (brain and spinal cord) is shown, while in (**b**) the brain and spinal cord are shown in situ in the skull. From an Introduction to Neurosciences, Curtis, Jacobson, Marcus. Saunders 1974

Fig. 1.5 Spinal cord



in the neck and upper extremity (cervical segments), thorax and abdomen (thoracic levels), anterior leg and thigh (lumbar segments), and buttock and posterior leg and thigh (lumbar segments). This ordered relationship between the spinal cord and body produces a somatotopic organization throughout the central nervous system.

In the spinal cord, the parenchyma is organized simply into columns of gray (location of neuronal cell bodies) and white matter (location of axons covered with myelin) with the gray matter centrally placed and surrounded by the white matter.

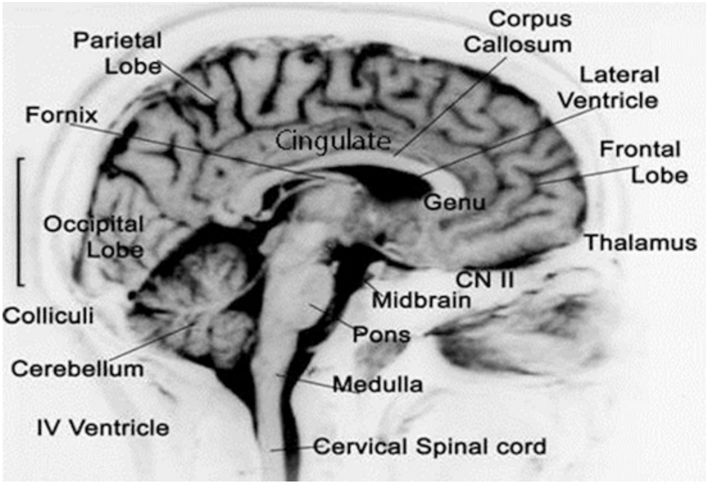


Fig. 1.6 The brain. MRI sagittal plain T2

This organization is not evident as one looks at isolated cross sections, but when these sections are reconstructed serially, this columnar organization in the gray and white matter is apparent. The columns of gray matter in the spinal cord appear in the shape of a butterfly and are called horns and are divided into a dorsal sensory horn, a ventral motor horn, intermediate zone, and commissural region. The largest neuronal cell bodies are found in the ventral horn (*ventral horn cells*), whose axons form the efferent division of the peripheral nervous system and innervate the skeletal muscles (Fig. 1.5). The white matter of the spinal cord is divided into three columns: anterior, posterior, and lateral. The pathways interconnecting the spinal cord and brain are found in these columns.

The spinal cord has a tubular shape and has two regions of enlargement, the lower cervical that controls the upper extremity and the lumbosacral enlargement that controls the lower extremity.

1.2.2.2 Brain

Brain Stem (Chaps. 5–7) (Fig. 1.6)

The columnar organization seen in the gray and white matter of the spinal cord is modified in the brain stem by the development of the ventricular system and the presence of the cranial nerves.

The brain stem (Figs. 1.6 and 1.7) consists of three regions from inferior to superior: *medulla*, *pons*, and *midbrain*. The brain stem is often the most difficult region of the central nervous system for the student to learn, because of the presence of the cranial nerves and associated nuclei. You may initially feel overwhelmed by its