

K. Shimoji
W.D. Willis, Jr.
(Eds.)

Evoked Spinal Cord Potentials

An Illustrated Guide to Physiology,
Pharmacology, and Recording Techniques



K. Shimoji, W.D. Willis, Jr. (Eds.)

Evoked Spinal Cord Potentials

An Illustrated Guide to Physiology, Pharmacology, and Recording Techniques

K. Shimoji, W.D. Willis, Jr. (Eds.)

Evoked Spinal Cord Potentials

An Illustrated Guide to Physiology,
Pharmacology, and Recording Techniques

With 130 Figures

 Springer

Editors:

Koki Shimoji, M.D., Ph.D., FRCA
Professor, Frontier University Ube Graduate School of Human Sciences
2-1-1 Bunkyo-dai, Ube, Yamaguchi 755-0805, Japan
Professor Emeritus, Niigata University
Visiting Professor, Saitama Medical College

William D. Willis, Jr., M.D., Ph.D.
Professor of Neuroscience and Cell Biology
University of Texas Medical Branch
301 University Blvd., Galveston, TX 77555-1069, USA

Authors:

Tatsuhiko Kano, M.D., Ph.D.
Professor and Chairman
Department of Anesthesiology
Kurume University School of Medicine

Yoichi Katayama, M.D., Ph.D.
Professor and Chairman
Department of Neurosurgery
Nihon University School of Medicine

Satoru Fukuda, M.D., Ph.D.
Professor and Chairman
Department of Anesthesiology and Reanimation
Fukui University School of Medicine

Library of Congress Control Number: 2005935847

ISBN-10 4-431-24026-8 Springer-Verlag Tokyo Berlin Heidelberg New York
ISBN-13 978-4-431-24026-6 Springer-Verlag Tokyo Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in other ways, and storage in data banks.

The use of registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Product liability: The publisher can give no guarantee for information about drug dosage and application thereof contained in this book. In every individual case the respective user must check its accuracy by consulting other pharmaceutical literature.

Springer is a part of Springer Science+Business Media
springeronline.com

© Springer-Verlag Tokyo 2006
Printed in Japan

Typesetting: SNP Best-set Typesetter Ltd., Hong Kong
Printing and binding: Hicom, Japan

Printed on acid-free paper

*Dedicated to Our Parents
and Teachers*

Preface

The technique of using evoked spinal cord potentials (SCPs) has become an important clinical tool for monitoring spinal cord surgery and diagnosing spinal cord diseases. The technique is a result both of the technical development of recording evoked SCPs from the epidural space without perforation of the dura mater and of the development of medical electronics. Its use as a monitoring tool is based on continuous epidural analgesia with an epidural catheter. Since the first development of epidural recording of evoked SCPs in 1971, the technique has been applied in various institutes, particularly for monitoring during spine or spinal cord surgery and cardiovascular surgery, and recently for diagnosis of spinal cord diseases.

Although the results of studies on monitoring during surgery have proved useful, more detailed neurophysiological mechanisms in the origin of each component of evoked SCPs remain to be explained in the area of diagnosis of spinal or central nervous system diseases. Further neurophysiological and neuropharmacological studies of the human spinal cord may contribute to the clinical application of recording evoked SCPs for diagnosis of spinal cord diseases.

The aim of this book is to furnish a survey of the neurophysiological and neuropharmacological bases of evoked SCPs with reference to animal studies and the techniques of recording the potentials mainly from the spinal epidural space. The authors have been involved in the field from the beginning of the 1970s. Many illustrations are presented for better understanding the neurophysiological and neuropharmacological backgrounds of monitoring spinal cord functions. Case studies also are presented and discussed to provide more insight into the monitoring and diagnosis of spinal cord dysfunctions and spinal cord diseases.

This book is thus appropriate even for students or those new to the fields of clinical neurophysiology, neurosurgery, neurology, orthopedics, and neuroanesthesia who are interested in monitoring spinal cord function during surgery or diagnosing spinal cord diseases. A diverse range of terminology has been used in the literature to date, sometimes leading to misinterpretation of each component in the field of evoked SCPs. To avoid such misinterpretation and to provide readers with an accurate understanding, terminology referring to basic animal studies is used, and lucid explanations are included in this volume.

K. Shimoji and W.D. Willis, Jr.
Editors

Acknowledgments

The editors wish to thank the late Dr. P.D. Wall, who gave us valuable criticism and encouragement throughout our studies. Special thanks are also directed to the Section of Research Promotion of Kurume University and to the Aderans Co., Ltd. for their financial support. The authors also thank Mr. Yukio Sato for his skillful assistance to prepare the illustrations.

Contents

Preface	VII
Section A: Bases of Understanding the Spinal Cord	1
Chapter 1 Neuroanatomical Considerations	
<i>WILLIAM D. WILLIS, JR.</i>	3
1.1 Gross Anatomy of the Human Spinal Cord	3
1.2 Spinal Meninges	8
1.3 Cross-Sectional Anatomy of the Spinal Cord	8
1.4 Afferent Input to the Spinal Cord	14
1.5 Somatosensory and Other Ascending Tracts	17
1.5.1 Dorsal Column System	17
1.5.2 Spinothalamic and Associated Tracts of the Anterolateral Quadrant	20
1.6 Input to the Spinal Cord from Pathways Descending from the Brain	21
1.6.1 Corticospinal Tract	22
1.6.2 Other Descending Pathways from the Brain	24
1.6.3 Spino-Bulbospinal and Other Spinal Cord–Brain Loops	24
Chapter 2 Physiology of the Spinal Cord	
<i>WILLIAM D. WILLIS, JR.</i>	26
2.1 Electrophysiological Recordings from the Spinal Cord	26
2.1.1 Single Unit Recordings	26
2.1.2 Population Recordings	26
2.2 Responses of Nociceptive Dorsal Horn Neurons to Peripheral Input	29
2.3 Responses of Spinal Cord Neurons to Corticospinal Volleys	32
	IX

Chapter 3 Pharmacology of the Spinal Cord	
<i>WILLIAM D. WILLIS, JR.</i>	34
Chapter 4 Overviews of Human (Evoked) Spinal Cord Potentials (SCPs): Recording Methods and Terminology	
KOKI SHIMOJI	40
4.1 Animal SCPs and Human SCPs	40
4.2 Recording Methods of Human SCPs from the Posterior Epidural Space	44
4.3 Six Different Kinds of Human SCPs Recorded from the Epidural Space	46
4.3.1 Segmental SCPs (Segmentally Evoked SCPs)	46
4.3.2 Conducting or Conducted SCPs	46
4.3.3 Slow SCPs Produced by Antidromic Stimulation of the Spinal Cord (Descending SCP)	48
4.3.4 Heterosegmental SCP, Heterosegmentally Evoked SCP	48
4.3.5 Motor Evoked Human SCPs: TCM-Evoked SCPs	49
4.3.6 Motor Evoked Human SCPs: TCE-Evoked SCPs	49
4.3.7 Polarity of Recording Spinal Cord Potential	49
 Section B: Somatosensory Evoked Spinal Cord Potentials (Segmental SCPs)	 51
Chapter 1 Segmental SCPs	
<i>SUMIHISA AIDA and KOKI SHIMOJI</i>	53
1.1 Waveform Characteristics	53
1.2 Comparison with Skin Surface Recordings	54
1.3 Comparison with Posterior Pharyngeal Recordings	54
1.4 Origins of the Segmental SCP	57
1.4.1 The Initially Positive Spike (Triphasic Spike) (P1)	57
1.4.2 The Sharp (or Slow) Negative Wave (N1)	57
1.4.3 The Slow Positive Wave (P Wave; P2 Wave)	61
Chapter 2 Spinal Cord Potentials Evoked by Ascending Volleys	
<i>YOICHI MARUYAMA and KOKI SHIMOJI</i>	65
2.1 Waveform Characteristics of SCPs Evoked by Ascending Volleys	65
2.2 SCPs Evoked by Two Ascending Volleys from the Cauda Equina	66
2.3 Conduction Velocities of Ascending Volleys Along the Cord	67
Chapter 3 Spinal Cord Potentials Evoked by Descending Volleys	
<i>HIROYUKI SHIMIZU and KOKI SHIMOJI</i>	71
3.1 Waveform Characteristics of SCPs Evoked by Descending Volleys to the Spinal Cord	71
3.2 Effects of Graded Stimulation to Determine the Population of Spinal Tract Fibers that Produce “Descending SCPs”	73

3.3 Effects of Double Shocks on “Descending SCPs”	76
3.4 Origins of Descending N and P Waves in Human SCPs	77
3.5 Spinal Tracts Producing N and P Waves	79
 Chapter 4 Heterosegmental SCPs (HSPs)	
<i>MISAO TOMITA and KOKI SHIMOJI</i>	82
4.1 The HSP in Humans	82
4.2 Fundamental Patterns of the HSP	83
4.3 Central Nuclei of the HSP	85
4.4 The Relationship Between WDR Neuron Activities and HSP	87
 Chapter 5 Clinical Pharmacology	
<i>TATSUHIKO KANO and YOSHIKADO MIYAGAWA</i>	90
5.1 Introduction	90
5.2 Effects of Intravenous Anesthetics	91
5.2.1 Thiamylal Sodium	91
5.2.2 Ketamine Hydrochloride	93
5.2.3 Fentanyl Citrate and Droperidol	94
5.2.4 Morphine Hydrochloride	94
5.2.5 Diazepam	95
5.2.6 Summary	96
5.3 Effects of Inhalation Anesthetics	98
5.4 Effects of Local Anesthetics	98
5.4.1 Epidural Lidocaine on Segmental SCPs	98
5.4.2 Epidural Lidocaine on Conducting SCPs	100
5.4.3 Intrathecal Lidocaine on Conducting SCPs	101
5.4.4 Summary	102
 Section C: Motor Evoked SCPs	103
 Chapter 1 Transcranial Magnetically Evoked SCPs (TCM-Evoked SCPs)	
<i>TOSHIYUKI TOBITA and KOKI SHIMOJI</i>	105
1.1 Recording Techniques	105
1.2 Basic Patterns of TCM-Evoked SCPs	106
1.3 Effects of Intravenous Anesthetics	107
1.4 Effects of Inhalation Anesthetics	110
 Chapter 2 Transcranial Electrically Evoked SCPs (TCE-Evoked SCPs)	112
2.1 Recording Techniques	
<i>CHIKASHI FUKAYA and YOICHI KATAYAMA</i>	112
2.1.1 Introduction	112
2.1.2 Anesthesia	112

2.1.3 Stimulation	112
2.1.4 Recording	113
2.1.5 Discussion	117
2.2 TCE-Evoked SCPs in Animals and Human	
<i>YOICHI KATAYAMA and TAKAMITSU YAMAMOTO</i>	118
2.2.1 Introduction	118
2.2.2 Experimental Studies	119
2.2.3 Comparison Between Direct- and TCE-evoked SCPs	121
2.3 TCE-Evoked Potentials from Muscle and TCE-Evoked SCPs	
<i>TAKAMITSU YAMAMOTO and YOICHI KATAYAMA</i>	124
2.3.1 Introduction	124
2.3.2 Methods	124
2.3.3 Results	125
2.3.4 Discussion	128
2.4 Effects of Intravenous and Inhalational Anesthetics	
<i>S. DENDA and KOKI SHIMOJI</i>	129
2.4.1 Introduction	129
2.4.2 Methods for Recording TCE-Evoked SCPs	130
2.4.3 The Effects of Inhalation Anesthetics	132
Section D: Case Studies (Clinical Applications)	135
Chapter 1 Monitoring by SCPs During Surgical Operations	137
1.1 Spine Surgery: Scoliosis Surgery	
<i>HITOSHI FUJIOKA and KOKI SHIMOJI</i>	137
1.2 Spinal Cord Surgery	140
1.2.1 Dorsal Root Entry Zone Lesion (DREZL)	
<i>TOMOHIRO YAMAKURA and KOKI SHIMOJI</i>	140
1.2.2 Spinal Cord Tumor	
<i>CHIKASHI FUKAYA and YOICHI KATAYAMA</i>	143
1.3 Spinal Cord Hypothermia During Aortic Surgery	
<i>TATSUHIKO KANO and SEIJI WATANABE</i>	150
1.3.1 Discussion	151
1.4 Spinal Cord Ischemia During Aortic Surgery	153
1.4.1 Somatosensory Evoked SCPs	
<i>TATSUHIKO KANO and HIDEKI HARADA</i>	153
1.4.2 TCE-Evoked Electromyograms During	
Thoracoabdominal Aortic Surgery	
<i>SATORU FUKUDA and HAI-LONG DONG</i>	156
1.5 Cardiovascular Surgery	160
1.5.1 Somatosensory Evoked SCPs	
<i>TOSHIKAZU TAKADA and KOKI SHIMOJI</i>	160
1.5.2 Motor Evoked Potential	
<i>SATORU FUKUDA and HAI-LONG DONG</i>	165

Chapter 2 Diagnosis by Spinal Cord Potentials of Spinal Diseases	
<i>HIROYUKI SHIMIZU and KOKI SHIMOJI</i>	174
2.1 Spinal Cord Potentials in Patients with ALS	175
2.2 Spinal Cord Potentials in Patients with Tabes Dorsalis	176
2.3 Spinal Cord Potentials in Patients with Spinal Tumors	177
References	180
Index	207

Section A
Bases of Understanding
the Spinal Cord

Chapter 1

Neuroanatomical Considerations

WILLIAM D. WILLIS, JR.

1.1 Gross Anatomy of the Human Spinal Cord

The central nervous system includes the spinal cord and the brain. The spinal cord is an elongated, roughly cylindrical structure that is found within the vertebral canal (Fig. 1.1A,C). It joins the medulla oblongata at the level of the foramen magnum of the skull (Fig. 1.1A), and in adults it terminates caudally at the interspace between the first and second lumbar vertebrae (Fig. 1.1C). The spinal cord of the adult human is about 42–45 cm long and 1 cm in diameter at its widest extent, and it weighs about 35 g (Nolte, 2002).

The spinal cord develops in relation to the body segments (somites) that it innervates. This gives the spinal cord a segmented structure. The segments are best recognized by reference to pairs of dorsal and ventral roots¹ that enter or emerge from the spinal cord at each segmental level (Figs. 1.1C, 1.2, 1.3). Each dorsal and ventral root breaks up into a series of rootlets that extend the length of the corresponding spinal cord segment; the number of rootlets varies with the segment (see Fig. 1.2). Therefore, a segment of spinal cord can be demarcated by locating the entry or exit points of the most rostral and most caudal of the rootlets of the appropriate root.

The dorsal roots contain axons from sensory neurons whose cell bodies are in the dorsal root ganglia (Figs. 1.2 and 1.3), which form swellings located at the intervertebral foramina. Sensory axons passing to the periphery from the dorsal root ganglion cells intermingle with ventral root axons in the spinal nerves, which are just distal to the dorsal root ganglia (Fig. 1.3A). The ventral roots are composed of axons from alpha and gamma motor neurons and, at the appropriate segmental levels (T1–L2; S1–S3), of autonomic preganglionic neurons. Sympathetic white and gray communicating rami contain axons that connect the spinal nerves with sympathetic paravertebral ganglia (Fig. 1.3A). Sacral parasympathetic preganglionic axons distribute through the pelvic nerves and terminate on parasympathetic postganglionic neurons in ganglia close to or in the walls of the pelvic viscera.

¹Dorsal and ventral are terms that apply best to quadrupeds. Posterior and anterior are more appropriate for humans. However, common usage equates dorsal with posterior and ventral with anterior with respect to human spinal cord structures.

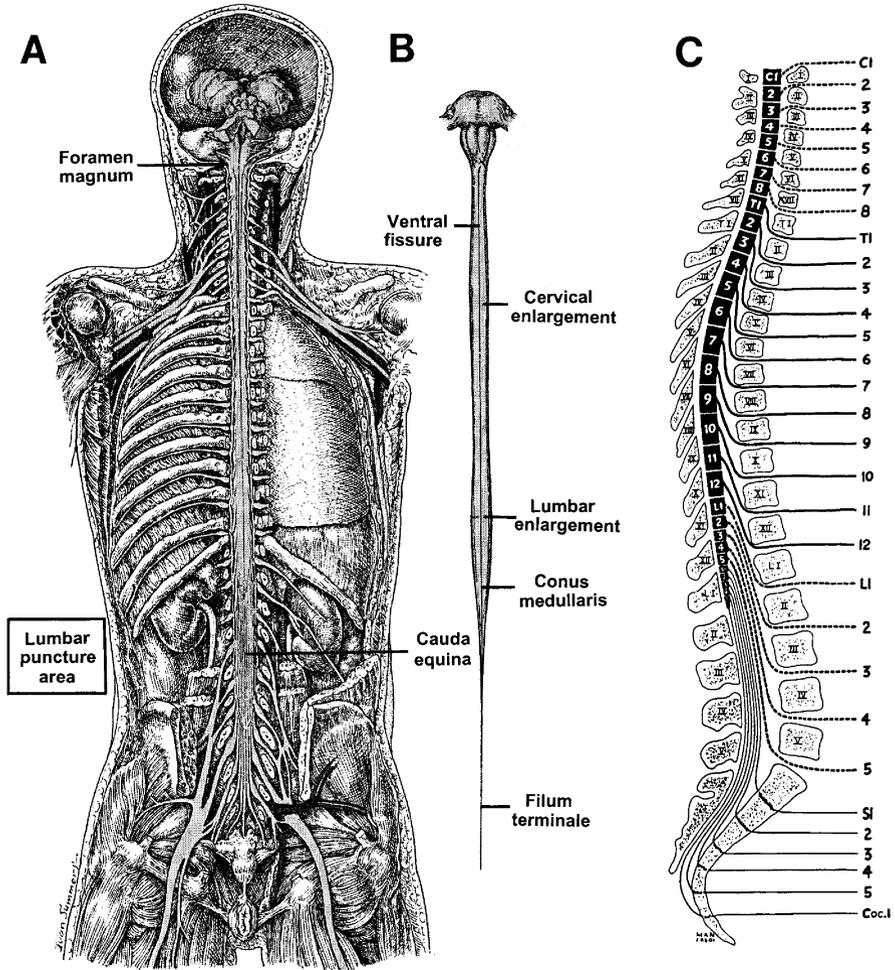


FIG. 1.1A-C. The shape of the spinal cord and its relationship to the vertebral column. **A** Gross dissection of the back in a human cadaver. A complete laminectomy was done and the dura opened, exposing the dorsal aspect of the spinal cord. The brachial and the lumbosacral plexuses are also shown. The spinal cord terminates at the L1-L2 interspace. The remainder of the dural sac contains the cauda equina. The filum terminale penetrates the dura and is attached to the coccyx. **B** Ventral view of the isolated spinal cord. The ventral fissure separates the two halves of the cord (**A** and **B** from Mettler, 1948). **C** Relationship of the spinal cord segments and spinal nerves to the vertebral column (from Crosby et al., 1962)

There are a total of 31 segments (8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal) in the human spinal cord (Figs. 1.1 and 1.2). Other mammals may have slightly different numbers of segments. There are seven cervical vertebrae, and so there is one more cervical spinal cord segment than cervical vertebrae. The ventral roots of the first cervical segment emerge rostral to the first cervical vertebra (there are generally no first cervical dorsal roots; Fig. 1.2), and the eighth cervical dorsal and

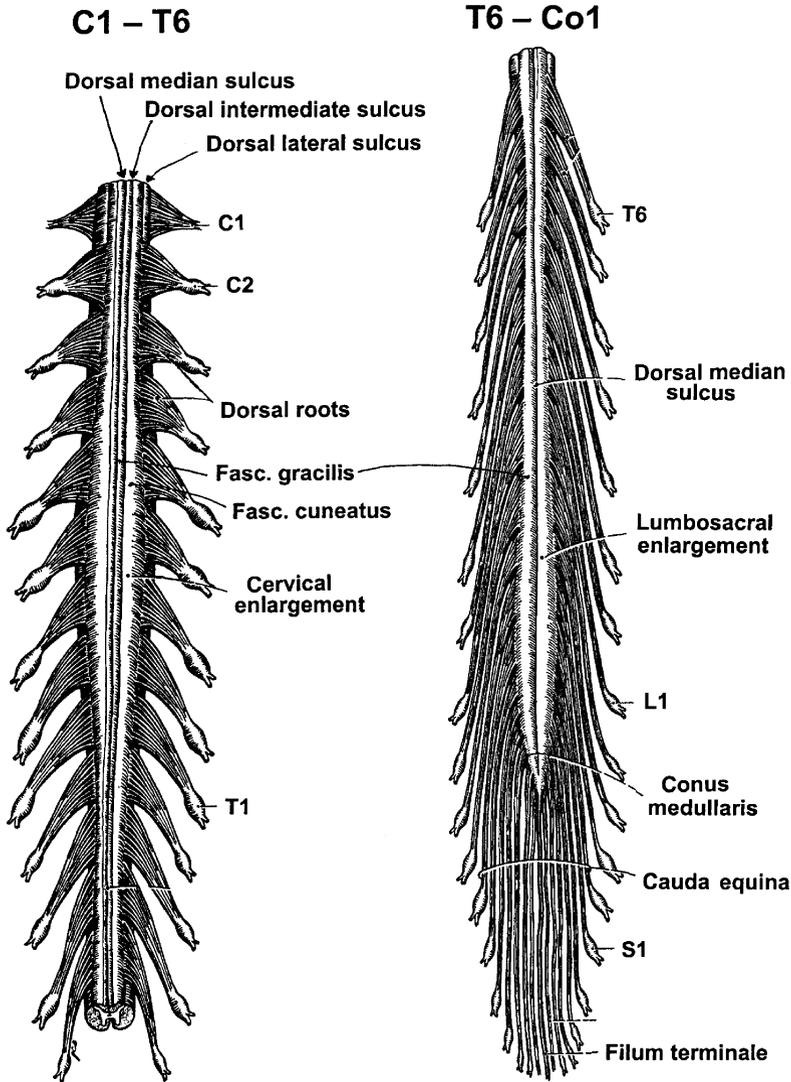


FIG. 1.2. Drawing of the dorsal surface of the spinal cord, dorsal roots and dorsal root ganglia. The spinal cord was transected between the T5 and T6 segments. The cervical and upper thoracic cord are shown at the *left* (including the cervical enlargement) and the lower thoracic and lumbosacral cord are shown at the *right* (including the lumbosacral enlargement). Note that at C1, only the ventral roots are seen because of the absence of C1 dorsal roots. The dorsal median sulcus is present throughout the length of the spinal cord, as is the dorsal lateral sulcus, which is the groove through which the dorsal roots pass to enter the spinal cord. However, there is a dorsal intermediate sulcus at T6 and more rostrally. This separates the fasciculus gracilis from the more laterally situated fasciculus cuneatus. Below T6, only the fasciculus gracilis is found. Caudal to the termination of the conus medullaris are seen the cauda equina and the filum terminale (from Crosby et al., 1962)

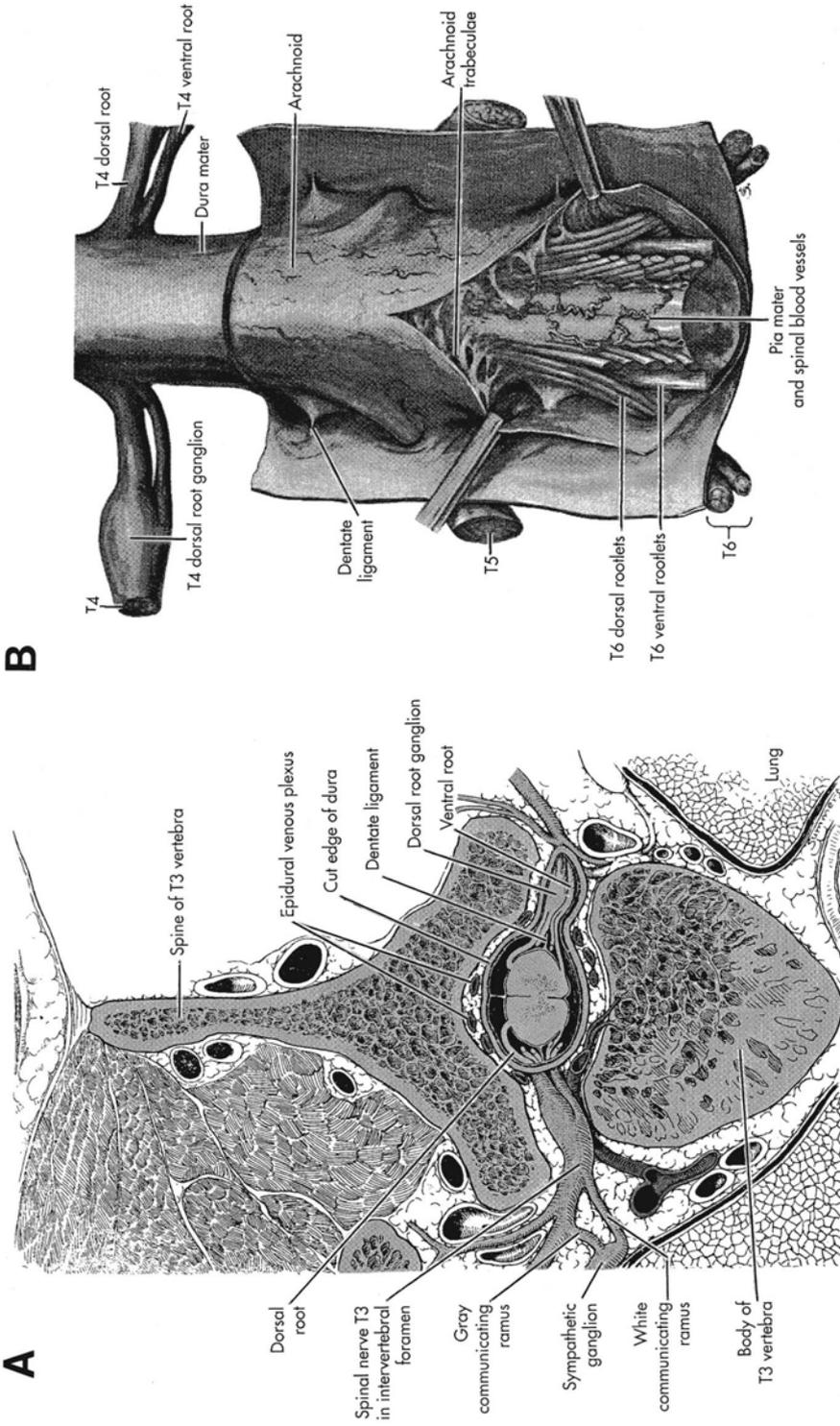


FIG. 1.3A,B. Spinal cord, associated components of the peripheral nervous system, and supportive bony and connective tissue structures. **A** Transverse section of the third thoracic vertebra, the spinal cord, T3 spinal roots, T3 dorsal root ganglia, T3 spinal nerves and meninges. Note the connections of the white and gray communicating rami with the T3 prevertebral sympathetic ganglion. Also note the epidural fat and venous plexus. **B** Dorsal view of the T4-6 levels of the spinal cord, showing the meningeal coverings, including the dura mater, arachnoid, and pia mater. Note the attachment points between the dentate ligament and the dura, as well as the arachnoid trabeculae (from Mettler, 1948)

ventral roots leave the vertebral canal just caudal to the seventh cervical vertebra (Fig. 1.1C). The roots of the remaining spinal segments exit from the vertebral canal below the vertebra of the same number.

The reason that the first cervical segment lacks dorsal roots is that it participates in trigeminal rather than in spinal cord sensory functions. Correlated with this lack of C1 dorsal roots is the absence of a C1 dermatome (see standard dermatome maps used for neurological examinations). The C1 segment receives input from descending branches of primary afferents belonging to the trigeminal nerve. Nociceptive, thermoreceptive, and tactile afferents with cell bodies in the trigeminal ganglion enter the brain stem at the level of the mid-pons through the trigeminal nerve and give off collaterals that project caudally through the spinal tract of the trigeminal nerve, which terminates in the spinal nucleus of the trigeminal nerve. This nucleus extends from the level of the pons to the upper cervical spinal cord. The subnucleus caudalis of the trigeminal complex, which is in the lower medulla and upper cervical spinal cord, resembles the dorsal horn of the spinal cord and is often referred to as the “medullary dorsal horn.” Neurons in this nucleus give rise to a part of the trigeminothalamic tract that has equivalent sensory functions for the head to the spinothalamic tract for the extremities and trunk (pain, temperature and crude touch).

In the upper cervical spinal cord, the spinal roots leave the spinal cord and pass directly laterally to the appropriate intervertebral foramen. However, since the adult spinal cord does not extend beyond the L1–2 intervertebral space, roots below L2 must travel progressively more caudally to reach the appropriate intervertebral foramen (Fig. 1.1C). The collection of spinal roots below L2 is called the cauda equina from its fancied resemblance to a horse’s tail (Figs. 1.1A and 1.2). At levels between the upper cervical spinal cord and L2, the roots angle progressively more. This leads to a discrepancy between vertebral level and spinal cord segmental level that can amount to a difference of 2 or more segments, depending on the level (Fig. 1.1C).

The diameter of the spinal cord is larger at the levels of the brachial (C5–T1) and lumbosacral (L2–S3) plexuses than at other levels (Figs. 1.1A,B and 1.2). The cervical and lumbosacral enlargements are produced by increases in the numbers of neurons and their connections at these levels, as required for the sensory and motor innervation of the upper and lower extremities.

The surface of the spinal cord is indented longitudinally by several sulci (shallow grooves) and a fissure (deep groove). These grooves define the boundaries between areas of the spinal cord white matter called funiculi (large bundles of axons) and between two fasciculi (smaller bundles of axons). At the dorsal midline is the dorsal median sulcus. This separates the left and right sides of the spinal cord (Fig. 1.2). The dorsal lateral sulcus is a groove that corresponds to the dorsal root entry zone. The dorsal funiculus extends from the dorsal median sulcus to the dorsal lateral sulcus. At some segmental levels (C1–T6), there is a dorsal intermediate sulcus, which separates the fasciculus gracilis from the more laterally placed fasciculus cuneatus (Fig. 1.2, left). Caudal to T6, there is no dorsal intermediate sulcus and there is only a fasciculus gracilis (Fig. 1.2, right). The ventral lateral sulcus is not well defined but marks the ventral root exit zone. The lateral funiculus extends from the dorsal lateral to the ventral lateral sulcus. At the midline ventrally is the ventral median fissure (Fig. 1.1B). The ventral funiculus lies between the ventral lateral sulcus and the ventral median fissure. Contained within the ventral median fissure is the ventral spinal artery.

1.2 Spinal Meninges

The spinal cord, like the brain, is enclosed within and protected by connective tissue sheaths called the meninges (Fig. 1.3A,B). The meninges include the dura mater, the arachnoid, and the pia mater. The dura mater is a thick connective tissue membrane that is continuous rostrally to the foramen magnum with the inner layer of the cranial dura mater. There is an epidural space between the spinal dura mater and the periosteum of the vertebral canal. This space contains epidural fat and a venous plexus (Fig. 1.3A). The dura mater extends caudally as far as the level of the S2 vertebra.

Beneath the dura mater is a thinner membrane, the arachnoid (Fig. 1.3B). The arachnoid bridges over surface features of the spinal cord, such as the sulci and the anterior median fissure. Tight junctions between cells of the arachnoid give this membrane a barrier function. The subarachnoid space contains cerebrospinal fluid, which is confined to this space by the barrier properties of the arachnoid. The cerebrospinal fluid originates largely from the choroid plexuses in the cerebral ventricles. The lumbar cistern, which is the subarachnoid space around the cauda equina, serves as a convenient reservoir from which to remove cerebrospinal fluid by lumbar puncture (Fig. 1.1A).

The innermost of the meninges is the pia mater (Fig. 1.3B). This thin membrane adheres tightly to the surface of the spinal cord and thus follows its contours closely. It fuses with astrocytic end-feet, forming a pia-glial membrane. Arachnoid trabeculi are connective tissue attachments between the arachnoid and pia. A thickening of the pia mater on each side of the spinal cord is called the dentate (or denticulate) ligament (Fig. 1.3B). Passing through the arachnoid, the dentate ligament makes a series of 20–22 firm attachments to the dura along the length of the spinal cord (Fig. 1.3B). The caudal end of the spinal cord is connected to the coccyx by the filum terminale (Fig. 1.1A,B). This is another thickening of the pia mater that penetrates the arachnoid and fuses with the dura. The dentate ligaments and filum terminale permit some movement of the dura without allowing much movement of the spinal cord (Romanes, 1981).

(Standard references that describe the anatomy of the spinal cord include Mettler, 1948; Crosby et al., 1962; Carpenter and Sutin, 1983; Nolte, 2002; Paxinos and Mai, 2004).

1.3 Cross-Sectional Anatomy of the Spinal Cord

A transverse section of the spinal cord reveals the basic arrangement of the spinal cord white and gray matter. The white matter is located around the periphery of the spinal cord, and the gray matter forms a butterfly-shaped region deep to the white matter (Fig. 1.4). The grooves at the surface of the spinal cord allow the subdivision of the white matter into dorsal, lateral and ventral funiculi, and, in the cervical and upper thoracic spinal cord, the further subdivision of the dorsal funiculus into the fasciculi gracilis and cuneatus (Fig. 1.4A,B). At lower thoracic levels and caudally, the dorsal fasciculus consists of just the fasciculus gracilis (Fig. 1.4C). Just deep to

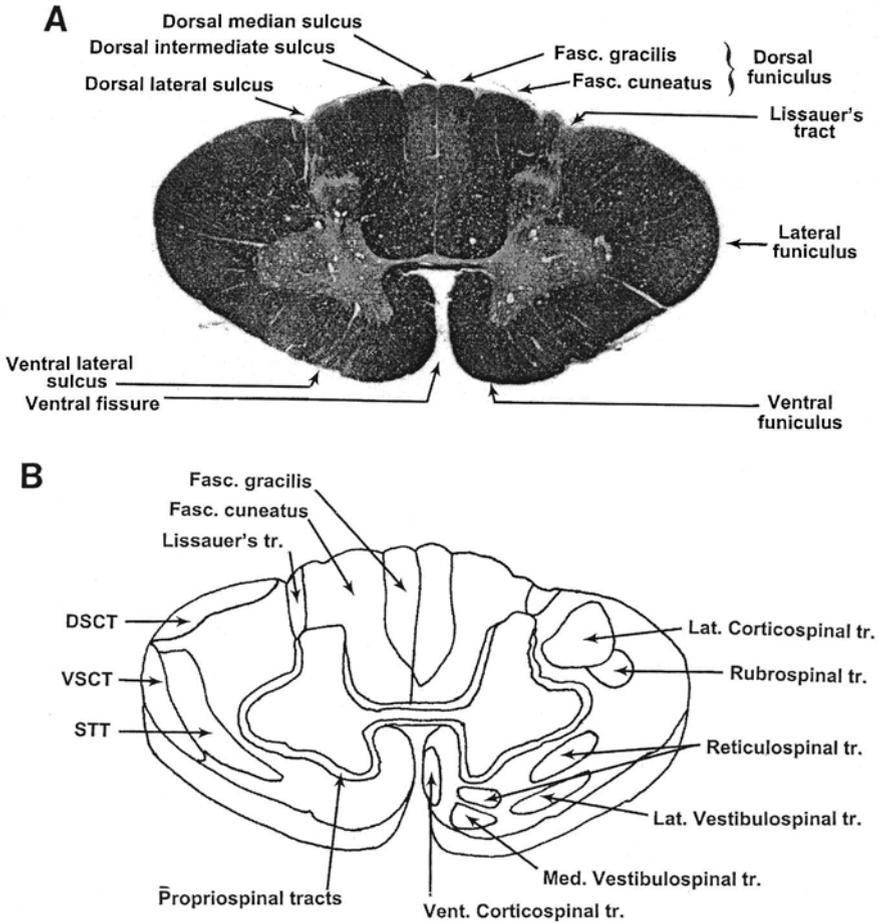
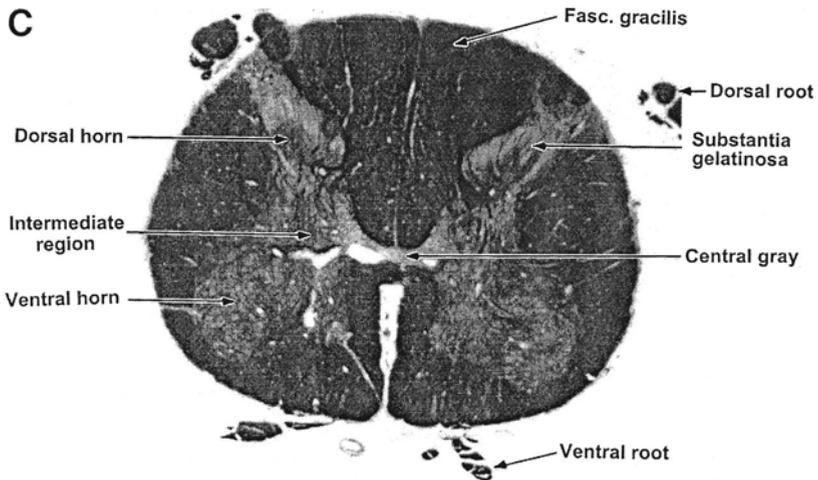


FIG. 1.4A-C. Transverse sections of the spinal cord. **A** Myelin-stained section of cervical enlargement of human spinal cord, emphasizing the different parts of the white matter. The dorsal median and dorsal lateral sulci demarcate the dorsal funiculus. Within the dorsal funiculus, the fasciculus gracilis is separated from the fasciculus cuneatus by the dorsal intermediate sulcus. Lissauer's tract is shown deep to the dorsal lateral sulcus. Between the dorsal lateral and the ventral lateral sulci is the lateral funiculus. The ventral lateral sulcus and the ventral median fissure are the boundaries of the ventral funiculus. **B** Drawing of a section through the cervical enlargement and showing the approximate locations of ascending (*left side of section*) and descending (*right side of section*) tracts. Propriospinal tracts surrounding the gray matter are also indicated. **C** Lumbar enlargement, emphasizing the main parts of the gray matter, including the dorsal horn, intermediate region, ventral horn and central gray. The dorsal funiculus includes only the fasciculus gracilis. The substantia gelatinosa is a special part of the gray matter that is lightly stained because of the relative lack of myelin in this region. These different parts of the gray matter are present throughout the length of the spinal cord

FIG. 1.4A–C. *Continued*

the dorsal root entry zone is a bundle of lightly myelinated and unmyelinated axons called Lissauer's tract (Fig. 1.4A,B; Lissauer, 1886).

The dorsal funiculus includes important ascending sensory pathways, the dorsal column pathway, and the postsynaptic dorsal column pathway (see below), and the lateral and ventral funiculi contain several ascending and descending tracts. These long pathways transmit information from the spinal cord to the brain or from the brain to the spinal cord (Fig. 1.4B). The names of these tracts often indicate the origin and destination of these pathways. For example, the dorsal and ventral spinocerebellar tracts (DSCT and VSCT) originate from neurons in the spinal cord and project to the cerebellum, and the lateral and ventral corticospinal tracts originate in the cerebral cortex and project to the spinal cord. Another ascending pathway is the spinothalamic tract (STT), and additional descending tracts include the pontine and medullary reticulospinal tracts, the lateral and medial vestibulospinal tracts, and the rubrospinal tract. The spinal cord white matter also contains propriospinal tracts, some of which are located just outside the gray matter and which interconnect different segmental levels of the spinal cord.

The gray matter of the spinal cord can be subdivided into the dorsal horn, intermediate region, ventral horn, and central gray (Fig. 1.4C). These extend longitudinally throughout the length of the spinal cord. A part of the dorsal horn called the substantia gelatinosa is prominent in myelin-stained sections because of the relative lack of myelin in this region (Fig. 1.4C; also Fig. 1.5A,B, left side of the sections). The substantia gelatinosa also extends the length of the spinal cord.

The cellular composition of the spinal cord gray matter is best revealed when the sections are stained by the Nissl method. In Nissl-stained sections, the substantia gelatinosa is seen to contain many small, densely packed neurons (Fig. 1.5A,B, right side of the sections). In the ventral horn are the motor nuclei, which contain numerous large alpha motor neurons, as well as smaller gamma motor neurons. An indi-

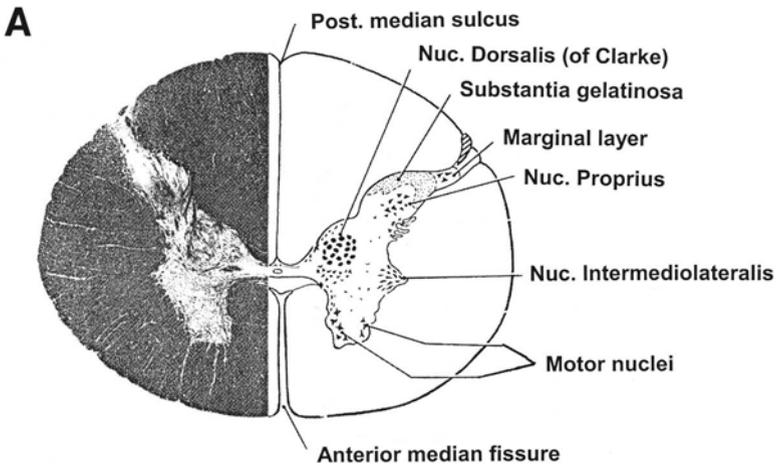


FIG. 1.5A–C. Transverse sections of the human thoracic and sacral spinal cord. The *left sides* of the sections in A and B are stained for myelin. The *right sides* of these sections are drawings of the locations of neuronal cell bodies stained with the Nissl technique. A Section through spinal cord segment T12 showing the locations of neurons in the marginal layer, substantia gelatinosa, nucleus proprius, Clarke’s column (or nucleus dorsalis), the intermediolateral cell column, and motor nuclei. B Section through the S3 segment showing the locations of neurons in the marginal layer, substantia gelatinosa, nucleus proprius, sacral parasympathetic nucleus and motor nuclei (modified from Carpenter and Sutin, 1983). C Section through the lumbar enlargement showing the cell body, dendrites, and axon of an alpha motor neuron that had been injected intracellularly with horseradish peroxidase (from Nolte, 2002)

vidual alpha motor neuron labeled intracellularly with horseradish peroxidase is shown in Fig. 1.5C to have dendrites that are widely distributed throughout much of the ventral horn. In the enlargements, the gray matter of the spinal cord is expanded compared with that in the thoracic, upper lumbar and sacral levels (cf. sections through enlargements in Fig. 1.4 with sections through the thoracic and sacral spinal cord in Fig. 1.5A,B). This is especially evident for the ventral horn, which contains several columns of motor neurons. A given motor neuron column innervates a particular muscle and may extend longitudinally for several segments. The motor nuclei have a somatotopic arrangement. Motor neurons that supply distal muscles are located dorsolaterally, those that supply proximal muscles are placed more ventromedially, and motor neurons that innervate axial muscles are located medially in the ventral horn (Figs. 1.5B and 1.6).

At certain levels of the spinal cord, there are additional components of the gray matter. In the thoracic and upper lumbar spinal cord, there is a lateral horn, which contains a column of sympathetic preganglionic neurons called the intermediolateral cell column (Fig. 1.5A). At the same segmental levels, the intermediate region also contains the nucleus dorsalis (or Clarke’s column); this nucleus projects to the cerebellum through the dorsal spinocerebellar tract (Fig. 1.5A). In the sacral spinal cord, the sacral parasympathetic nucleus (Fig. 1.5B) is located in a position similar to that of the sympathetic intermediolateral cell column and is composed of parasympathetic

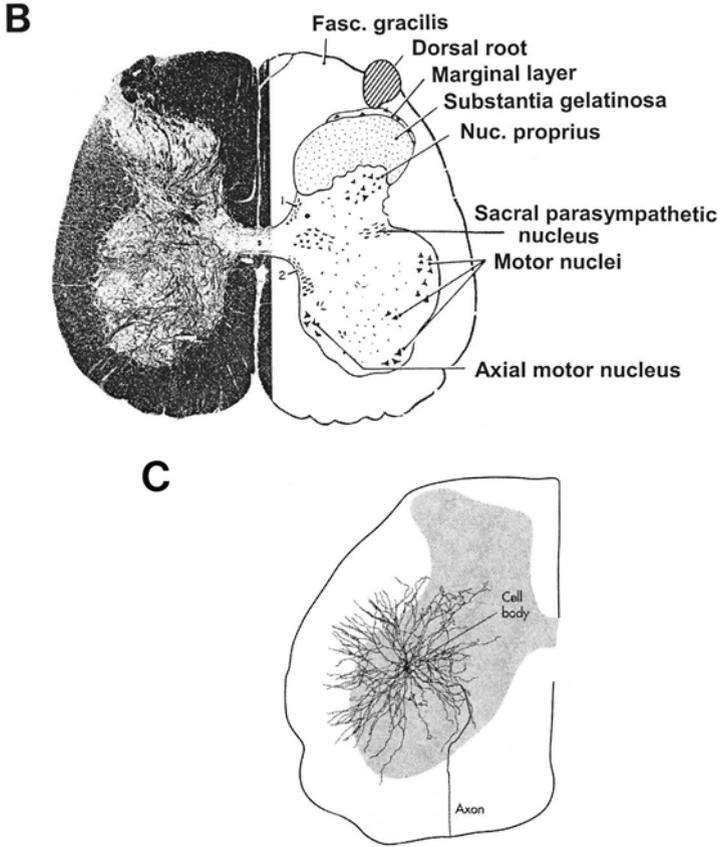


FIG. 1.5A-C. *Continued*

preganglionic neurons (Nadelhaft et al., 1983). The sacral parasympathetic nucleus extends through segments S1–S3. Visceral afferents reaching the spinal cord through the pelvic nerve enter Lissauer’s tract and synapse on interneurons in the vicinity of the sacral parasympathetic nucleus. The neural circuits that are formed contribute to visceral reflexes.

A Swedish neuroanatomist named Rexed was able to show in Nissl-stained material that the spinal cord gray matter of cats is layered (Fig. 1.6A; Rexed, 1952, 1954). He subdivided the gray matter into 10 layers (Rexed’s laminae). In the enlargements, the dorsal horn includes laminae I–VI (the substantia gelatinosa is equivalent to lamina II). The intermediate region is the dorsal part of lamina VII. The medial ventral horn is lamina VIII, and the motor nuclei collectively form lamina IX (which includes several separate motor neuron columns). The gray matter around the central canal (central gray) is lamina X. In the thoracic and upper lumbar cord, the intermediolat-