英文影印版

脊柱外科手术学

OPERATIVE SPINE SURGERY

William C. Welch • George B. Jacobs • Roger P. Jackson

科学出版社

McGraw-Hill

英 文 影 印 版

脊柱外科手术学

Operative Spine Surgery

William C. Welch

George B. Jacobs

Roger P. Jackson

科 学 出 版 社

McGraw-Hill

2 0 0 0

IE ISBN 0-07-1184864

北京市版权局版权登记号：图字 01-2000-1763

图书在版编目（CIP）数据

脊柱外科技术学 = Operative Spine Surgery：英文影印版/（美）韦尔奇（Welch, W. C.），（美）杰科比（Jacob, G. B.），（美）杰克逊（Jackson, R. P.）主编. 北京：科学出版社，2000
据麦格劳—希尔出版公司原版影印
ISBN 7-03-008725-9

Ⅰ. 脊…　Ⅱ. ①韦…　②杰…　③杰…　Ⅲ. 脊椎病-外科手术　Ⅳ. R681.5

中国版本图书馆 CIP 数据核字（2000）第 67028 号

科学出版社出版
北京东黄城根北街16号
邮政编码：100717
中国科学院印刷厂印刷

科学出版社发行　各地新华书店经销

*

2000年9月第一版　开本：889×1194　1/16
2000年9月第一次印刷　印张：18　插页：1
印数：1—3 000　字数：611 000

定价：59.00 元

（如有印装质量问题，我社负责调换〈科印〉）

CONTRIBUTORS

Gordon R. Bell, MD
Vice Chairman, Department of Orthopaedic Surgery
Head, Section of Spinal Surgery
The Cleveland Clinic
Department of Orthopaedic Surgery
Cleveland, Ohio

Stephen M. Bell, MD
Resident Surgeon
Department of Orthopaedics
The University of Michigan Medical Center
Ann Arbor, Michigan

Kimberly Cantees, MD
Staff Anesthesiologist
The Western Pennsylvania Hospital
Pain Management Center
Pittsburgh, Pennsylvania

William F. Donaldson III, MD
Director
Spine Service and Orthopaedic Surgery
University of Pittsburgh Medical Center
Assistant Professor of Orthopaedic
and Neurological Surgery
University of Pittsburgh Medical School
Pittsburgh, Pennsylvania

Joseph A. Epstein, MD
Long Island Neurological Associates
New Hyde Park, New York

Nancy E. Epstein, MD
Associate Clinical Professor of Surgery (Neurosurgery)
Cornell University Medical College
New York City, New York

Robert J. Goitz, MD
Resident
Department of Orthopaedic Surgery
University of Pittsburgh School of Medicine
Pittsburgh, Pennsylvania

Gregory P. Graziano, MD
Associate Professor
University of Michigan Medical Center
Ann Arbor Michigan

Roger P. Jackson, MD
Spine and Scoliosis Surgery, Inc.
North Kansas City, Missouri

George B. Jacobs, MD
Chairman, Department of Neurosurgery
Chief, Spine Services
Hackensack University Medical Center
Hackensack, New Jersey
Professor of Surgery
University of Medicine and Dentistry of New Jersey
Newark, New Jersey

Parviz Kambin, MD
Professor of Orthopaedic Surgery
Allegheny University of the Health Sciences
MCP Hahnemann School of Medicine
Director, Spine Diagnostic and Treatment Center
Allegheny University Hospitals
Philadelphia, Pennsylvania

James D. Kang, MD
Assistant Professor of Orthopaedic Surgery
University of Pittsburgh School of Medicine
Pittsburgh, Pennsylvania

Reginald Q. Knight, MD
Seattle Spine Group
Seattle, Washington

William C. Lauerman, MD
Chief
Division of Spinal Surgery
Associate Professor of Orthopaedic Surgery
Georgetown University Hospital
Washington, DC

Steven C. Levin, MD
Assistant Professor of Anesthesiology
and Pain Management
Director, Pain Fellowship
Yale University School of Medicine
New Haven, Connecticut

Thomas J. Lovely, MD
Albany-Troy Neurosurgical Associates
Albany, New York

Joseph V. McDonald, MD
Emeritus Neurosurgeon-in-Chief
Division of Neurosurgery
Strong Memorial Hospital
Emeritus Professor of Neurosurgery
University of Rochester School of Medicine
Rochester, New York

Aage R. Møller, PhD
Margaret F. Jonsson Professor
University of Texas at Dallas
Callier Center for Communication Disorders
Dallas, Texas

Irene P. Osborn, MD
Director
Division of Neuroanesthesia
New York University Medical Center
Assistant Professor of Anesthesiology
New York University Medical School
New York City, New York

Gregory J. Przybylski, MD
Assistant Professor
Department of Neurosurgery
Jefferson Medical College
Philadelphia, Pennsylvania

Patrick A. Roth, MD
Assistant Professor of Surgery
Hackensack University Medical Center
Assistant Professor of Neurosurgery
University of Medicine and Dentistry of New Jersey
Hackensack, New Jersey

Harry L. Shufflebarger, MD
Professor
Department of Orthopaedics and Rehabilitation
University of Miami School of Medicine
Coral Gables, Florida

Michael D. Smith, MD
Staff Surgeon
Minnesota Spine Center
Clinical Instructor
University of Minnesota
Minneapolis, Minnesota

Brett R. Stacey, MD
Associate Professor
Director, Pain Management Center
Oregon Health Sciences University
Portland, Oregon

William C. Welch, MD
Associate Professor
Departments of Neurological Surgery
and Orthopaedic Surgery
University of Pittsburgh School of Medicine
The University of Pittsburgh School of Health
and Rehabilitation Sciences
Director of Neurosurgical Spine Services
University of Pittsburgh Medical Center
Pittsburgh, Pennsylvania

PREFACE

The rapid growth of the specialty of spine surgery has made it extremely difficult for residents in general orthopedics and neurosurgery and for physicians practicing in other disciplines to master the knowledge required to understand this complex and constantly changing field. Physicians who provide primary care to patients and specialists in general orthopedics and neurosurgery are often asked to explain the technical details of instrumentation and implants as well as the reasons for selecting a specific spine surgery procedure. *Operative Spine Surgery* is the first simple reference guide that makes this type of information readily available.

Our involvement with the education of residents in orthopedics, neurosurgery, and general surgery, as well as fellows in spine surgery, motivated us to undertake this major task. Discussions with our colleagues reinforced the conclusions that the effort was justified and filled a void in the plethora of ever-increasing spine literature.

Operative Spine Surgery is not an exhaustive compendium of spine surgery because multiple comprehensive reference texts already exist. But these texts were prepared with surgeons and allied specialists in the spine field in mind, whereas this book is intended for residents at the beginning of their training and for practitioners of primary specialties.

To accomplish our goal, we recruited respected experts in the field of spine surgery in order to present an organized overview of our relatively new surgical specialty. The illustrations that were chosen for the book were selected because of their clarity and ease of presentation. The book editors have spent countless hours attempting to simplify the material presented and make it easier to understand.

The distinguished surgeon Allen O. Whipple defined surgery as the branch of medical science which uses mechanical or operative measures for healing diseases, deformities, or injuries. There is no better definition for spine surgery. *Operative Spine Surgery* is devoted to this concept.

William C. Welch, MD
George B. Jacobs, MD
Roger P. Jackson, MD

OPERATIVE SPINE SURGERY

CONTENTS

1

INTRODUCTION

William C. Welch, George B. Jacobs, and Roger P. Jackson

Leon Wiltse, in the *The Adult Spine,*[1] justified the development of the spine as a specialty. "The spine remains a most challenging subject. Every new advance in surgical technique or diagnostic capability opens up new possibilities for treatment. There is reason to believe that we are on the threshold of even greater moves forward."

One hundred years of progress distance us from the first recorded instrumentation of the spine by W.F. Wilkins, who used a silver wire to reduce and hold together a fracture dislocation of T12 on L1.[2] His attempt was daring and primitive, but the theoretical framework of fracture treatment has not changed.

Early spinal fusion for nontraumatic disorders was an attempt to correct the progressive deformities of tuberculosis. Early fusion techniques were expanded to the treatment of fractures, scoliosis, and finally degenerative and neoplastic disease.

Diagnostic modalities have kept pace with the new surgical techniques over the last century. Accurate imaging studies with contrast enhancement, thin cuts, three-dimensional reconstruction, and dynamic motion sequences have eliminated, except for special circumstances, the need and potential risk of invasive and uncomfortable diagnostic studies like myelography.

The spine patient continues to consume more and more efforts and funds of the health care market. Claims for workers' compensation and automobile injuries often include demands for physician-certified disabling spine problems. This trend can be expected to increase over the next decade based on prior performance.

The specialty of spinal surgery is well established at this time. Primary training in orthopedics or neurosurgery, followed by a spine fellowship of 1 year, represents entry-level education for new spine specialists. Interest in deformity or degenerative disease has further subspecialized an already narrow field.

The need for quality control in the treatment of spinal disorders has led to the development of dedicated multidisciplinary spine centers and the algorithmic approach to the care of the spine patient. The use of algorithms is intended to standardize reasonable treatment plans and eliminate unnecessary operations or useless conservative therapy.

The list of new publications in the treatment of spinal disorders appears longer each year. We believe our book occupies a distinct place in the current spine literature and meets a heretofore unanswered need. Our contributors, all recognized experts in their field, were asked to concentrate on an analysis of the problems encountered in specific spinal disorders or areas and provide the current concepts of treatment for our readers.

This book is directed to the orthopedic or neurosurgical resident beginning training or intending to remain a generalist. It provides a simple background of data for the primary care physician who serves as the single major resource for information to his or her patients. The spine fellow or spine specialist will find this book useful in organizing a topic and in reviewing basic concepts.

The treatment of spinal disorders is assuming more complexity as new modalities and techniques develop. If our work serves to clarify an increasingly more complicated topic we will be completely satisfied with our efforts.

REFERENCES

1. Wiltse LL. The history of spinal disorders, in Frymoyer JW, Ducker TB, Hadler NM, Kostuik JP, Weinstein JN, Whitecloud TS III (eds). *The Adult Spine,* ed 2. Philadelphia: Lippincott-Raven;1997:pp 3–40.
2. Wilkins WF. Separation of the vertebrae with protrusion of hernia between the same-operation-cure. St. Louis Med Surg J. 1888;54:340–341.

2

SURGICAL ANATOMY OF THE SPINE

Thomas J. Lovely

The spine is an excellent example of how form follows function in the human body. Nowhere else in the skeletal system do the intricacies of the relationships between bone, ligaments, neural tissue, the vascular system, and biomechanical principles become more apparent. As our understanding of these complex interrelationships grows, so do our options for medical and surgical treatments of congenital abnormalities, trauma, degenerative disease, tumors, and infectious processes of the spine.

A basic knowledge of spinal anatomy, therefore, is critical for any surgeon undertaking a spinal operation. Our knowledge of anatomic means, extremes, and relationships has attempted to keep pace with rapidly expanding choices in our surgical armamentarium. The purpose of this chapter, then, is to provide the surgeon with a basic overview of the anatomy of the cervical, thoracic, and lumbosacral spine, and to provide some important points for consideration when contemplating surgical procedures.

The spinal column usually consists of 33 vertebrae: 7 cervical, 12 thoracic, 5 lumbar, 5 fused segments forming the sacrum, and 4 to 5 irregular bony segments making up the coccyx (Fig. 2–1). Typically, an individual vertebral segment is formed by the body anteriorly, connected to paired pedicles. The paired lamina join dorsally at the spinous process, and together the body, pedicles, and lamina with midline spinous process form a ring that defines the vertebral or spinal canal, the home of the spinal cord and caudally, the cauda equina. The lateral transverse processes are near the junction of the pedicles and lamina. Also at the junction of the pedicles and lamina are the lateral masses, forming the articular processes, or zygapophyseal joints. These joints, also known as facet joints, have a superior process, which is directed dorsally and medially, as well as an inferior facet directed ventrally and laterally. These facets form true joints, which are encapsulated, allowing a gliding action between the superior and inferior articulations of the vertebral segments. The individual segments are also connected by paired ligamenta flava, intertransverse ligaments, and the unpaired interspinous ligament, supraspinous ligament, posterior longitudinal ligament, and anterior longitudinal ligament. These ligaments and articulations will be considered separately.

CERVICAL SPINE

The first two cervical vertebrae—the atlas and axis, respectively—are specialized in form and function and deserve special mention (Fig. 2–2). The atlas is a bony ring, formed by an anterior and a posterior arch connected by paired lateral masses. There is no vertebral body, but rather an anterior ring which connects the lateral masses and contains a small tubercle, the insertion point of the longus colli muscle. The lateral masses are a combination of pedicles and articular processes. The superior facets are concave, and face rostrally in order to articulate with the occipital condyles of the skull, while the inferior facets angle caudally and medially to rest on the superior facets of the axis, which project rostrally and laterally. The posterior arch is rounded and corresponds to the lamina. In the midline posteriorly is a small tubercle, the analog of the spinous process, which serves as an attachment for some of the suboccipital musculature.

The atlas is also characterized by grooves that are found posteriorly behind the lateral masses. These grooves house the vertebral arteries, which turn from their exit at the lateral transverse foramen to run horizontally and medially along the posterior arch of C1 for a variable distance before piercing the atlanto-occipital

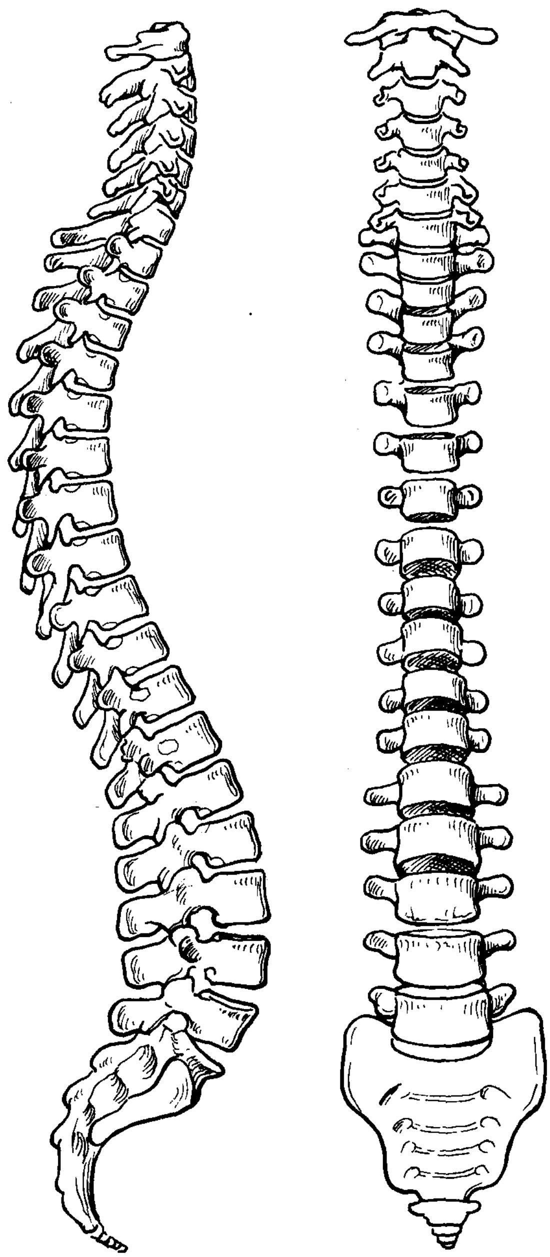

Figure 2–1. Lateral **(A)** and anterior **(B)** views of the adult spine with the normal cervical and lumbar lordoses and thoracic kyphosis.

membrane and entering the skull through the foramen magnum.

Doherty and Heggeness[1] examined 88 anatomic specimens of C1. There was considerable variability in measurements of the height of the lateral mass, sagittal width of the bone, anterior-posterior thickness, height of the anterior and posterior rings, and the thickness of the cortical versus cancellous makeup of the bone. There was, however, a striking uniformity of the size and shape of the vertebral foramen, measuring 32 mm in the sagittal plane and 29 mm in the transverse plane.

The second cervical vertebra, the axis, is also unusual. Its most prominent feature is the odontoid process, or dens, which prevents horizontal displacement of the atlas. The base of the dens melds into the body of C2, which anteriorly and caudally has a prominent lip that extends over the first disc and the upper body of C3. Laterally, the superior facets angle rostrally and laterally, to articulate with the facets of the atlas. The pedicles, which merge with the sides of the body and dens, are caudal to the superior facet. They extend into the lamina, which are also broad and strong. The lamina meet in the midline at the spinous process, which is quite prominent. The spinous process is grooved on its caudal surface for muscular attachments and is bifed. The lower aspect of C2 is a transition from the specialized articulations above, to the more uniform subaxial cervical vertebrae. This articulation comes in the form of the inferior facet, which like others is directed caudally and somewhat laterally. The transverse processes are small and are perforated by the foramen transversarium to allow passage of the vertebral artery.

Doherty and Heggeness[2] have also looked at the quantitative anatomy of the axis. In examining 51 specimens, they have found that like C1, there is a large variation. The largest variation was found in the angle of the dens in the coronal plane. This angle ranged from −2° (pointing anteriorly) to 42°. They could find no significant correlation between the various measured dimensions. Interestingly, like their study of the atlas,[1] the spinal canal dimensions were quite constant, despite the anatomic variations of the bone. The dens angle has been used as a criterion to determine fracture or instability. The recognition that the dens can have a variable angle and, therefore, is not a reliable indicator of injury is not only suggested by anatomic studies[2] but by clinical radiographic studies as well.[3]

The quantitative anatomy of the dens has also been examined.[4,5] The dens projects superiorly for approximately 1.5 cm from the body of C2. It usually has a slight constriction where it joins the body, known as the "neck" or "waist." A smooth oval area is found ventrally where it articulates with the posterior aspect of the anterior arch of C1. This articulation is a true synovial lined joint. Grooves on the dorsal surface near the arch, extending to the sides of the dens, are for attachments of the transverse atlantal ligament, which keeps the odontoid in position. The top, or apex, of the dens is pointed, serving as the attachment for the apical ligament. The alar ligaments attach to roughened promi-

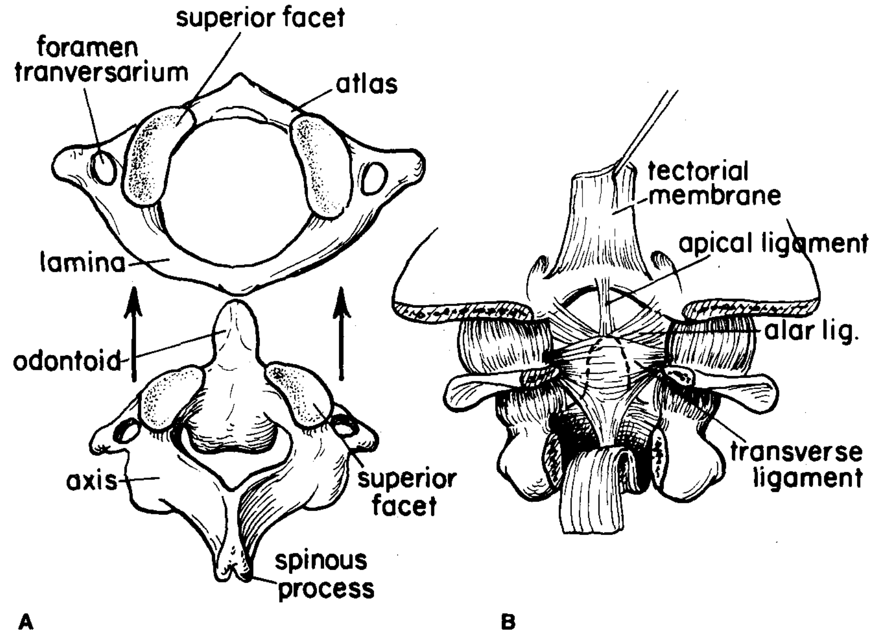

Figure 2–2. A. Rostral view of the atlas and posterior view of the axis. **B.** Posterior view of the atlantoaxial articulation. The tectorial membrane has been sectioned and retracted to expose the apical, alar, and transverse ligaments, which combine to form the "cruciate" ligament.

nences just posterior to the apex. The apical and alar ligaments connect the dens to the base of the skull.

Schaffler and associates[5] examined 122 C2 specimens in order to describe the morphology of the dens. They found the mean odontoid height to be 14.4 mm in all specimens, but that significant differences existed in that men were higher than women in dens height and that dens height was approximately 11% greater in whites than blacks. Anterior vertebral body height was always greater than the posterior body height measurement and dens diameters were variable. The smallest anterior-posterior diameter was always located at the level of the transverse ligament at the odontoid "neck." In odontoid fractures treated with anterior screw placement, typically 4.0 or 4.5-mm cancellous screws are employed, and if possible, two screws are placed to afford better stability and to prevent rotation of the odontoid. From their measurements, not all odontoids will have the necessary dimensions to accommodate two screws, and therefore, it is imperative that accurate measurements be made radiographically before choosing an operative approach. A similar study by Heller and co-workers[4] likewise noted variations in odontoid diameters that might limit screw placement. They also noted that cortical thickness is variable, and because the screws are inserted into the medullary cavity, this too may be an eliminating factor and needs to be evaluated prior to attempting anterior fixation.

The middle and lower cervical vertebrae share more common characteristics (Fig. 2–3). As they bear the least weight with respect to the rest of the spine, they are smaller. The vertebral bodies are characterized by a general increase in width and depth from C2 to C7.[6] The transverse dimensions are always greater than the sagittal dimensions.[7] The heights, however, remain relatively constant. The rostral surface is unique in that the lateral edges of each body take a sharp turn upward, giving it a concave shape, to form the uncinate processes. The caudal surfaces are convex and, laterally, have shallow concavities to receive the projecting uncinate processes of the body below. These articulations form the "uncinate" or "oncovertebral" joints. The oncovertebral joint may contain cartilage, loose connective tissue, or even a synovial lining.[8]

The pedicles attach anteromedially, midway between the cranial and caudal borders of the body. They project out posterolaterally at an angle between 40 and 60° with respect to the posterior margin of the vertebral body, connecting to the lateral masses dorsally.[8] This angle, however, does decrease with progression caudally.[7] The pedicles also initially project caudally about 8°, gradually changing to angle 11° above the transverse plane at C7. The lateral masses are formed by the superior and inferior facets, which are fused to form an "articular pillar." The pillars project laterally from the point that the pedicle joins the lamina. The surfaces of the joints are flat

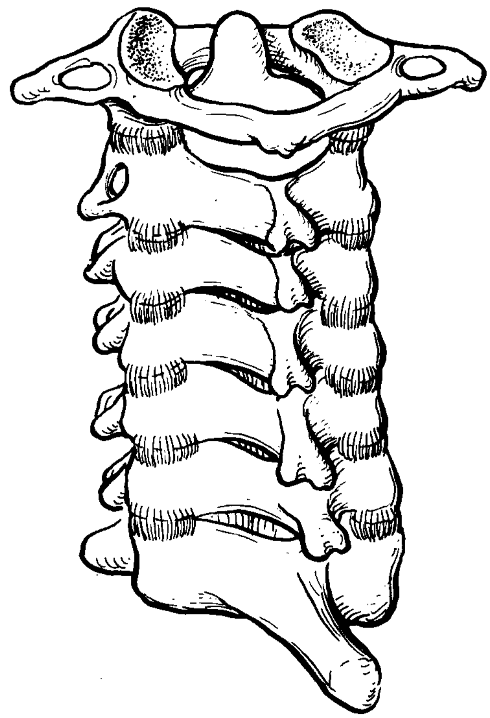

Figure 2–3. An oblique-posterior view of the cervical spine.

and oval in shape. The superior facets face dorsally, rostrally, and slightly medially; the inferior surfaces face ventrally, caudally, and slightly laterally.[9] The joints form an angle of 45° both in the coronal and sagittal planes.[10] Anatomic studies analyzing the position of the nerve roots with respect to the articular pillars have shown that the posterior midpoint of the lateral mass is a safe point for screw insertion for cervical plating.[11]

The lamina are narrow, and have a thinner superior edge compared to the caudal margin.[12] They join in the midline at the origin of the spinous processes. The processes tend to be short and bifed, often with the two divisions being unequal in size. The length of the spinous processes decreases from C2 to C3, remains relatively constant from C3 to C5, and then increases to C7.[7]

The vertebral body and posterior arch form a triangular-shaped canal that is greater in its transverse diameter than sagittal. The transverse diameter remains relatively constant, averaging 24 to 30 mm, while the sagittal diameter decreases from C2 to C7, moving toward the more oval-shaped canal of the thoracic spine, and giving C7 the smallest cross-sectional area.[7,8] Lastly, the transverse processes of the first six cervical vertebrae are perforated by the foramen transversaria, which allows for passage of the vertebral artery and vein and sympathetic nerves. Each process has a ventral and dorsal aspect that ends in a tubercle. The ventral aspect ends in the anterior tubercle, while the dorsal aspect ends in the ventrally and laterally directed posterior tubercle. The tubercles serve as the attachment for anterior and posterior cervical musculature, respectively. The bone connecting the ventral and dorsal aspects is grooved on its rostral surface to accommodate the passage of the corresponding cervical nerve. It has been noted that there can be double foramina in the transverse processes, most commonly occurring at C6.[13]

The seventh cervical vertebra represents the transition from the cervical to thoracic spine. It is characterized by the caudal surface of the vertebral body being larger than the rostral surface. The articulating facets are more steeply inclined, as will be found in the thoracic region, and the transverse processes are blunt and thick. The presence of a foramen transversarium is variable. C7 is also characterized by a prominent spinous process, projecting more in a horizontal plane. This large process is not bifurcated, is easily palpable, and ends in a tubercle that is the insertion point for the nuchal ligament.

THORACIC SPINE

The thoracic spine can be divided into three areas, each distinctive (Fig. 2–4).[14] The upper thoracic spine represents the transition from cervical to thoracic region; the lower thoracic spine represents the transition from thoracic to lumbar region; and there is a middle zone. The vertebral bodies of the thoracic spine are intermediate in size between the cervical and lumbar areas. Vertebral body width in the coronal plane and depth in the sagittal plane were measured by Panjabi and associates[14] in 144 vertebrae. They found that there was a gradual increase in the width and depth from T1 to T12 and that width was greater than the depth in both the upper and lower thoracic segments, but equal in the middle levels. Posterior vertebral body heights were measured and increased at each level, with an average increase of 0.8 mm per level. This allowed for a transverse plane wedge angle of 3.8° per body, giving the thoracic spine its normal kyphotic configuration.

Connecting to the vertebral bodies are the pedicles. In light of the recent explosion of instrumentation devices available, a lot of attention has been focused on the pedicles. In the thoracic spine they angle rostrally from a maximum of 27° at T1, decreasing to 10° at T12. In the

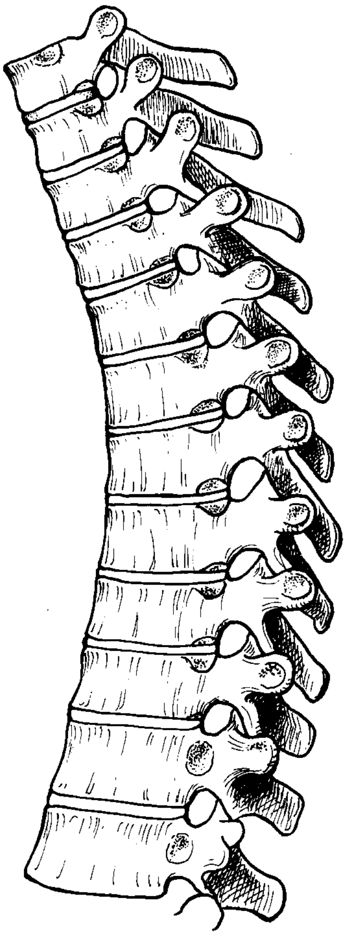

Figure 2–4. Lateral view of the 12 vertebrae of the thoracic spine.

transverse plane they project laterally 9° from T3 to T11, decreasing to 5°at T12, making the transition to the lumbar spine.[14] Pedicle diameters have been measured as well. The average height of 9.6 mm at T1 increases to 11.9 mm at T3, and then remains constant with a mean of 11.9 mm from T3 to T8. From T8 to T12, the height increased by an average of 1 mm per level. The pedicle width was larger at T1, measuring 8.4 mm, and decreasing to 6.3 from T3 to T8. From T8 to T12 the width also increased 0.7 mm per level.[14] Pedicle dimensions have been reviewed for the thoracic and lumbar spines, and more variation was found in the thoracic level than in the lower lumbar segments.[15–18] These variations are important in that preoperative measurements need to be made before pedicle screw fixation is attempted. The lamina are thick, broad, and slightly shingled over one another. Connecting the two is the pars interarticularis, which shows an increase in size as the spine progresses caudally.[14] The large spinous processes are triangular in coronal configuration, and remain constant in length from T1 to T10, decreasing in length at T11 and T12. The processes point caudally and have a tuberculated ending.[9]

The articular joints are steep and vertically angled. The superior facets arise from the pedicular-lamina junction, and are oval and convex. All thoracic superior facets face dorsal, and superiolaterally. The inferior facets are fused to the lamina, and project caudal, medial, and ventral. The body and posterior arch form a small oval-shaped vertebral canal. The width of the canal decreases in the upper levels, is smallest from T4 to T9, and enlarges again in the lower thoracic segments, making the midthoracic level the "critical vascular zone."[14]

The transverse processes arise dorsal to the pedicle and superior facet. They are thick and angled in an oblique dorsal-lateral direction. The ventral side has a small concave surface for articulation with the tubercle of the rib. Rib articulations characterize the thoracic spine and deserve special attention. The first rib articulates solely with T1. The caudal border of the body of T1 has a "demi-facet" for articulation with the rostral portion of the second rib. From T2 to T8, demi-facets are found at the superior and inferior posterolateral aspects of the vertebral bodies. T9 may contain a rostral demi-facet but no caudal one, as the tenth rib may articulate solely with T10, via a facet that is partly on the lateral surface of the pedicle. T11 and T12 likewise articulate solely with their respective ribs, via large facets placed laterally over the posterior body and proximal pedicular surface. The transverse processes of the last two thoracic vertebrae no longer attach to the ribs and are smaller in size, making the transition to the lumbar spine.

LUMBAR SPINE

The five lumbar vertebrae are the largest movable segments of the spine (Fig. 2–5). The vertebral body is thicker, with a general increase in width in the transverse plane of approximately 14% from L1 to L5.[19] The sagittal depths, however, remain relatively constant. The height of the body increases as well, except for the posterior body height, which decreases only slightly at L4–5, giving the lumbar spine its characteristic lordosis.[15]

The pedicles extend from the cranial aspect of the body and have been extensively studied.[15–19] In the sagittal plane, the pedicle angle measures from 14.5° at L1 to 24.5° at L5.[16,19] In the transverse plane, the pedicle inclines rostrally above the horizontal plane from 2.5° at L1 to 5.5° at L5.[19] The height and width of the

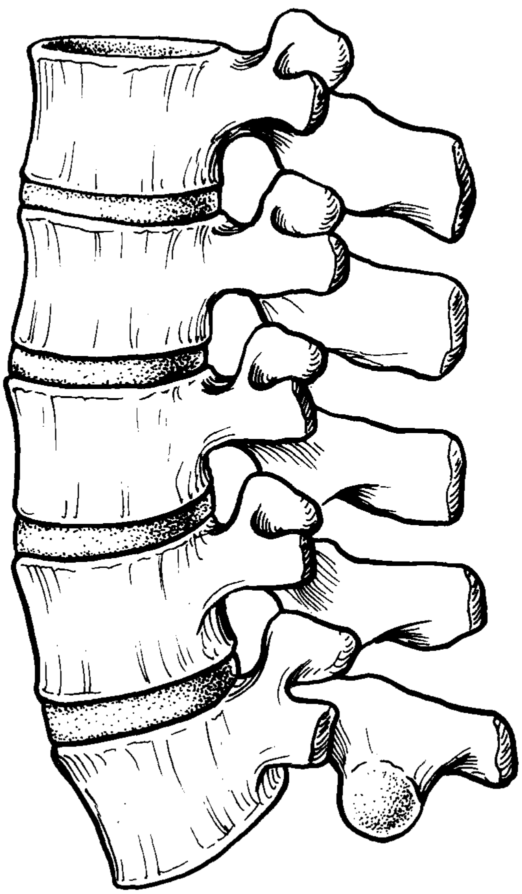

Figure 2–5. Lateral view of the five segments of the lumbar spine.

lumbar pedicles are also of importance with the advent of pedicle screw fixation. Pajabi and colleagues[19] have noted that the average pedicle height of 15.9 mm at L1 decreases to 14.4 mm at L3, increasing again to 19.6 mm at L5. The pedicle widths also show this trend, measuring 8.6 mm at L1, decreasing to 8.2 at L2, and then increasing 3.5 mm per level from L2 to L5, with L5 measuring 18.9 mm. Scoles and co-workers,[17] however, noted that there is more variation in the upper segments than in the lower, and also noted that not all upper lumbar pedicles will accommodate screws.

Like elsewhere in the spine, the pedicles connect to the lamina. In the case of the lumbar spine, the lamina are strong, broad, and short. The midline spinous processes are more rectangular shaped than in the thoracic spine, and are long and strong. Their length increases from L1 to L3 and then decreases somewhat through L5.[19] The spinal canal formed by these elements is triangular in shape, with a width that increases with caudal migration, and depth (anterior–posterior) that decreases from L1 to L3, then increasing from L3 to L5, making L3 the narrowest lumbar segment in the sagittal plane.[19] The cross-sectional area of the canal, then, decreases from L1 to L2, remains relatively constant from L2 to L4, and increases again at L5.

The superior facets, arising at the pedicle-lamina junction, are directed dorsal medially and have concave surfaces. The inferior articulating processes extend from the lamina, are convex, and face ventrolaterally, locking with the laterally placed superior facets of the next caudal vertebrae in a way that limits rotation and flexion. The transverse processes extend off the pedicles and lamina and are long and slender in the upper three lumbar vertebrae, and while straight horizontally above, they incline in the lower two vertebrae. In L4 and L5, the transverse processes are found further ventral, arising from the pedicles and dorsal aspect of the bodies. Unlike the thoracic spine, where they are dorsal to the facet joints, the transverse processes are located ventrally in the lumbar spine. Where the transverse process melds with the superior articulating facet, a large tubercle is found dorsally, which is known as the mammillary process. The mammillary process serves as the origin and insertion site for the epaxial muscles.

The neural foramen of the lumbar spine are quite large and the roots pass under the pedicles to exit the most rostral aspect of the foramen. Unlike the cervical spine, where the angle of the roots is not as steep, the dorsal root ganglion is found at the level of the disc extraforaminally. The rest of the foramen is filled with epidural fat and veins.[8] The space for root exit, however, can be limited by the presence of transforaminal ligaments, which are variable in location, can vary in number, and may not be symmetric.[20]

SACRUM

The sacrum, consisting of five fused vertebrae, is large and triangular shaped (Fig. 2–6). The cephalad surface of the sacrum articulates with the last disc, and laterally, the large oval-shaped superior facets of S1 face dorsally, articulating with the last lumbar vertebrae. These facets prevent ventral migration of L5. The ventral surface of the sacrum is notable for the broad rostral expansion of the body of the first sacral vertebra, known as the sacral promontory, which projects into the pelvis. The concave ventral surface has four transverse ridges. Lateral to the ridges are four paired sacral foramina, which transmit the important motor and sensory ventral sacral roots. They diminish in size with caudal progression.

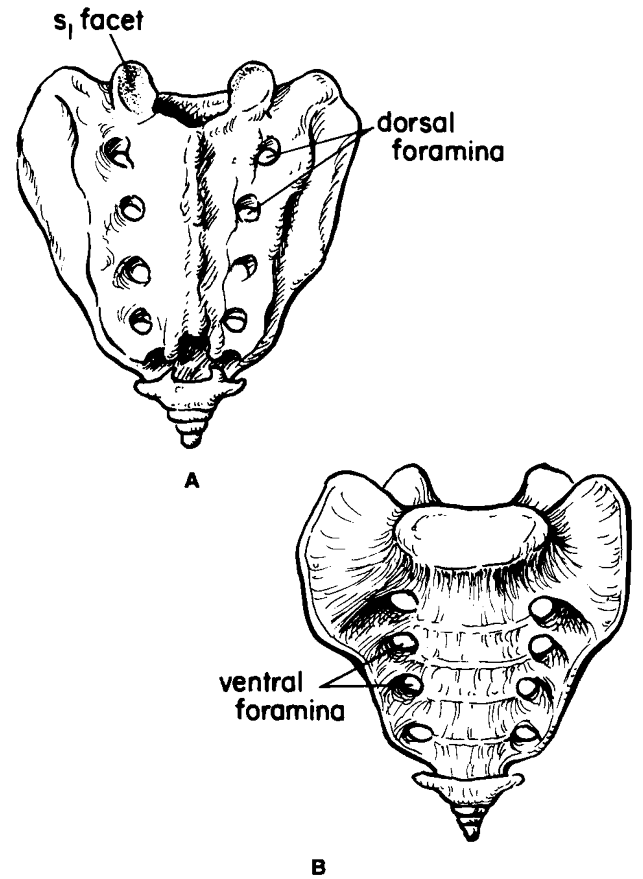

Figure 2–6. Dorsal **(A)** and ventral **(B)** views of the five fused vertebrae composing the sacrum.

Dorsally, the sacrum is characterized by a midline middle sacral crest, the result of the fused spinous processes. A sacral groove is found on either side of the middle crest and is the product of the fused lamina, with the fused articular processes forming an intermediate crest lateral to the grooves. Four paired dorsal sacral foramina lie just medial to the lateral sacral crest, which is the fused analog of the transverse processes. These foramina transmit sensory rootlets only. In the midline the last, or fifth sacral lamina, fail to meet, creating an opening known as the sacral hiatus.[9]

THE COCCYX

Generally comprising four vertebral rudiments, the coccyx not uncommonly has one more or less. The first segment is usually mobile while the latter three are usually fused. The latter three have the rudiments of a vertebral body and transverse process, but no posterior arch.[12]

ARTICULATIONS OF THE VERTEBRAE

The Disc

The intervertebral discs make up about 25% of the height of the spinal column excluding the sacrum. They correspond to the shape of the vertebral bodies they are positioned between, and are composed of an outer annulus fibrosus and an internal nucleus pulposus. They can be of varying thickness in the cervical and lumbar areas, where they are thicker ventrally, contributing to the lordotic curves of these areas. They are usually of uniform thickness in the thoracic spine.

The nucleus pulposus is composed of fibrous strands in a gelatinous matrix. It is elastic and located near the posterior margin of the disc. The outer annulus fibrosus is fibrocartilage arrayed in concentric layers. These layers, or laminae, are composed of fibrocartilage fibers running obliquely. Each successive lamina has the fibers running in opposite directions such that the fibers are almost perpendicular to each other, like the arms of the letter X. As the nucleus is more posteriorly located, the bands are more closely packed and thinner dorsally. The function of the annulus is to withstand tension. The annulus is firmly attached to the outer bony ring of the vertebral body by penetrating fibers known as Sharpey's fibers, which blend with the vertebral periosteum and longitudinal ligaments (Fig. 2–7).

Anterior Longitudinal Ligament

The anterior longitudinal ligament (ALL) stretches cranially from the body of the axis, where it combines with the anterior atlantoaxial ligament, to where it melds with the sacral fibers. It is formed of three layers. The deepest layer connects one vertebral body to another, the intermediate layer stretches across two to three vertebral bodies, and the outermost connects four to five bodies. The fibers are interlaced so that there is much overlap. The ALL is most adherent to the margins or lips of the vertebral bodies, and somewhat to the outer fibrous layers of the discs. It fills the concave anterior surfaces of the vertebral bodies, but is only loosely attached here. It is thickest in the thoracic level and narrowest in the cervical region, widening with caudal progression, so that at the lumbar level it covers most of the anterior and lateral spine.

Posterior Longitudinal Ligament

The posterior longitudinal ligament (PLL), like the ALL, extends from the base of the skull, where it is combined with the tectorial membrane, to the sacrum. It is also thickest in the thoracic area and is broader cra-