Stanley Jacobson · Elliott M. Marcus

Neuroanatomy for the Neuroscientist

Second Edition

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To our wives: Avis Jacobson and Nuran Turksoy.
To our children: Arthur Jacobson, Robin Seidman,
Erin Marcus, and Robert Letson, and
to our grandchildren: Ross Jacobson, Zachary Letson,
and Amelia Letson.
To our teachers, students, and colleagues.

About the Author

Dr. Elliott Marcus, Professor of Neurology at University of Massachusetts (Emeritus). At 78, Dr. Marcus – a neurologist and educator for five decades at Tufts Medical Center, Tufts University School of Medicine, and the University of Massachusetts Medical School at Saint Vincent Hospital – died on July 25, 2011 in Massachusetts General Hospital in Boston.

Even as the end drew near, Dr. Elliott Marcus pressed on with his life's work: sharing the knowledge he had gleaned through a lifetime of dedicated study and teaching neuroscience. He received his undergraduate education at Yale University and earned an MD from Tufts University School of Medicine. He was trained in neurology at Tufts Medical Center and also served with distinction for two years in the US Army. He taught at Tufts University School of Medicine from 1964 to 1976 where he was the "father" of neuroscience teaching to medical students. He then moved to St. Vincent's Hospital in Worcester Massachusetts in 1976 where he was Chief of Neurology. He also was a Professor of Neurology at the University of Massachusetts and an active member of that department. He was a clinical neurologist and he published many papers on diagnosis and treatment of seizure disorders. He retired in 1998 and continued active teaching of neurology residents and medical students at UMass until just before his death.

Even as non-Hodgkin's lymphoma took its toll on Dr. Marcus, he pushed himself, discussing his contributions to a forthcoming book that he and Dr. Stanley Jacobson, a Professor of Anatomy and Cellular Biology at Tufts Medical School and a friend and colleague for over 40 years, were collaborating on and telling friends to make sure the work continued beyond the span of his limited days. He wanted to live and be there to teach and to be there for his grandchildren.

Friends and colleagues said he was dedicated to his work, loved his family, and inspired generations of doctors. Dr. Thomas Sabin, a Professor of Neurology at Tufts Medical School described Dr. Marcus as a superb neurologist and someone with a brilliant intellect. Dr. David

Chad, a Professor of Neurology and Pathology at UMass Medical School, said Dr. Marcus's passion for neurology and teaching was always evident. Dr. Marcus often traveled from Florida more than a decade after his official retirement in 1998 to work with neurology students. He would talk with them, letting them learn through conversations, rather than just giving the answers, Chad said.

"He had a Socratic method of teaching; he let students sort of find the truth," Chad said. "He would open the subject up. He would bring out the key issues to be discussed. He wouldn't stand up and give the answers. He'd ask questions and give feedback. He was an excellent communicator. He loved sharing what he knew. He brought scholarship to his teaching."

Dr. Cynthia Brown, who first met Dr. Marcus in 1980 as a resident neurologist at UMass Medical School and Saint Vincent's Hospital, described neurology as a "very intellectual specialty." "To have someone as bright and inspiring as Dr. Marcus helps to validate one's choice to be a neurologist," she said. "He's really a doctor's doctor, and it is very sad to think that the upcoming classes of medical students will not be able to have his tutorials."

Boston Globe
Boston, MA

Melvin Mason
Stanley Jacobson

Preface

Neuroanatomy for the Neuroscientist

The purpose of this textbook is to enable a Neuroscientist to discuss the structure and function 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 two authors have a long experience in teaching neuroscience courses at the first or second year level to medical and dental students in which clinical information and clinical problem-solving are integral to the course. In addition, the first author has taught for many years 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 help engage the students. The second author has developed a case history of problem-solving sessions in the book "Integrated Neurosciences" by E.M. Marcus and S. Jacobson, Kluwer 2003 and he also conducted a problem-solving seminar in which all medical students at the University of Massachusetts participated during their clinical neurology clerkship rotation. This provides the students an opportunity to refresh their problem-solving skills and to review that basic science material is essential for clinical neurology. At both levels, we have observed that this inclusion of case history materials reinforces the subject matter learned by markedly increasing the interest of the students in both basic and clinical science material. This text is a modified version of "Integrated Neurosciences" published by Kluwer in 2003. This book is also an updated version of an earlier integrated textbook originally developed by the authors along with Dr. Brian Curtis and published by W.B. Saunders in 1972 as "An Introduction to the Neurosciences." The text provides an updated approach to lesion localization in neurology, utilizing the techniques of computerized axial tomography (CT scanning), magnetic resonance imaging (MRI), and magnetic resonance angiography (MRA). Multiple illustrations demonstrating the value of these techniques in clinical neurology and Neuroanatomical localization have been provided. The clinical cases illustrations have been utilized in the body of the text.

In this, the second edition, decisions had to be made so that the size of the textbook remained within limits that could be managed in most of today's neuroscience courses and we could respond to some of the very worthwhile suggestions from our colleagues. The printed book contains the core topics concerned with the central nervous system. We have divided this book into four sections: I: Introduction to the Central Nervous System (Chaps. 1–10), II: The Systems (Chaps. 11–17), and III: The Non-Nervous Elements (Chaps. 18–21). We have added a chapter with case histories, Chap. 20, and following suggestions from our colleagues have been added as an Atlas (Chap. 22). We have updated "Movies on the Brain", Chap. 21, and we have used several of these movies as an adjunct to the course ("Young Dr. Frankenstein" directed by Mel

Brooks has a wonderful scene introducing the CNS, and “Little Shop of Horrors” directed by Frank Oz features Steve Martin as a dentist. Making 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 with its many episodes and its Medical Manual are at the top of our list!

We have added Chap. 20 with representative cases of disease within the CNS to add in the students, ‘understanding of the disease process within the CNS. We have also included a discussion on the eighth nerve in the cranial nerve chapter and a discussion on the olfactory system in the limbic system chapter. In addition, we have added material in the form of an Atlas at the end of the spinal cord chapter, the brain stem, and thalamic chapters and finally we have included a separate chapter, Chap. 21 as an Atlas with labeled gross sections and myelin stained sections of the brain to aid in identifying the regions within the brain. A number of other topics including cell biology, cell physiology, embryology, nerve, and muscle are usually covered in other courses and the students should examine these topics in those courses. The anatomy of the peripheral nervous system and autonomic nervous system 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 Dr. Marcus. For a number of the cases, our associates at the New England Medical Center, St. Vincent Hospital, Fallon Clinic, and the University of Massachusetts School of Medicine either requested our opinion or brought the 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 the 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 Segaraa 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 MD, MPH while still a medical student at Tufts Medical School developed the illustrated drawings that have been used throughout the second edition of this book to illustrate the retina, pathways, levels of the spinal cord, levels of the brain stem, and levels of the thalamus. Dr. Mary Gauthier Delaplane while a medical student at Boston University School of Medicine provided the anatomical drawings illustrating the cranial nerves, and the Neuroembryology chapter. Anne Que, Paul Ning, Tiffany Mellott, Elizabeth Haskins, and Tal Delman aided Dr. Delaplane. Dr. Marc Bard provided drawings for the earlier version of this text while a student at Tufts University School of Medicine. 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 editors Ann Avouris and Joseph Burns for all their help. Any faults or errors are those of the authors and we would therefore appreciate any suggestions or comments from our colleagues.

Boston, MA — Stanley Jacobson
Worcester, MA — Elliott M. Marcus

Contents

Part I

Essential Organization of the Central Nervous System

1 Introduction to the 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 12 cranial nerves attached to the brain form the upper part of the 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.

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.

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 cells 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.

There are three basic categories of neurons: (1) Receptors, the ganglia of the spinal dorsal roots and of the cranial nerves with general sensory components; (2) Effectors, the ventral horn cells, motor cranial nerve nuclei, and motor division of the autonomic nervous system; (3) Interneurons, 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.

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.

Motor/autonomic ganglia are found throughout the body, and they are either sympathetic or parasympathetic ganglia.

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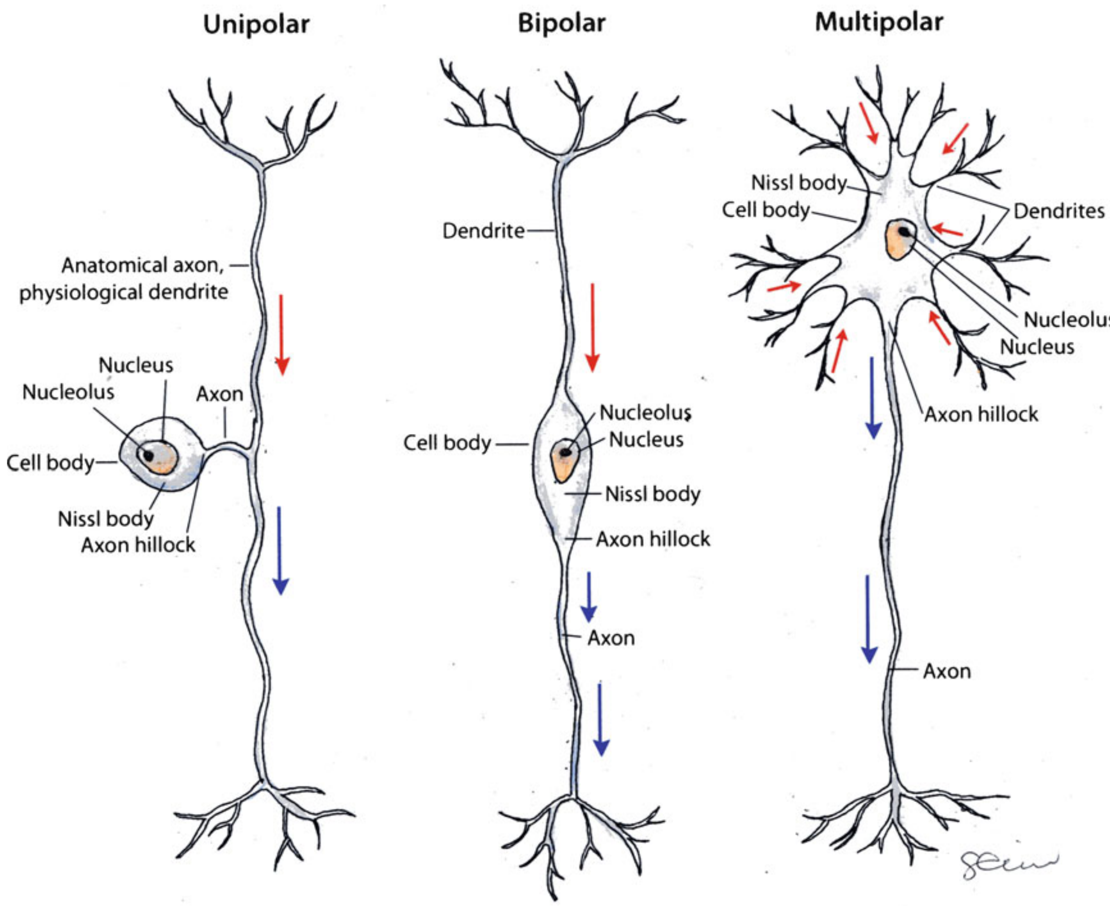

Fig. 1.1 Types of neurons in the central nervous system. The cells in the nervous system are classified based on their shapes: unipolar, bipolar, and multipolar. The input (*red*) reaches the dendrites of each cell and is then transported (*blue*) into the axon where it connects to the next neuron via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

Table 1.1 Types of neurons in the nervous system

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

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) and diencephalon (nuclei of thalamus, hypothalamus, subthalamus, and metathalamus), basal ganglia (caudate, putamen, globus pallidus, substantia nigra), and in the 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* (mechanicoreceptors, nociceptors, and thermoreceptors) are located primarily in the bodies' largest organ, the skin. Certain areas, e.g., the lips, fingers, feet, and genitalia, have a proliferation of the tactile mechanicoreceptors. 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 than 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.

Table 1.2 Sensory receptors

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

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 auricles and ventricles of the heart (Fig. 1.2).

Each muscle group has a specialized nerve ending that permits the impulse carried down 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.

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

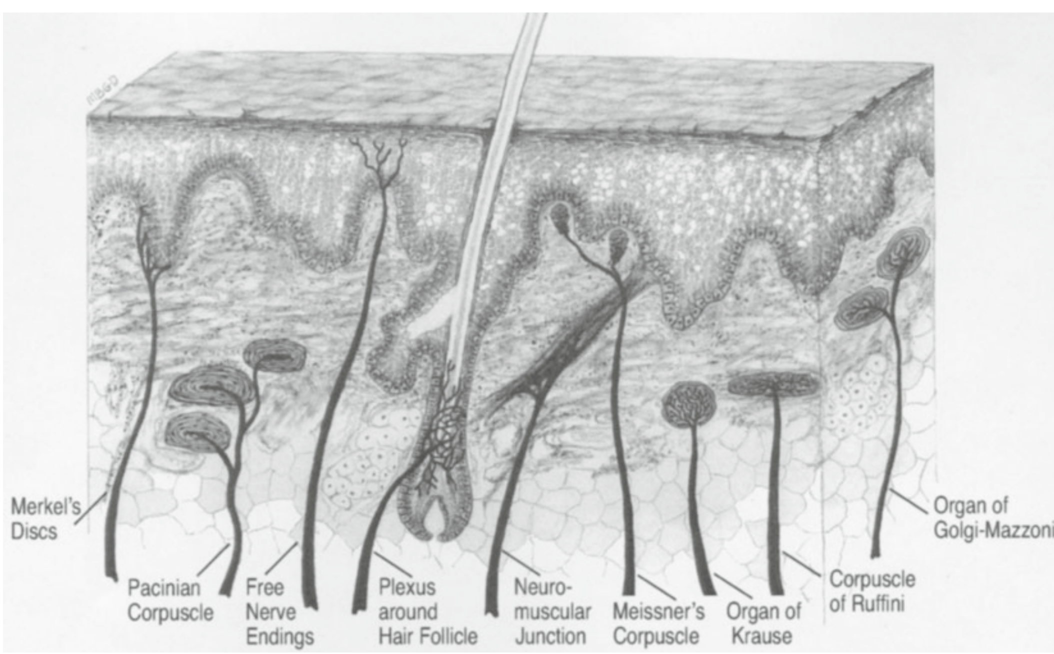

Fig. 1.2 Hairy skin showing receptors

The Nervous System

The nervous system consists of a Peripheral and Central division. The central nervous system (brain and spinal cord) is surrounded by fluid-filled membranes (meninges, see Chap. 16) and housed in either the bony skull or vertebrae. By 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.

Peripheral Nervous System

Peripheral nerves are found everywhere in the body: skin, muscles, organs, and glands. Peripheral nerves originate from either the spinal cord or 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.

Central Nervous System

The central nervous system consists of the spinal cord and brain (brain stem, cerebellum, diencephalons, and cerebrum). The organization of the gray matter varies in each of these regions. Attached to all of the 32 segments of the spinal cord and the brain stem are 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 (Fig. 1.3).

Spinal Cord

The spinal cord is the 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 innervates specific regions in the neck and upper extremity (cervical segments), thorax and abdomen (thoracic levels), anterior leg and thigh (lumbar segments), 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 into columns of gray and white matte with the gray matter centrally placed and surrounded by the white matter. 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. 1.4).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.

Brain

Brain Stem

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 (Fig. 1.5) 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 intricacy but be patient. Approach neuroanatomy as you would a foreign language: first master the vocabulary and grammar before becoming fluent in conversation.

Reorganization of gray and white matter from spinal cord gray to tegmentum of brain stem. In the center of the brain stem, the narrow spinal canal enlarges forming the wide fourth ventricle that divides each level of the brain stem into a region forming the floor of the ventricle *of tegmentum* and a region that form the roof of the ventricle the *tectum* (consists of cerebellum, inferior and superior colliculi). The region that lies on the most anterior surface of the tegmentum