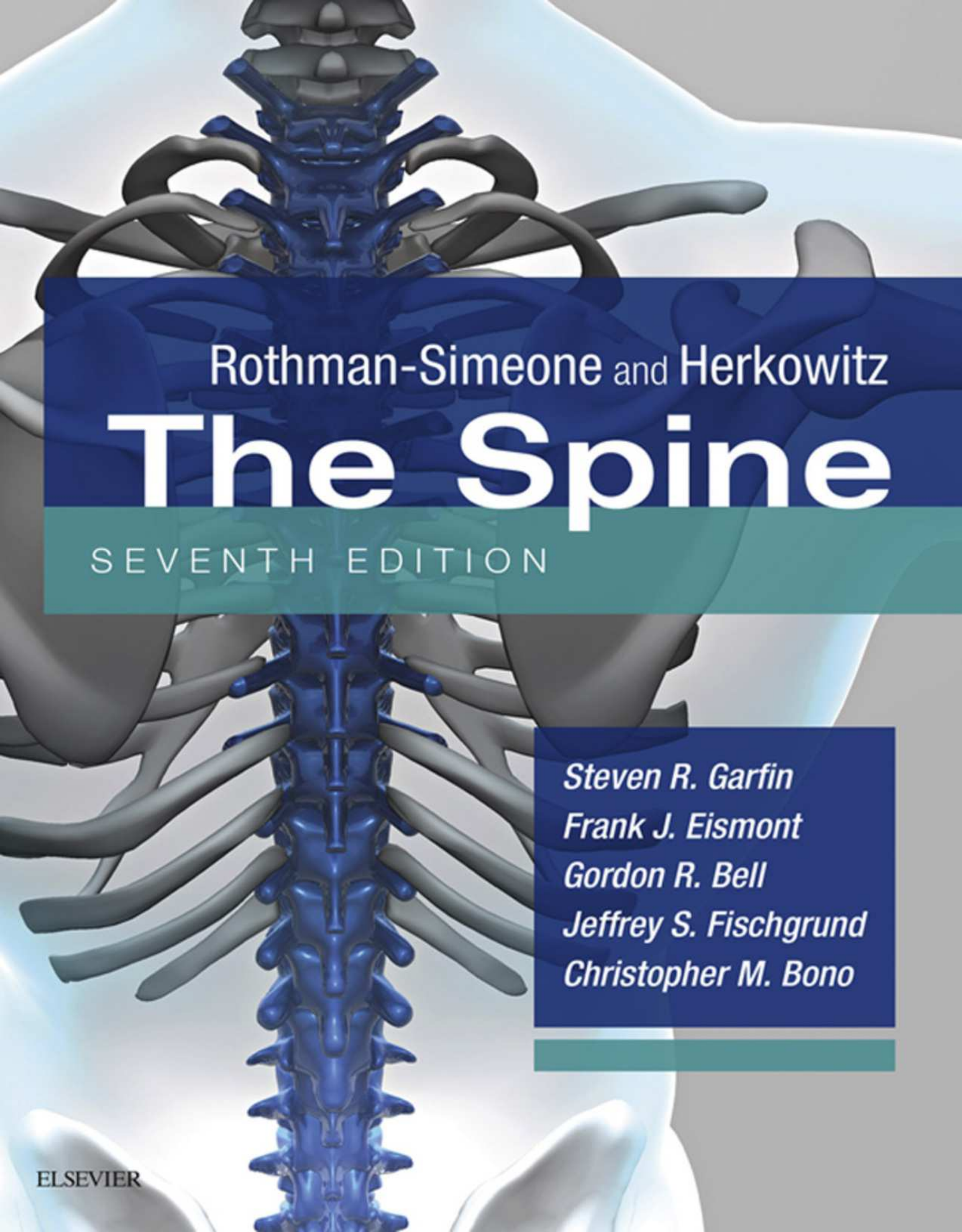

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The Spine

SEVENTH EDITION

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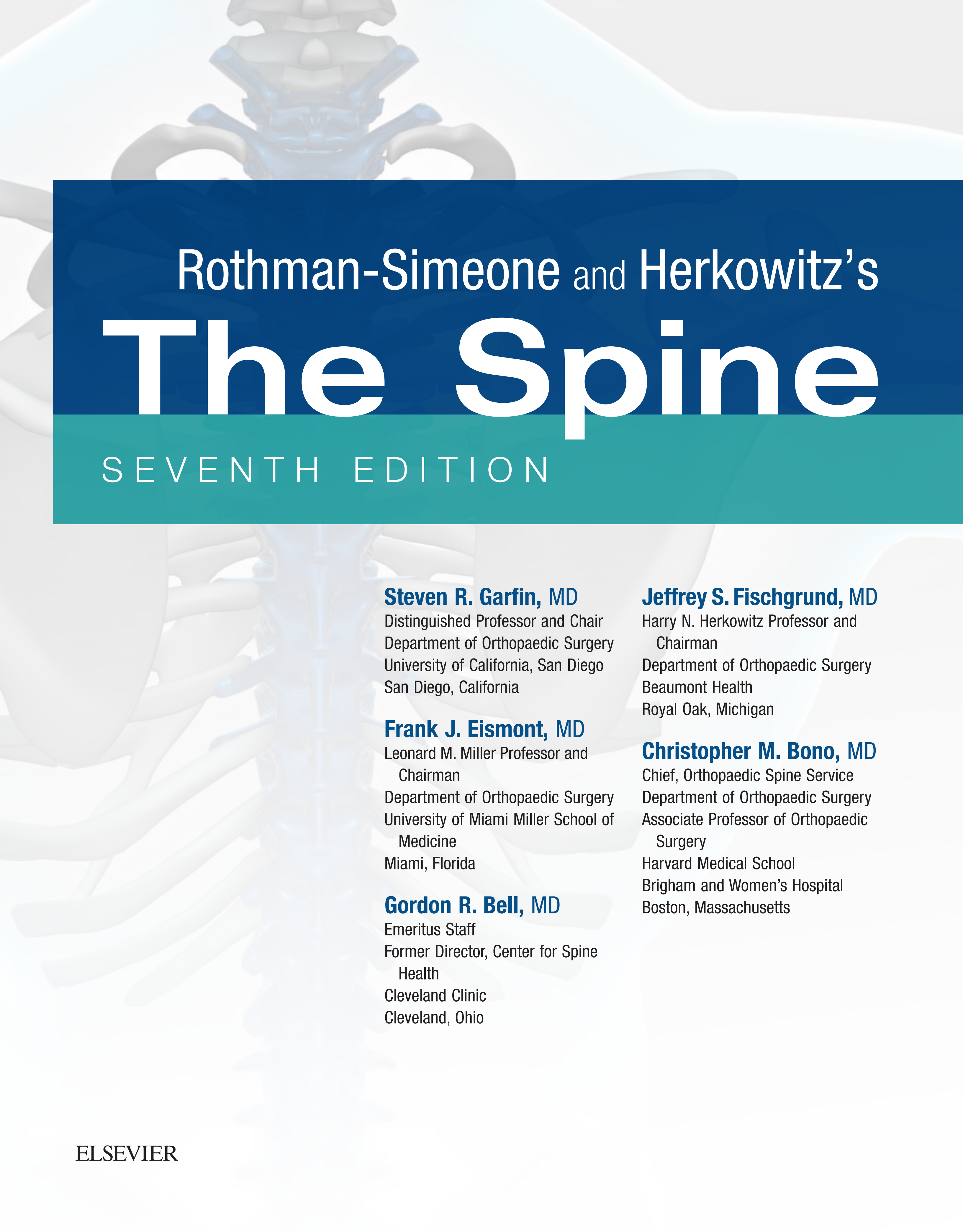

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This edition is dedicated to our esteemed colleague and close friend, Harry N. Herkowitz, MD, who passed away, too early, in June 2013. In a humble attempt to honor him and his legacy, we list Harry's name along with our mentors, thus changing the title of this book to *Rothman-Simeone and Herkowitz's The Spine.* Harry abruptly and unintentionally left the editorship of this great work, of which he truly was the lead and driving force for the first six editions. We present this seventh edition proudly and with the hope that our departed friend would approve. To fill the void left by this one man, we have added two new editors whom Harry respected immensely.

Harry was a luminary in spine. Orthopedic surgeons and neurosurgeons worldwide have benefited from his extensive and significant contributions to the field. Harry worked incredibly hard and accomplished much during his career, rising to the presidency of multiple organizations. He was an excellent and exceptionally active surgeon. He was a surgeon's surgeon, as we say, who was respected as a superb educator, a leader among leaders, and a shining example of a clinical researcher. Harry emphasized and fostered patient-oriented care long before it was in vogue. His manner of practice and teaching epitomized evidence-based medicine, once again before it became a defined process. With an intrinsic drive, he continued to search for excellence. His accomplishments, for a single person, were extraordinary.

Unlike most of us, Harry did not begin his career in a university setting with its attendant peer pressure to publish and produce; his was an internal force. Ultimately he surpassed his original goals. "Don't worry, I will get it done," was a consoling and affirming phrase he used often. And after he uttered those words, we didn't worry, and he would always get it done. Today, it would be unusual to get through a round of fellowship candidate interviews without hearing the word "privademics," and it is to this type of practice that many of our young colleagues aspire. Harry, under the guidance of our mentor Richard Rothman, MD, PhD, blazed a trail into this heretofore unknown hybrid world brilliantly and selflessly, setting aside his and his group's personal finances and time.

In so many ways and in so many settings, Harry changed the lives of patients, colleagues, and trainees. He rewarded those who lived up to his expectations with a lifetime of honor and friendship. He changed the course of contemporary spine surgery through his research and his leadership of numerous professional organizations, not the least of which was the American Board of Orthopaedic Surgery.

Harry was cordial to everyone, tough when needed, and extremely loyal to his friends. His professional and personal life was about giving and sharing with others what he had learned along the way (much of which was from Richard Rothman). Those of us who knew him well saw his softer side. Besides being a great, loyal, and true friend, he was, most importantly, a devoted family man. He adored his wife, Jan, and children, Seth (and wife Lauren) and Rachel (and husband Michael). Sadly, he never met his granddaughter.

We all strive to move forward, improving on the past when possible and appropriate. But the spine world, and the friends Harry left behind, are not the same without him. He bound contemporary orthopedic and spine communities together.

Thank you to Harry's mentors, and family, who shared this giant with us.

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Preface

As can be seen from the Dedication and Acknowledgment pages, the Editorial Board for this seventh edition of *The Spine* has undergone some changes. With the passing of Harry N. Herkowitz, MD, and the fact this may be the last edition for some of the remaining long-term editors, two new editors—Christopher N. Bono, MD, and Jeffrey S. Fischgrund, MD—have stepped in, and up, to help us create this new edition of *Rothman-Simeone and Herkowitz's The Spine*. We hope readers will find this edition—as well as future editions—as important and useful as previous ones.

This edition of *The Spine* comes 7 years after the sixth edition. We have strived to continue the original concepts of Richard H. Rothman, MD, PhD, and Frederick A. Simeone, MD, which was to correlate basic science, knowledge of the natural history, and clinical course of spinal disorders with current treatments based on established scientific principles and evidence-based literature. This edition, as in those of the past, provides a comprehensive look at spinal disorders affecting adults and children. It is directed at clinicians of all levels and specialties who treat spinal conditions and who need and appreciate our underlying principles, which ultimately lead to enhanced quality of care for patients.

Since this may be the last edition for some of the editors, we feel it is important to briefly describe the background for this seventh edition of *The Spine*. In our Preface to the sixth edition, we highlighted each of the previous editions by choosing important wording from the Prefaces. We have followed the same pattern here so that new readers, as well as long-term ones, can put this edition in historical perspective.

The forerunner to *The Spine* was *The Intervertebral Disc* by Drs. Rothman and DePalma. In their preface written in 1970, the authors wrote: "The role of the intervertebral disc in the production of neck and back pain, with or without radiation into one of the extremities, has been the subject of much investigation for many decades…The disc has been attacked from every conceivable angle, the most important of which is its biochemical nature and its response to physiologic aging and trauma. In spite of the exhaustive studies recorded in the literature, it is alarming to find how little of this knowledge has been acquired by those concerned with neck and back disorders…We are sure that much that is recorded in this book is still very controversial. Yet, we believe that our approach to this complex problem will be helpful and rewarding to others." This comprehensive monograph on the disc totaled 373 pages. It crystallized concepts of the disc for spine physicians of the day and served as the forerunner of many books to follow.

In the Preface to the first edition, Rothman and Simeone stated, "*The Spine* had as its genesis a strong feeling on the part of its editors that a need existed for a comprehensive textbook to include all aspects of diagnosis and treatment of spinal disease. Our goals were to lower the traditional disciplinary barriers and biases and to present a uniform guideline to problem solving in this area…This book has been designed to include all facets of disease related to the spine, whether orthopedic, neurosurgical, or medical in nature… An attempt has been made to achieve completeness without exhaustive and burdensome details. The contributing authors have not merely recorded the possibilities in diagnosis and treatment of spinal disorders, but have relied on their personal experience to offer concrete recommendations." The first edition of *The Spine,* following the dictates of the editors, covered the full range of knowledge of spinal disorders known at the time and became an essential component of the libraries of all medical personnel who dealt with spinal disorders. The authors, one a neurosurgeon (F.A.S.) and one an orthopedic surgeon (R.H.R.), combined their efforts to teach the world not only diseases of the spine, but also the importance of working together in an attempt to understand and treat the disease processes. Their spinal fellowship, as well as personal fellowship, was based on this multidisciplinary yet regimented approach to the spine and has been the model that we have sought to achieve in our own clinical and teaching environments.

The Preface to the second edition of *The Spine* stated, "Advancements in medicine generally follow broader scientific and even social trends. The treatment of spine diseases is no exception. Consequently, increments of new information have been added to the general body of knowledge in spotty, but predictable, areas. These new developments constitute the raison d'être for this second edition. The dramatic progress in radiologic imaging stands out as the most useful innovation [at that time, computed tomography]. Each contributor has demonstrated his commitment to summarizing the most recent information in a manner useful to students and clinicians alike, and for this the editors are proud and appreciative."

The Preface to the third edition included the following: "The current edition has new editorial leadership. Those of us involved in the direction of this project have tried to follow the model previously established by Drs. Rothman and Simeone in finding the best authors for each chapter. We, hopefully, have emphasized, as in the past editions, the importance of understanding the basic science in a concise manner, which leads to the ability to make appropriate decisions and manage patients with simple or complex spinal problems. We have attempted to update each section, have eliminated those areas that are not current, and have separated some components of the basic science from the clinical to aid readers in locating pertinent information in the ever-increasing body of knowledge related to the spine."

The Editorial Board for the fourth edition of *Rothman-Simeone The Spine* carried over from the third edition. "It provided expanded information on magnetic resonance imaging and laparoscopic and endoscopic surgery. It contained a comprehensive discussion of disc degeneration and its treatment. This edition also introduces a chapter on outcomes research and its importance to our assessment of functional outcome in addition to the more traditional measurements of success, including radiographic parameters."

The fifth edition of *The Spine* added much new information, along with significant updates in content and references. This edition introduced Key Points, which were four or five important concepts and facts contained at the end of many of the clinical chapters. A Key References section was added for each chapter that highlighted the most significant references. Chapters new to the fifth edition included surgical management of osteopenic fractures, disc and nuclear replacement, management of flat back deformity, use of transforaminal lumbar interbody fusion, and use of bone graft extenders and bone morphogenetic protein in the lumbar spine. Other new chapters included thoracoscopic surgery and its clinical applications and intraoperative monitoring, including motor-evoked potentials. A new chapter on genetic application and its exciting role for future treatments of degenerative disease was included in the basic science section. Minimally invasive posterior approaches to the lumbar spine were also introduced in that edition.

The sixth continued under the same Editorial Board as the fifth edition. The editors were charged with ensuring that the chapters within their sections contained the latest evidence-based information whenever available. New chapters included those devoted to arthroplasty for cervical and lumbar degenerative disorders. In addition, revision strategies for failed disc replacements highlighted the potential difficulties in dealing with this complex surgical problem. The sixth edition also significantly expanded the discussion of minimally invasive techniques with six chapters devoted to the rationale for minimally invasive surgery and the surgical techniques, results, and complications. A chapter devoted to soft stabilization for lumbar fixation was also added. Also new to that edition were a chapter devoted to anulus repair and a chapter devoted to the basic science of spinal cord injury. As had been done in previous editions, chapter updates were incorporated throughout the book whenever appropriate.

This, the seventh edition of *The Spine*, includes many of the chapters and authors from the sixth edition. However, all have been updated to include what is new in the basic and clinical sciences related to the topic, with relevant references and updates on clinical outcomes where warranted. In essence, as in all other editions, these chapters epitomize the newer academic catchphrase of "clinical translational research."

We have also expanded international authorship, including adding new contributors. The genetics chapters have been enhanced with both basic and clinically relevant information. Even more content on minimally invasive surgery has been added, with updates on outcomes, approaches, and techniques. We have eliminated some topics (e.g., facet replacement) that have fallen out of favor and/or use. We have added discussion on the sacroiliac joint, since that is one of the newest areas in spine care. We have updated the current status on motion-sparing techniques, including disc replacement with now longer-term follow-up and experiential updates in complications and their treatment. Although this is specifically important to disc replacement, it is the crux of change in most preexisting chapters.

The current Editorial Board remains committed to the broad-based appeal of this book. The authors include basic scientists, neuroradiologists, neurologists, physiatrists, and rheumatologists, along with orthopedic surgeons and neurosurgeons. In addition, this book remains unique in providing comprehensive sections on pediatric disorders and adult disease. Its comprehensive content ranges from degenerative disease to deformity to trauma and tumor. Afflictions of the spinal cord, along with detailed discussions of complications and their management, contribute to this book's broad appeal.

We feel this edition of *The Spine* continues to be the primary reference resource for all physicians and other clinicians with an interest in spinal disorders and treatments.

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Acknowledgment

In the past six editions, the editors have always dedicated this book to our mentors Drs. Rothman and Simeone, our families, and our associates, who have given us the time, support, love, and energy to pursue our careers as well as to coordinate, write, and edit this tome, which in fact was a dedication of love toward Drs. Rothman and Simeone. All of this is still true today. This edition, however, represents our feelings toward Harry N. Herkowitz, MD, our deceased lead editor and organizer, colleague, and close, close friend (see Dedication). The senior editors would like to thank and acknowledge our new "junior" editors, Christopher M. Bono, MD, and Jeffrey S. Fischgrund, MD, who have accepted this responsibility for now and the future—carrying on the spine care educational lineage provided by Drs. Rothman, Simeone, and Herkowitz. They stepped in as if they had been with us since the first edition. In addition, the full editorial team would like to thank all of the authors and contributors, some who have done this many times before and accepted our request to submit an updated chapter because it was dedicated to Harry, as well as the new contributors, who did the same thing. It is a monumental effort on everyone's part. We truly appreciate all of them and their hard work. We also thank the readers and the publishers, who have made this one of, if not the, longest-lasting and most-read complete texts on spine care in the world.

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SECTION I

BASIC SCIENCE

1 CHAPTER

Development of the Spine

Christopher M. Bono
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Steven R. Garfin

The embryologic development of the human spine is an enormously complex process that is only partially understood. Differentiation of the pluripotent tissues of the embryo leads to early formation of a repetitive segmented vertebral structure. Because the embryo is exquisitely susceptible to malformation and developmental error, each step of formation is critical.[1-4] Familiarity with these various steps can be helpful in understanding not only congenital syndromes, but also the possible developmental role concerning predisposition to some degenerative spinal processes, typically considered "wear and tear" conditions.[5,6] The continuously expanding understanding of the genetic basis of life, with the genetics of spinal development no exception, has aided the understanding of these syndromes.[7-13]

Fundamental to understanding spinal embryology is the concept of metamerism. In principle, *metamerism* is the development of a highly specialized organism, with multifunctional organ systems, from many anatomically similar segments arranged in a linear fashion. This is particularly easy to conceptualize in the spine because the fully developed spine comprises numerous units with similar shape, arrangement, and function. Metamerism also pertains to the development of the appendages from the metameres, however, which do not have such repetitive arrangement of consecutive units.

In embryonic development, the metameric segments are called *somites*. Primitively, all somites have the same developmental potential. Genetic signaling, specific to the species, determines the degree of regional specialization, such as limbs in mammals versus fins in fish or the lack thereof in snakes. Using these comparative examples, one can also understand the concepts of isomerism and anisomerism. *Isomerism* is characteristic of more primitive animals, in which the number of somites is greater but more uniform and not so highly specialized. This is akin to the snake, which has a great number of vertebral units sustaining its long body, but no limbs. In contrast, *anisomerism* is present in more developed species, such as mammals, in which many of the somites have been deleted (resulting in a lesser number of vertebrae), whereas the remaining somites are more highly specialized so that complex, specialized appendages can be developed.

Although the mature vertebral column is composed of numerous similar units, the tissues within each of those units are highly specialized. The vertebrae, discs, nerves, and blood vessels have embryologic precursors that form according to rapidly dynamic interstructural relationships. This chapter provides the essentials of human spinal development as they relate to the fully developed structure to understand its form, function, and various pathologic possibilities better.

Early Embryologic Spine Precursors: Day 17 to Week 4

The development of the human spine begins on the seventeenth day of gestation. This is within the triploblastic stage of the embryo, during which it is shaped as a disc (Figs. 1.1 and 1.2). On one side of the disc is the amnion cavity, and on the other is the yolk sac. On the dorsal layer (which is in contact with the amnion) of the disc, there are epiblastic cells that converge and invaginate into the disc to form the primitive pit or node. When embedded within the tissue, it forms a tubelike structure that extends craniad, "burrowing" deep to the embryonic disc along its ventral surface. The tube cavity is in continuity with the amniotic fluid. This extension is known as the *notochordal tube*.

At this point, the ventral wall of the notochordal tube is in contact with the yolk sac, which causes disintegration of these cells. A flat remnant of dorsal wall cells from the notochordal tube forms the notochordal plate on the nineteenth day. This plate matures and thickens to form a solid round structure known as the *notochord*. The yolk sac reforms, which obliterates the temporary communication between the amnion and the yolk sac (persistence of this yolk sac/amnion communication is lethal). The presence of the notochord induces a thickening in the overlying ectodermal cells, which are fated to become neuroectodermal cells. The thickening forms the neural plate. At this time, the neural plate is in continuity with the amniotic cavity. On the eighteenth day, the sides of the plate begin to curl up to form a tube. When the edges have

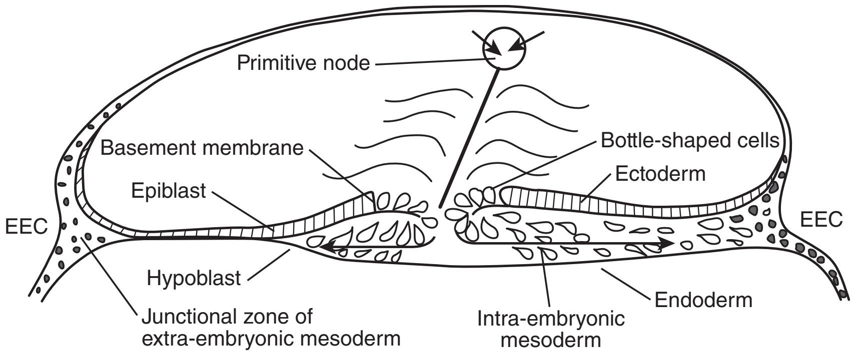

FIG. 1.1 During triploblastic stage (seventeenth day of gestation), the embryo is shaped as a disc. *EEC,* extraembryonic coelom. (From Brooks M, Zietman AL. *Clinical Embryology: A Color Atlas and Text.* Boca Raton, FL: CRC Press; 1998:57.)

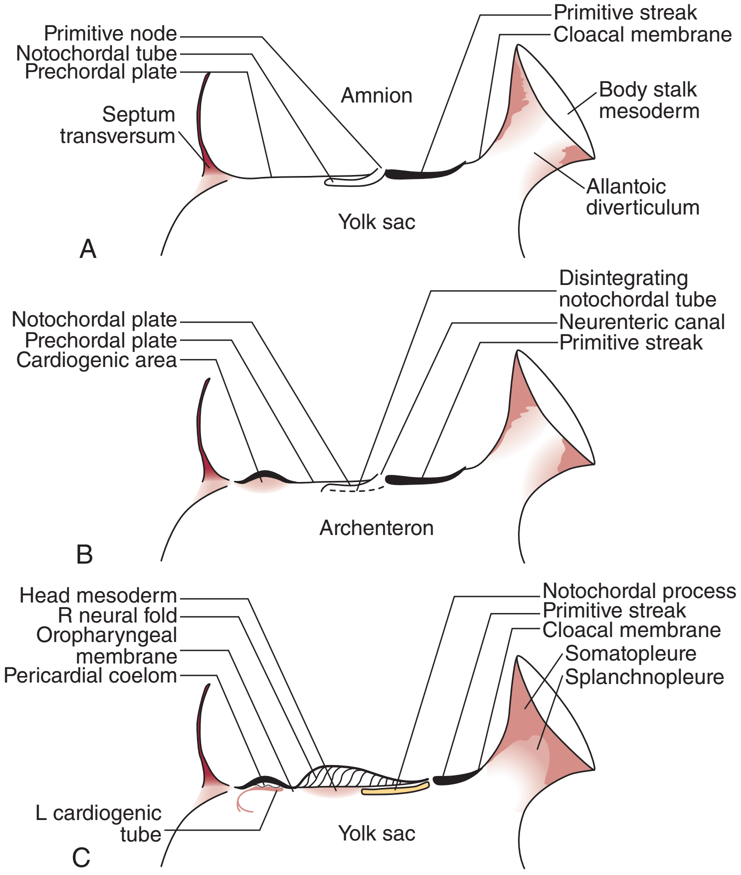

FIG. 1.2 (A) On one side of the disc is the amniotic cavity, and on the other is the yolk sac. The notochordal tube "burrows" deep into the embryonic disc. (B) When the ventral wall of the notochordal tube contacts the yolk sac, it disintegrates. (C) Remaining dorsal wall cells thicken to form the notochordal plate; this matures and thickens to become the notochord. *L,* left; *R,* right. (From Brooks M, Zietman AL. *Clinical Embryology: A Color Atlas and Text.* Boca Raton, FL: CRC Press; 1998:57.)

fused together, it is known as the *neural tube*. The amniotic fluid trapped inside is the precursor to spinal fluid.

The notochord lies ventral to the neural tube in the midline. Mesodermal tissues on either side of these structures condense to form longitudinal columns. By the nineteenth day, there are three distinct columns on either side of the midline: (1) medial paraxial columns, which give rise to the somites; (2) intermediate mesodermal columns, which form the urogenital organs; and (3) lateral mesodermal plates, which form the gut cavities. In considering the development of the spine, attention is focused on the medial paraxial columns. The juxtaposition to the intermediate columns may help explain, however, why abnormalities of the urogenital tract are frequently associated with vertebral anomalies.[1]

The somites are arranged in consecutive fashion along the dorsal aspect of the embryo. They are first formed in the rostral (or cranial) aspect of the embryo, continuing caudad to form 42 to 44 individual segments over a period of days where the medial paraxial columns previously existed. Because they are close to the dorsal surface, they are visibly apparent as a series of beaded elevations (Fig. 1.3).

Within the somite different regions have specialized fates (Figs. 1.4 and 1.5). The dorsolateral cells become the dermomyotomes. These eventually give rise to the skin (lateral) and muscle (medial) overlying the spine. The ventromedial cells within the somite become the sclerotomes. These are the precursors of the skeletal components (vertebrae) of the spine. The neural tube is fated to become the spinal cord.

From Somites to Spinal Column

The sclerotomes, myotomes, notochord, and neural tube eventually develop into the discoligamentous vertebral complex, paraspinal musculature, nucleus pulposus, and neural elements. This development is achieved through numerous sequential steps and stages.

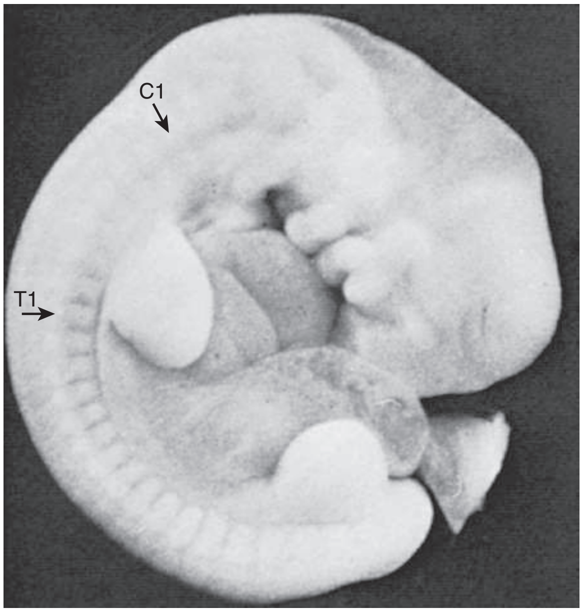

FIG. 1.3 Somites of the human embryo are externally represented as a series of dorsolateral swellings.

Precartilaginous (Mesenchymal) Stage: Weeks 4 and 5

The mesenchymal cells within the sclerotome divide into three main regions. One immediately surrounds the notochord. This region is the precursor for the vertebral bodies and the anulus fibrosus portion of the intervertebral discs. A second region surrounds the neural tube; this is destined to develop into the posterior arch of the vertebra. The third region of cells is within the body wall and is related to extraspinal tissue.

In metameric fashion, the sclerotomes are organized into a consecutively stacked arrangement. The next step in spinal development has been explained by the "resegmentation" theory.[14-18] *Resegmentation* describes the division of each sclerotome into a cranial and caudal half. The cranial half is loosely arranged, whereas the caudal half is composed of densely packed cells. A small portion of the densely packed

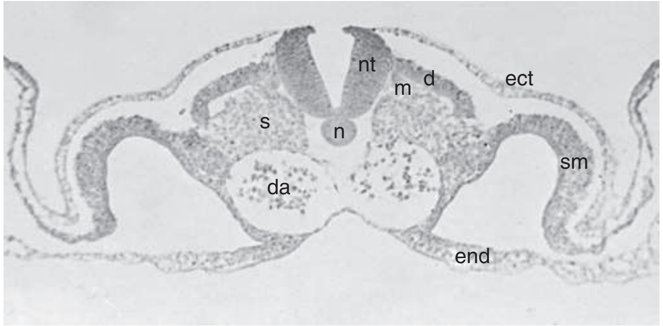

FIG. 1.4 Cross section of thoracic somite in a chick embryo. The notochord (n) underlies the neural tube (nt). The somite is divided into dermatome (d), myotome (m), and sclerotome (s). Lateral to this, the somatic mesoderm (sm), endoderm (end), and ectoderm (ect) are shown. Ventral to the sclerotomes lie the paired dorsal aortae (da).

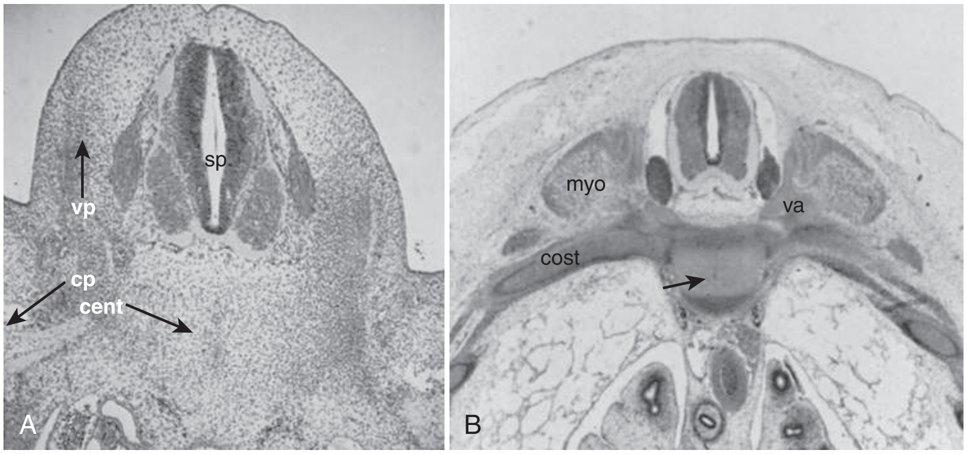

FIG. 1.5 (A) Cross section of pig embryo. *Arrows* indicate the direction of somite cell migration to form the vertebral process (vp), costal process (cp), and centrum (cent). The neural tube shows the anterior horn masses and the dorsal root ganglia. (B) Cartilaginous vertebral arch (va) and costal process (cost) are evident, as is the myotomic precursor to the spinal muscles (myo). *Arrow* indicates the intracentral vestige of the notochord, called the mucoid streak.

cells migrate superiorly to form the annular portion of the intervertebral disc, surrounding the notochord. Most of the densely packed cells fuse with the loosely packed cells of the adjacent caudal sclerotome. This fusion creates the centrum, the precursor of the vertebral body. The centrum develops from portions of two neighboring sclerotomes. This has significance on the anatomy of the fully developed spinal column. Initially, the segmental nerve precursors are located at the midportion of each sclerotome, whereas the segmental artery lies at the junction between two adjacent levels. After resegmentation, the nerve lies at the level of the disc and the artery lies at the mid-centrum, where one would expect to find them in the fully developed specimen.

Experimental data support the resegmentation theory.[8,19-22] The crux of these experiments includes implanting a quail somite (from a quail embryo) within a chick embryo's native somites. The quail somite is juxtaposed to a chick somite, and they develop together as the embryo grows. The quail tissue can be differentiated from the chick tissue using special staining techniques. Eventually, the somites give rise to sclerotomes that develop into centra. With the use of this model, it has been shown that the centrum does arise from the caudal and cranial halves of adjacent sclerotomes. The posterior arches (i.e., laminae) appear to follow this same pattern of growth.

This process seems to be highly influenced by the *Pax1* and *Pax9* genes.[22] It is unclear whether the spinous process develops from one sclerotome or two adjacent levels.[8,22] Other investigators have produced evidence of resegmentation using genetic labeling techniques.[20] These studies involved injection of retroviral particles containing the lacZ transducing vector BAG into a single somite of a chick embryo. In other words, a single somite was genetically altered so that its cells would produce the lacZ gene product—the protein β-galactosidase. When the investigators evaluated the developed embryo, they detected β-galactosidase in the caudal and cranial halves of two adjacent vertebrae, suggesting that cells from the labeled somite were incorporated into two neighboring vertebrae.

Cartilaginous Stage: Weeks 6 and 7

Before the sixth week, the embryonic spinal precursor is composed of mesenchymal cells. Starting in the sixth week, cartilage-producing centers, or chondrification centers, form within each developing vertebra. Although type II collagen production within the extracellular matrix has been detected in the fifth week, it is most active during the cartilaginous stage; it tapers off during the ossification stage, but its production persists within the notochordal remnants of the nucleus pulposus.[12] Two chondrification centers form in each half of the centrum, which eventually fuse into a solid block of cartilage. A hemivertebra is formed because of a failure of chondrification in one half of the vertebral body. The segmental arteries from either side of the centrum fuse at its middle aspect. Chondrification centers also form within each half of the vertebral arch and eventually fuse with each other in the midline and to the posterior aspect of the centrum.

Next, primitive cartilaginous transverse processes and spinous processes develop from the vertebral arch. More recent evidence has shown that the cartilaginous spinous process is formed from Msx1 and Msx2 (two embryologic proteins), producing mesenchymal cells, which require BMP4 to differentiate.[23] These relationships highlight the important interactions of primordial proteins in governing further development of the spine.

The developing centrum and vertebra have the notochord as a central axis. Intervening segments of loosely packed cells are present between the regions of densely packed cells. The outer disc is formed by these loosely packed cells of the sclerotome, which are fated to become the anulus fibrosus. The notochord disintegrates within the centrum during resegmentation and chondrification except in the region of the intervertebral disc, where some of its cells remain. The nucleus fibrosus is the replacement of the embryologic notochord.

Ossification Stage: Week 8 and Beyond

Primary ossification centers develop in utero. In the spine, ossification centers form within the cartilaginous template. There are three primary ossification centers in the typical embryonic vertebra: one in the center of the centrum and one in each of the vertebra arch halves. At about the ninth week, the preparation for ossification of the centrum is heralded by anterior and posterior excavations of the cartilaginous centrum produced by the invasion of pericostal vessels.[24] These vessels produce ventral and dorsal vascular lacunae, which support the initial ossification (Fig. 1.6). Ossification of the centra starts first at the lower thoracic spine working craniad and caudad from that point.[25]

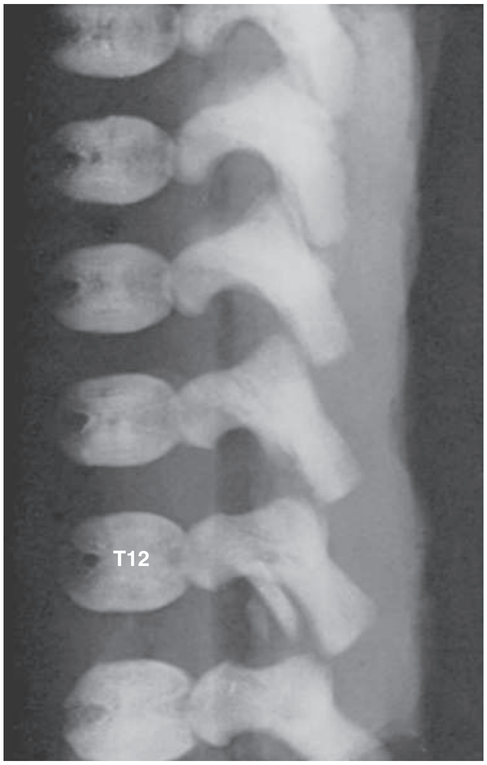

FIG. 1.6 Lateral radiograph of a 34-week spine. Ossification of the centra starts first at the lower thoracic spine, working craniad and caudad from that point.

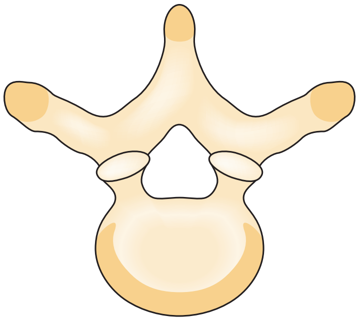

FIG. 1.7 Secondary centers of ossification of a thoracic vertebra. The centers at the tips of the spinous and transverse processes appear at 16 years and fuse at approximately 25 years. The ring apophysis of the centrum ossifies at around 14 years and fuses at about 25 years.

Secondary ossification centers develop after birth. In the spine, these appear after puberty. There are five centers: one in the tip of the spinous process, one in each transverse process tip, and one ring epiphysis in the superior and inferior endplates of the vertebral bodies. This development occurs at about 15 or 16 years of age, but eventually these ossification centers fuse in the middle of the third decade (Fig. 1.7).[26] The transverse processes of the lower cervical vertebrae, particularly C7, may show an additional costal center of ossification that produces the troublesome cervical rib; this reinforces the concept that all vertebrae primitively had the potential of forming ribs.

A pair of embryologic joints, known as *neurocentral joints,* is not present in the fully developed spine. These are located at the junction of the vertebral arches and the centrum but are anterior to the site of the future pedicle. Although not true "joints," they allow expansion of the vertebral arch and spinal canal along with growth of the vertebral body. This expansion is most rapid between 18 and 36 weeks of gestation.[2] At birth, the spinal canal diameter at L1 through L4 is approximately 70% of adult size, whereas at L5 it is only 50%.[2] This indicates differential growth within regions of the vertebral column during fetal development. Full adult dimensions are reached by 1 year of life at L3 and L4 levels. The neurocentral joints persist until 3 to 6 years of age. The fusion of the fetal vertebral arches to the centra occurs well anterior to the pedicles, at the site of the neurocentral joints. The definitive vertebral body includes more than just the bone derived from the ossification center of the centrum, so the terms *body* and *centrum* are not accurately interchangeable (Figs. 1.8 and 1.9).

It is commonly thought that isthmic spondylolysis occurs because of a stress-type fracture within the pars interarticularis of the lower lumbar vertebrae, most commonly L5. Specific anatomic features of the adult lumbar spine, such as variation of the dimensions of the "lateral buttress" within the lumbar spine, have been described. Prenatal factors have been sought, but with limited success. Sagi and colleagues[5] analyzed histomorphologically the lumbar spines of fetal spines aged 8 to 20 weeks to determine the sequence and location of ossification of the pars interarticularis of the various levels. They reported several findings. First, the pars begins to ossify in the twelfth to thirteenth week of gestation. In the upper lumbar levels, ossification begins at the posterior portion of the pedicle and continues caudad, creating uniform ossification and trabeculation of the pars interarticularis. In contrast, the pars of the lower lumbar levels begins within the center of the pars itself, extending from this point to connect to the neighboring structures. Sagi and colleagues[5] found that this resulted in uneven ossification. This finding may help explain areas of weakness within the pars interarticularis of the lower lumbar levels and may suggest that there is a prenatal predilection for a stress fracture in most individuals.

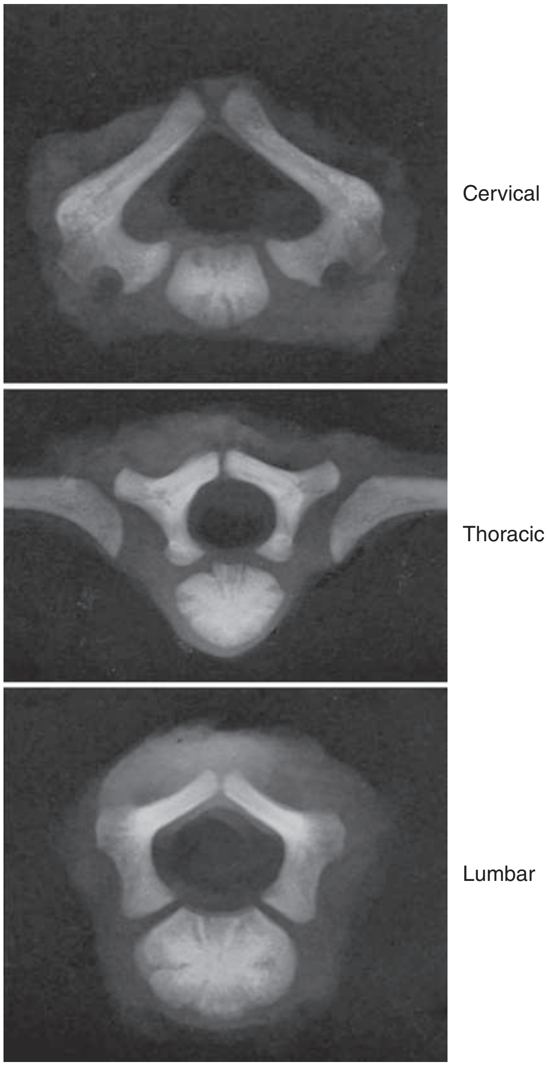

FIG. 1.8 Fusion of the fetal vertebral arches to the centra occurs well anterior to the pedicles, at the site of the neurocentral joints. The contributions of the vertebral arches to the dorsolateral parts of the bodies are apparent. The definitive vertebral body includes more than just the bone derived from the ossification center of the centrum, so that the terms *body* and *centrum* are not accurately interchangeable.

Fate of the Notochord

In the early embryo, the notochord serves as a rigid template around which the future vertebral column develops. It is a uniform structure that is present throughout the entire length

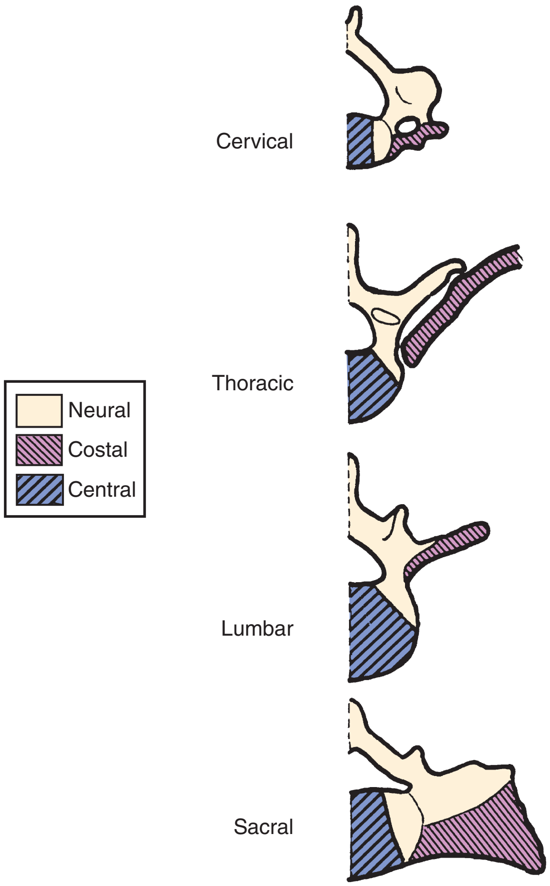

FIG. 1.9 Neurocentral synchondroses lie well within the vertebral body in all cases. Normally, costovertebral synchondroses develop a true diarthrodial joint only in the thoracic region.

of the primordial spinal column. A sheath exists around the notochord in its early stages. Immunohistochemical staining studies of 4- and 5-week embryos identified that a complex of extracellular matrix molecules is already present within this sheath, including sulfated glycosaminoglycans, hyaluronic acid, fibronectin, laminin, tenascin, and collagen II.[27] Aggrecan, keratan sulfate, and other large aggregating proteoglycans (present in the mature spine) were not detected at this stage, suggesting that these appear later in development. The notochordal cells themselves showed reactivity to transforming growth factor-β (TGF-β), suggesting an early influence of this growth factor on the developing extracellular matrix, and the formation of vasculature, cartilage, and bones.[27,28] Disruptions in the TGF-β signaling pathways have been implicated in the abnormal bone morphology and ligamentous laxity found in Loeys-Dietz syndrome, an autosomal dominant mutation of TGF-BR1 or TGF-BR2. Patients with this syndrome, first described in 2005, may have cervical osseous deformity and instability.[29]

In the 20-mm embryo, the notochord becomes an intrinsically segmented structure in the thoracic and lumbar region; in the 30-mm embryo, this structure is evident in the cervical region as well. Segmentation leads to areas of fusiform enlargements in the region of the intervertebral disc, while the notochord is slowly obliterated in the region of the developing vertebral bodies. Within the developing vertebral body, the notochord is stretched into a "mucoid streak" (see Fig. 1.5B). With continued growth, the mucoid streak disappears, leaving behind only bone.

The notochord expands in the region of the intervertebral disc to form the nucleus pulposus. This was originally described in detail by Luschka.[30] The notochord is a major source of the nucleus pulposus, and it has been shown histochemically and autoradiographically that notochordal cells proliferate and remain vital several years after birth.[31] Although notochordal cells generally do not seem to be demonstrable in the human nucleus pulposus of individuals older than 5 years of age, Schwabe[32] reported their survival in the incarcerated discs of the sacrum in a series of specimens ranging from 22 to 45 years in age. A chordoma is abnormal neoplastic growth of notochord cells that remain within the spine in adult life. This suggests that notochordal rest cells can persist well into middle age in some individuals. These neoplasms may develop at any point along the original notochordal track but are usually in the rostral (basisphenoid or basiocciput) and caudal (sacral) regions.

As a theme of development of the spine, the region of the previous notochord lies anterior to the center of the fully developed vertebral body. This has been verified by Nolting and colleagues,[25] who detected remnants of notochordal tissue anterior to the cartilaginous body center in 13 fetal spines aged 10 to 24 weeks. This finding further reinforces that using the terms *centrum* and *vertebral body* interchangeably is inaccurate.

From Neural Tube to Spinal Cord

On the twentieth day, ectodermal tissues on either side of the neural plate become thick and "pucker up." This area is known as the *neural crest,* which contains cells that eventually compose the neural elements. The mesenchymal tissue beneath the neural crest is the neural fold. As the folds grow toward the midline, the two neural crests meet and fuse on day 22. The underlying neural plate forms a tube, known as the *neural tube,* whose walls are composed of the previous neural plate. The neural tube invaginates itself within the dorsum of the embryo. On the twenty-sixth day, the fused neural crest cells invaginate into the embryo and divide into right and left globules. They are termed the *dorsal root ganglia*. They are oval and appear before ossification of the spine.[33]

By the fifth week, the neural tube has changed into a diamond shape and is termed the *neural canal.* A sulcus limitans forms between its anterior (basal) and posterior (alar) halves, which are destined to become motor and sensory tracts. The dorsal root ganglion is composed of sensory cells alone. It develops two "arms." One arm is an extension toward the posterior aspect of the neural canal, which eventually joins the future site of the posterior column of the spinal cord. The other arm is a lateral extension that projects from the dorsal ganglion to reach peripheral tissues.

During the sixth week, the sulcus limitans disappears, and the basal and alar halves join together, while keeping their respective motor and sensory functions. Ventral horns form in the basal portion, which appear as gray matter because they are composed of motor cell bodies. Axons grow out from the ventral horns to peripheral structures. These axons join with the dorsal root ganglion to form the spinal nerves, which exit the vertebral column as a single unit.

In the seventh to eighth week, white matter finally develops within the spinal cord, representing myelin formation along axon sheaths; this occurs in ascending and descending tracts. The central part of the spinal cord retains a small cavity lined with ependymal cells that allows the transfer of fluid. This cavity was previously filled with amnion, the early embryologic analogue of cerebrospinal fluid.

Development of the Costal Elements

The costal elements persist only in the thoracic spine of the fully developed normal spinal column. During the fifth week, costal processes are formed and project from either side of the centrum. By the seventh week, they become sequestrated, or separated, from the centrum, by forming costovertebral and costotransverse joints. The cartilaginous structures begin to ossify in the eighth week, recognizable as ribs. In the cervical spine, the primordial costal processes fuse with transverse processes to form the costotransverse bar. Eventually, the unique cervical transverse processes form, which contain the transverse foramen for the vertebral artery. In the lumbar spine, the costal processes do not fully form. They persist only partially as the transverse processes of the fully developed spine. The embryonic transverse process forms the mammillary process (not the transverse process). The transverse and mammillary processes eventually fuse. In the sacrum, the costal processes fuse with the embryonic transverse processes and merge to become the anlage of bone of the lateral sacral mass.

Development of the Intervertebral Disc

The intervertebral disc warrants special attention because it is the pathologic focus of many spinal conditions. In the early stages of embryonic development, there are an increasing number of cells in the peripheral portion of the disc and a decreasing number adjacent to the notochord. As the embryo grows beyond a crown-rump length of 10 mm, the cells in the peripheral zone become elongated and are arranged in a lamellar pattern. When it reaches a length of 20 to 40 mm, collagen fibers begin to be synthesized and are exported from the cells, forming a collagen-rich extracellular matrix. The collagen fibers follow the pattern of the cells and are arranged in a lamellar pattern as well, giving the peripheral disc (or anulus fibrosus) its characteristic composition of circumferential bands of tissue. No fully continuous fibers span the entire periphery of the disc; rather, multiple strands interdigitate to create a highly tensile structure. These lamellar bundles appear to be more densely arranged in the anterior anulus and less dense in the posterior anulus of the developing spine, which may explain the propensity for posterior disc rupture in young patients.[6] As the embryo passes into the fetal stage at 2 months, the cells begin to decrease in number, and the production of extracellular matrix is increased.

By the start of the fetal period, the disc has three distinct regions: (1) an external fibrous zone, (2) an internal hyaline zone surrounding the notochord, and (3) a fibrocartilaginous zone. The disc grows by interstitial and appositional growth.[34] *Interstitial growth* refers to growth that occurs at the outer attachment of the anulus to the cartilaginous endplates. *Appositional growth* refers to growth that occurs longitudinally between the vertebra and the disc. Lamellar fibers form attachments to the cartilaginous endplates in the region of the nucleus pulposus, which completely encases the gel-like structure. The outer layers of the anulus become deeply embedded into the peripheral portion of the endplate cartilage.

As the endplate ossifies, forming the ring apophysis, the inserted annular fibers become tightly fixed. The “weak link” in this complex is between the ring apophysis and its corresponding vertebral body, so that apophyseal separation fractures are more common than rupture of the intervertebral disc in the immature spine. The interval between the apophysis and the vertebral ossification center provides an entrance for vessels to supply nutrition to the endplate and to the intervertebral disc by diffusion. This supply is obliterated after union of the ring apophysis to the vertebral body.

There is a lack of agreement regarding the extent of the vascularity of the fetal intervertebral disc. In the fetal disc, the anulus pulposus seems to be vascularized. Taylor and Twomney[35] found that a plexus of vessels around the circumference of the disc sent branches deep within the anulus. In contrast, Whalen and colleagues[36] reported that these vessels entered only the outermost lamellae of the anulus fibrosus. In addition to vessels within the anulus, regularly spaced vascular channels within the cartilage have been shown within the interface between the cartilaginous endplate and the disc (Fig. 1.10). These channels most likely do not act as blood vessels but rather as a sinusoidal “cul-de-sac” system that delivers nutritional factors by diffusion. The deep regions of the disc

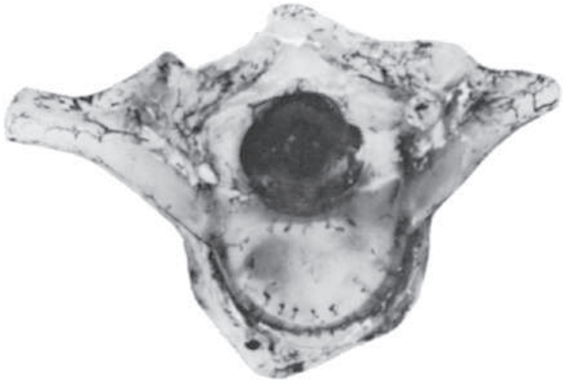

FIG. 1.10 Section through cartilaginous vertebra of 30 weeks after vascular injection. Note the coronal vascular pattern. Each tuft consists of a central artery entwined by recurrent veins that end in a chondrous lacuna as a terminal arteriovenous anastomotic sinusoid (cul-de-sac). Nutrients diffuse from the sinusoid into the surrounding tissues.

are probably not vascularized at any point in development. The adult intervertebral disc is avascular, receiving nutrition only through diffusion through the endplates aided by the flux of fluid to and from the nucleus pulposus. This avascularity may be present at 17 to 24 weeks.[24]

Spinal Ligament Development

There is a paucity of literature concerning the development of the spinal ligaments in the human fetus. Misawa and colleagues[37] dissected 25 human fetuses 6 to 24 weeks of age. They found that, at 6 to 7 weeks, "light zones" represented areas of low cell density that correlated with vertebral bodies, whereas "dark zones" were areas of high cell density and corresponded to the intervertebral regions. The posterior longitudinal ligament was first recognized at 10 weeks, whereas the appearance of the ligamentum flavum was concomitant with that of the lamina at 12 weeks. The fibers of the ligamentum flavum became discernible only at 15 weeks.

Influence of Fetal Movement

Development of the human skeleton seems to be strongly influenced by the interaction of its immature moving parts. In the appendicular skeleton, the opposing surfaces of the femoral head and acetabulum are codependent on each other for normal development into a highly mobile, but stable, weight-bearing joint. In the spine, the development of facet joints is thought to be influenced by torsional loading. It is commonly thought, however, that these demands are placed on the spine only postnatally during upright posture.

The importance of fetal spinal movement has been recognized only more recently. Boszczyk and colleagues[38] used ultrasonography to study the movements of 52 normal fetal spines in utero. They found that rotational movements of 4 to 10 degrees were measurable in fetuses at 9 to 36 weeks. These investigators concluded that this amount of rotation influenced the ultimate morphology of the joint and that torsional stresses are present prenatally and postnatally. Functional demands on the spine may begin even before birth.

Development of Specialized Vertebral Regions

Most of the spine develops in a very uniform manner. The more particular mechanical requirements of the cranial and caudal extremes of the spine have led to unique development processes, however, enabling functional transition between the head and lower limbs.

Occipitocervical Complex

Four occipital myotomes can be readily identified in the human embryo of 4-mm crown-rump length.[39] The first is small, the second is of intermediate size, and the third and fourth are equivalent to the succeeding cervical segments. The first cervical nerve and the hypoglossal artery clearly delimit the most caudal occipital segment. Eight rootlets of the hypoglossal nerve can be discerned rostral to the hypoglossal artery, and these usually unite into four, but no less than three, main roots. This confirms the involvement of at least three precervical segments in the formation of the occiput. DeBeer[40] claimed that a total of nine segments might be involved in skull formation. The first four appear very primitive but contribute to the preotic cranium, whereas the fifth is rudimentary, without a myotome. The last four segments are definite precursors of the occipital complex.

The definitive hypoglossal nerve shows some retention of its multisegmental origins. Its rootlets usually coalesce into two distinct fascicles that exit through separate openings in the dura, and occasionally these do not unite until they have left the skull. The formation of the hypoglossal canal may also indicate a multisegmental relationship. The usual single aperture has been regarded in some texts as homologous to the intervertebral foramen between the neural arch equivalents of two occipital somites, but during chondrification a membranous strut that separates the two main fascicles of the nerve may be observed. By further chondrification and ossification, a double hypoglossal canal accommodating both strands of the nerve may result. Most likely, this mesenchymal strut is a representative of the membranous neural arch process of an intervening segment and is a good indicator that at least three somitic levels were involved in forming the part of the occipital bone surrounding the hypoglossal canal.

Atlantoaxial Complex

The axis and atlas, although considered two vertebral levels in the fully developed spine, actually arise from three different centra. Sensenig[41] first described this in detail in 1937, and later O'Rahilly and Meyer[42] provided a description. These three centra have been named the *X, Y,* and *Z* components. The apical *X component* at first projects into the early foramen magnum and forms an occipitoaxial joint. It has come to be known as the *proatlas* and constitutes the main portion of the odontoid process. Although it is commonly written that the odontoid process develops from the centrum of C1, this is probably not entirely true.[43] Remains of the occipitocervical syndesmosis are apparent by the formation of the alar ligaments. The *Y component* becomes the centrum of the atlas, and the *Z component* becomes the centrum of the axis (C2). The X, Y, and Z components are related to the first, second, and third cervical nerves, which explains the redundancy of the numbering of the upper cervical nerves. Muller and O'Rahilly[44] determined that these three components actually develop from only two and a half sclerotomes in the chick embryo.

Considering the segmental complexities involved in the development of the normal human craniocervical articulations, the occasional occurrence of anomalous separations, fusions, and intercalated ossicles should not be surprising. The odontoid process has origins from the axial portion of the

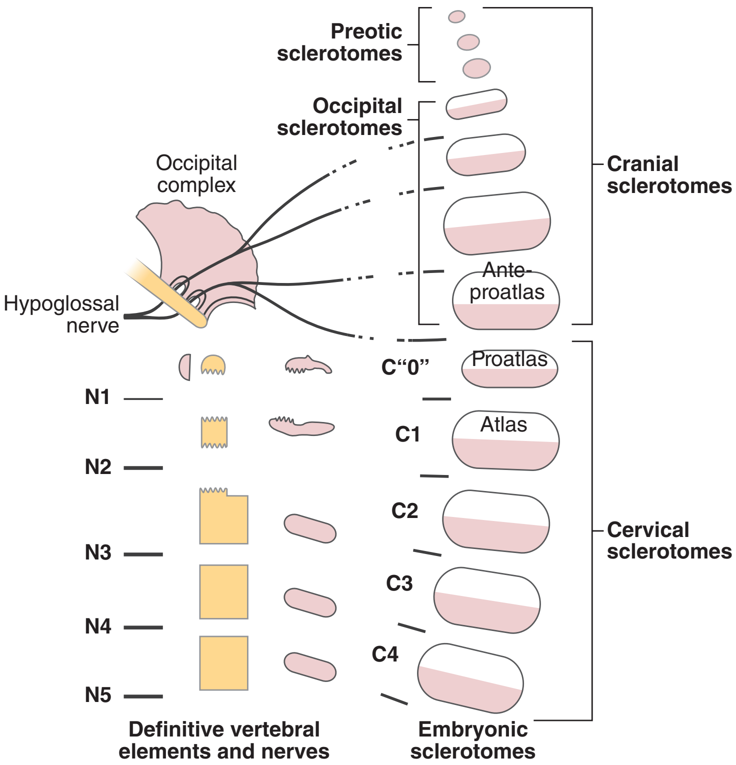

FIG. 1.11 Schematic representation of craniocervical sclerotomes and their segmentally related definitive cranial and vertebral elements and nerves. The cranial and cervical sclerotomes originally formed a continuum. The axis incorporates three sclerotomic elements. The caudal four cranial sclerotomes contribute to the occiput, and their nerves coalesce to form the hypoglossal nerve.

occipital and upper two cervical sclerotomes and is formed from two separate ossification centers that fuse by the seventh month of gestation.[45] A second ossification center, forming the tip of the odontoid, appears by age 3 to 6 and fuses by puberty. Because the odontoid process develops from its own centrum, it can be better understood how an os odontoideum may arise. This anomaly is manifested as a spherule of bone suspended between the two alar ligaments without any apparent bony connection to the C2 body. Os odontoideum has been theorized to be related to prior injury to the odontoid process, but its etiology may also be developmental. Os odontoideum can manifest clinically as neck pain, myelopathy, or even sudden death.[45] Its embryologic development also helps explain the region at the base of the odontoid process that predisposes to nonunion after displaced fractures.

Morphologic anomalies of the odontoid have been described and are attributable to early development. With absence of the midline integration of the primary ossification centers, bifid odontoid process may result, which may lead to craniocervical instability. Furthermore, inclination of the odontoid process may be influenced by traction of the apical ligament on the tip of the odontoid process during development of the craniocervical junction.[46] Retroflexion of the odontoid has been described in patients with Chiari I malformations.[47]

The most frequent manifestation of variant segmentation is the appearance of a third (midline) occipital condyle, also known as a *basilar tubercle*. This structure occurs as a projection on the basion (anterior central point) of the foramen magnum. Sometimes it is expressed as a simple rounded tubercle, but in better developed cases there is actually an articular facet that receives the tip of the odontoid process forming a true diarthrosis (joint). Occasionally, accessory facets lateral to the central projection are present. In a series of 600 skulls, some suggestion of a third condyle was present in 14% of specimens.[48]

Toro and Szepe[49] observed that the third condyle often occurs with occipitalization of the atlas. They also thought that it may be the expression of the hypochordal arch of the "ante-proatlas." As they used this term, it seems to designate the most caudal occipital somite (Fig. 1.11). A more complete separation of this ante-proatlas may form a true occipital vertebra. First described by Meckel in 1815, this malformation forms a more or less complete ring inferior to the foramen magnum, and its anterior arch is often fused to the skull, bearing a third condyle. This condition is distinguished from occipitalization of the atlas by the radiologic identification of the true atlas beneath it. Transverse processes of variable relative size may be present in occipital vertebrae, but these do not show a transverse foramen.[50] Because bony eminences on either side of the third condyle are common to these structures, they may encroach on the foramen magnum, causing neurologic sequelae.

Occipitalization of the atlas occurs in 0.1% to 0.8% of the population according to the series of skulls examined. If the occipitalization is complete, there is no movable atlanto-occipital articulation, and the atlas ring is more constricted. Also, the level of the odontoid tip shows a higher relative

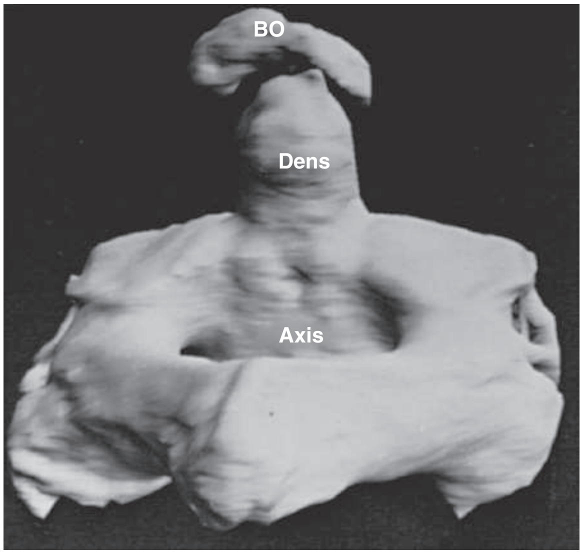

FIG. 1.12 Nonfused "floating" ossicles may occur within craniocervical syndesmoses. A variably shaped, usually pea-sized ossification that occurs between the basion and the tip of the odontoid (in the presence of a complete odontoid process) has been labeled Bergmann ossicle (BO).

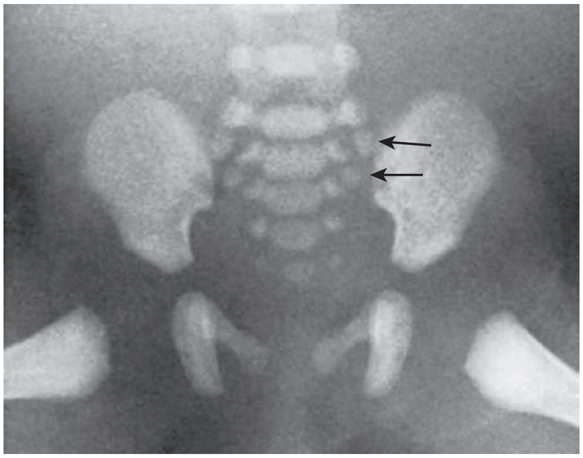

FIG. 1.13 Anteroposterior radiograph of a 34-week fetal pelvis showing two of the eventual three ossific centers (*arrows*) of the costal contributions to the alae. These form in the cartilage that anchors the fetal sacrum to the auricular processes of the iliac wings.

position, and the fusion is often asymmetrical. Inglemark's series of skulls showed that in 78% of the true congenital cases the posterior arch was fused to the posterior rim of the foramen magnum; the anterior arch was fused in 54%, and lateral fusions occurred in 23%.[51] Toro and Szepe[49] suggested that the variable expressions of fragments of the proatlas arch, which normally form parts of the atlas, may enhance the predilection of this segment to fuse to the skull.

Nonfused "floating" ossicles may occur within the craniocervical syndesmoses. A variably shaped, usually pea-sized ossification that occurs between the basion and the tip of the odontoid (in the presence of a complete odontoid process) has been labeled Bergmann ossicle (Fig. 1.12)[52] and is most likely a variant derivative of the ante-proatlas mesenchyme. Putz[53] also recorded the incidence of a small ossicle between the anterior lip of the foramen magnum and the anterior arch of the atlas and within the anterior atlanto-occipital membrane. He was convinced that this was a manifestation of the hypochordal potential of the last occipital (ante-proatlas) somite.

Sacrum

Ossification of the bodies of the sacral vertebrae is unique in that, in addition to the single central ossific zone, two true epiphyseal plates later provide accessory ossification to the superior and inferior surfaces of each segment. The central centers for the superior three sacral vertebrae are evident at week 9, whereas these centers for the fourth and fifth segments do not appear until after week 24. Each vertebral arch of the sacrum shows the conventional bilateral centers, but in addition six centers produce the sacral alae. Between weeks 24 and 32, these centers appear anterolateral to the anterior sacral foramina of the upper three sacral vertebrae. They are expressions of the ever-present potential of the vertebral anlagen to produce costal equivalents (Fig. 1.13).

In the early part of the first year after birth, the sacral vertebrae are still separated by intervertebral discs, and the lower two are the first to fuse in late adolescence. Before this, the ossific centers for the superior and inferior epiphyseal plates of the bodies appear, and between 18 and 20 years of age, lateral epiphyseal plates form on the auricular surfaces of the sacral alae. By the middle of the third decade, the entire sacrum should be fused, although internal remnants of the intervertebral plates remain throughout life. These may be visualized in a sagittal section or in radiographs taken at the appropriate anteroposterior angle.

The coccygeal segments lack neural arch equivalents and form a single ossific center for their bodies. The first usually appears before 5 years of age, and the succeeding three ossify during consecutive 5-year intervals.

Genetic Control of Spinal Segmentation

In the previous edition, an extensive discussion of the genetic control of segmentation was presented. This discussion focused on the wealth of information provided by studies performed on the fruit fly, *Drosophila*. The most essential concept provided by these studies is the fact that the individual aspects of the advanced stages of development are the result of a sequential action of numerous genes, and the mutation of single-effect genes, whose phenotypic expressions have provided the classic mendelian patterns of heredity, usually show errors in only a single step in this concatenation of events. *Drosophila* development shows that a set of maternal effect genes (so labeled because they are exclusively derived from the maternal genome) initially establishes the axial symmetry of the body within the ovum. A group of approximately 20 segmentation genes guides cellular construction of the defined segments. Mutations of these genes are manifest as deletions affecting the normal segment number. Most mutations of the segmentation genes are lethal, and knowledge of them has been obtained from the doomed larval forms. Because they are commonly recessive, however, the mutant strain can be propagated for continuous study. The equivalent genetic effects would not be so readily observable in vertebrates, but comparative evidence strongly indicates that similar genetic mechanisms are operable.

Only after the segmental boundaries have been established can the structures characteristic of each segment be determined. These designations are effected by the homeotic selector genes. The term *homeotic* (from the Greek *homoeos,* meaning "similar") was originally used by Bateson[54] to label the mutant substitution of segment appendages because he surmised that they indicated a similarity (genetic homology) in their underlying developmental mechanisms. In contrast to the segmentation genes whose mutations affect the whole segment, mutations of the homeotic genes are expressed as homologous structures (e.g., legs and wings) grotesquely appearing on inappropriate segments. It is now known that these homeotic genes are closely grouped in two locations on the third chromosome of *Drosophila*'s four chromosomes.

Another significant outcome of *Drosophila* genetic research has been the identification of a sequence of nucleotide base pairs that is common to the homeotic selector genes.[10] Intergenetic cross homologies of certain gene regions are not unusual, but the relatively small sequence common to these homeotic genes contained only a 180–base pair unit that could easily be used as a probe to identify the locations of its homologues. This compact genetic fragment was called the *homeobox* by McGinnis and associates,[55] and the protein it encodes is known as the *homeodomain*.[10]

Links Between Fly and Human

Evolution recognized a fundamental advantage in deriving a body plan from the regional diversification of a series of basically similar modules because virtually all higher organisms develop from some type of segmental organization. Although vertebrate segmentation is not externally obvious in the postembryonic stages, the sclerotomic contributions to the axial skeleton retain the original metameric organization; the common neurologic examination based on a knowledge of the myotomic and dermatomic distribution of the cranial and spinal nerves pays perpetual homage to the truth that humans and the other vertebrates are segmentally constructed animals.

As would be expected, the homeobox-containing genes discovered in humans[9] do not act in exactly the same manner as they do in *Drosophila* because the types of segmental organization are quite different. Nevertheless, the nucleotide sequence cognates of the *Drosophila* homeobox genes found in mammals seem to have considerable influence in the early establishment of brainstem and spinal cord formation.[13] As in the more primitive forms, malfunctions of the genes controlling the more fundamental aspects of segmentation most likely produce early lethal mutations. Because higher vertebrates do not have an autonomous larval stage, the occurrence of such mutations would be lost to general observation. Nevertheless, some gross errors of segmentation that may reach parturition do show genetic implication.

Congenital Syndromes: Genetic Evidence of Segmentation in Humans

Klippel-Feil Syndrome

In humans, congenital vertebral fusions, most commonly manifested in the various types of Klippel-Feil syndrome, serve as a prime example of segmentation. Many instances of this syndrome seem to result from spontaneous mutations or individual teratogenic accidents in the early developmental sequences because most reports present single case histories without examination of the extended family and the family's pedigree. Gunderson and colleagues[11] provided substantial evidence, however, that many cases of Klippel-Feil syndrome are probands of a familial history of the condition. These authors provided the pedigrees of 11 probands. Of particular interest is their type II of the syndrome, which exhibits fusions limited to the cervical regions at C2–C3 and C5–C6. Gunderson and colleagues[11] concluded that this disorder, which produced segmentation errors at consistent spine levels through several successive generations, strongly indicated a dominant mutant defect of a gene that controls these specific levels of segmentation.

Caudal Dysplasias

Another class of segmental spinal malformations that indicates genetic import is grouped under the generic term of *caudal dysplasias*.[4] This malformation complex has proved to be heritable and has a marked association with maternal diabetes. From this complex, certain insights into genetic mechanisms of mammalian spinal development may be derived. That some degree of caudal segment regression is a natural phenomenon is shown by the reduction of the original postsacral somites from eight (±2) to four (±1) in normal human development. In more severe forms of lumbosacral agenesis, all vertebral elements as far cephalad as the upper lumbar region may fail to develop. The association with maternal diabetes has been attributed to a teratogenic effect of hyperglycemia because experimental elevations of blood glucose have produced varying degrees of caudal deficiencies in animals.[53] Similar effects have been induced by various toxic insults during embryogenesis of the spine.

Because caudal agenesis is not a consistent occurrence in the offspring of diabetic mothers, a more complex genetic association has been suspected, particularly as diabetes mellitus and spine defects have been associated with human leukocyte antigen (HLA)-type histocompatibility genes.[4] This inference has been supported by studies of the T-locus genes in the mouse. This locus apparently is a segment of the mouse chromosomes with a collection of genes that have a profound effect on spine development and other aspects of embryogenesis.[56] There is evidence that a gene complex, functionally similar to the mouse T locus, may be operable in humans because an association between histocompatibility antigens of the HLA type and the inheritance of human spina bifida has been reported.[57]

The HLAs are controlled by a cluster of contiguous genes located on the human chromosome 6. As in the mouse T locus, each gene in this group has several alleles, and numerous serologically discrete forms of cell surface antigens may be coded by the gene complex. The total ensemble of the HLAs produced within an individual determines its HLA "personality."[57] The comparative evidence suggests that the HLA complex, because of its defined chromosomal localization, its coding for the antigen complex, and its effect on spine development, is a reasonable candidate for the human analogue of the mouse T locus.

In vertebrates, as in other forms of segmented animals, a definite sequence of genetically controlled events establishes the basic aspects of segment formation. When this has been accomplished, some analogue of the homeotic system of genes most likely determines the regional specializations of the individual segments. This system provides an early determination within the vertebrate sclerotome because these embryonic cell masses exhibit a marked "position effect" before any regional differentiation of the somite is visibly evident. This effect has been shown in the chick embryo, in which the transplantation of an early thoracic sclerotome into the cervical region results in a rib-bearing thoracic vertebra whose specific character development was not modified by its heterotopic location.[58] This early position identity may be because vertebrate embryonic patterns are mostly established through early cell-to-cell interactions subsequent to cell cleavages, and these involve the antigen-mediated cell surface recognitions and adhesions as shown by the HLAs. Nevertheless, some analogues of the homeotic mechanisms in *Drosophila*, although differing in their modes of expression, must determine whether a given vertebra exhibits cervical, thoracic, or sacral characteristics.

The range of anomalies observed in the human spine well support the concept that regional vertebral specification may be the result of a homeotic type of selective repression. In addition to the obvious articulated ribs of the thoracic region, each human vertebral level shows some expression of the costal element potential, but it is usually incorporated as an immovable projection. Anomalous free or articulated rib components have been observed at virtually every vertebral level, including the sacrum and coccyx.[59] The hypochordal potential may best indicate the existence of early segmental totipotency in the vertebrates, however. This component is normally expressed at only the C1 level in humans and in the caudal region in other mammals. If there is some interference in the normal control mechanisms, it may also arise at other levels because hypochordal elements have been observed to occur below the last normal vertebra in some cases of lumbosacral agenesis.

Acknowledgment

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CHAPTER 2

Applied Anatomy of the Spine

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Amandeep Bhalla
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The spine is a segmental column of similar formed bones that constitutes the major subcranial part of the axial skeleton. Its individual elements are united by a series of intervertebral articulations that form a flexible, although neuroprotective, support to the trunk and limbs. The spinal column typically consists of 33 vertebrae. The mobile section of the spine comprises 7 cervical, 12 thoracic, and 5 lumbar vertebrae; 5 fused vertebrae form the inflexible sacrum that offers a relatively rigid connection to the innominate bones. Caudad to the sacrum, four or five irregular ossicles compose the coccyx.

Vertebrae

The movements of the spine involve 97 diarthroses (i.e., synovial joints, having substantial motion) and an even greater number of amphiarthroses (i.e., fibrocartilaginous joints, having less motion). The individual vertebrae bear multiple processes and surface markings that indicate the attachments of the numerous ligaments that stabilize these articulations. Despite an appreciable degree of regional variation of these characteristics, the embryologically homologous segmental origin of the spine provides a basic uniformity so that a single generalized description can be applied to the basic morphology of all but the most superior and inferior elements.

The typical vertebra consists of two major components: a roughly cylindrical ventral mass of mostly trabecularized cancellous bone, called the *body,* and a denser, more cortical posterior structure, called the *dorsal vertebral arch*. The vertebral bodies vary considerably in size and sectional contour but exhibit no salient processes or unique external features other than the facets for rib articulation in the thoracic region. In contrast, the vertebral arch has a more complex structure. It is attached to the dorsolateral aspects of the body by two stout pillars, called the *pedicles*. These are united dorsally by a pair of arched flat laminae that are surmounted in the midline by a dorsal projection, called the *spinous process*. The pedicles, laminae, and dorsum of the body form the vertebral foramen, a complete osseous ring that encloses the spinal cord.

The transverse processes and the superior and inferior articular processes are found near the junction of the pedicles and the laminae. The transverse processes extend laterally from the sides of the vertebral arches, and because all vertebrae are phyletically and ontogenetically associated with some form of costal element, they either articulate with or incorporate a rib component. In the thoracic spine, the costal process persists as a rib proper. In the cervical spine, the costal process becomes the anterior part of the transverse process that encloses the vertebral artery foramen, and in the lumbar spine it becomes the mature transverse process; the immature posterior (neural arch) component becomes the mammillary process.

The articular processes (zygapophyses) form the paired diarthrodial articulations (facet joints) between the vertebral arches. The superior processes (prezygapophyses) always bear an articulating facet, whose surface is directed dorsally to some degree, whereas the complementary inferior articulating processes (postzygapophyses) direct their articulating surfaces ventrally. Variously shaped bony prominences (mammillary processes or parapophyses) may be found lateral to the articular processes and serve in the multiple origins and insertions of the spinal muscles.

The superoinferior dimensions of the pedicles are roughly half that of their corresponding body, so that in their lateral aspect the pedicles and their articulating processes form the superior and inferior vertebral notches. Because the base of the pedicle arises superiorly from the dorsum of the body, particularly in the lumbar spine, the inferior vertebral notch appears more deeply incised. In the articulated spine, the opposing superior and inferior notches form the intervertebral foramina that transmit the neural and vascular structures between the corresponding levels of the spinal cord and their developmentally related body segments.

Pars Interarticularis

The pars interarticularis defines the parts of the arch that lie between the superior and inferior articular facets of all subatlantal movable vertebral elements (Fig. 2.1). The term *pars interarticularis* arose to designate that area of the arch that is most stressed by translational movement between adjacent

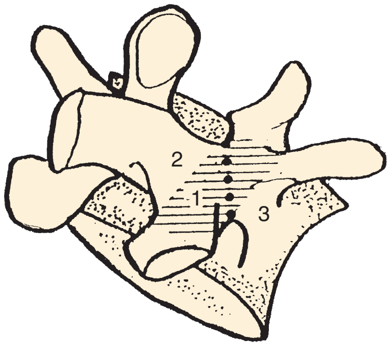

FIG. 2.1 Rendering of the oblique dorsal view of the L5 vertebra showing the parts of the vertebral arch: (*1*) pars interarticularis as the *cross-hatched area,* (*2*) pars laminalis, and (*3*) pars pedicularis. *Dotted line* indicates the most frequent site of mechanical failure of the pars interarticularis.

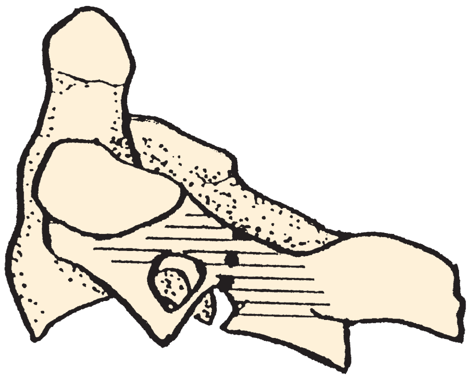

FIG. 2.2 Depiction of lateral view of C2 (axis) vertebra. The offset relationship of the superior facet to the inferior facet elongates the pars interarticularis (*cross-hatched area*). *Dotted line* indicates the most frequent site of failure in upper cervical hyperextension injury (hangman's fracture).

segments, particularly in the second cervical and fifth lumbar vertebrae, which are susceptible to traumatic and stress fractures in this region (i.e., hangman's fracture of C2 and isthmic spondylolysis of L5).[1] In sequential alternation with the intervertebral facet joints, it roofs the lateral recesses of the spinal canal and contributes to the dorsal margins of the intervertebral foramina. In the subcervical vertebrae, it also provides the dorsal part of the base of the transverse process.

Biomechanical forces on the pars interarticularis place it in a position to receive the shearing stresses that occur when translational (spondylolisthetic) forces tend to displace, in a dorsoventral plane, the superior articular processes with respect to their inferior counterparts on the same vertebra. The usual site of failure in the pars interarticularis permits the superior articular facets, pedicles, and vertebral body to be ventrally displaced as a unit, while the inferior articular facets remain attached to the dorsal arch components. These tend to retain their articular relationships with the superior facets of the next lower vertebra.

In the case of the second cervical vertebra (axis) there is a unique anterior relationship of its superior articular facets with the more posteriorly positioned inferior processes that elongates the C2 pars interarticularis. As this offset area receives the greatest leverage between the "cervicocranium" and the lower cervical spine, the indicated line in the illustration in Fig. 2.2 shows the common site of mechanical failure in hyperextension injuries to the upper cervical spine.

In the case of the lumbar vertebrae, the pars interarticularis has been subdivided further. McCulloch and Transfeldt[2] referred to the "lateral buttress," which they believed offered particular structural support to the intervening structures. They described it as the bony bridge that connects the superolateral edge of the inferior facet to the junction of the transverse process and the pedicle. In a follow-up anatomic study, Weiner and colleagues[3] measured the surface area of the lateral buttress in human cadaveric lumbar spines. They found the greatest areas (about 80 mm^2) from L1 to L3, whereas area averaged 50 mm^2 at L4 and only 15 mm^2 at L5. These investigators thought that the broadness of the buttress in the upper lumbar spine can obscure or confuse landmarks for placement of pedicle screws, and its relative thinness (or nonexistence) in the lower lumbar spine can be a predisposing factor to stress fractures or iatrogenic injury to the pars interarticularis. Cadaveric study of L5 pedicle morphology in patients with L5-S1 isthmic spondylolisthesis has shown greater L5 pedicle length compared to that of unaffected subjects, which increases with age.[4]

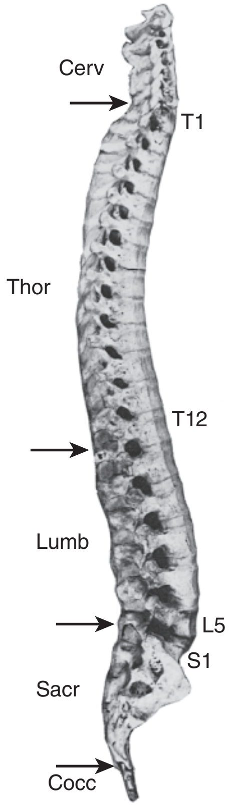

FIG. 2.3 Lateral view of dried preparation of the spine with anterior longitudinal and supraspinous ligaments intact.

Regional Characteristics

Although the 24 vertebrae of the presacral spine are divided into three distinct groups (Fig. 2.3), in which the individual members may be recognized by one or two uniquely regional features, there is a gradual craniocaudal progression of morphologic changes. The vertebrae found above and below the point of regional demarcation are transitional and bear some of the characteristics of both areas. There may be variations in the number of vertebrae, particularly with adolescent idiopathic scoliosis, where up to 10% of individuals can have atypical number of thoracic or lumbar vertebrae.[5]

Cervical Vertebrae

Of the seven cervical vertebrae, the first two (Fig. 2.4A–D) and the last require special notation, but the third to the sixth are fairly uniform, and a common description suffices (Fig. 2.4E–F). Because the cervical vertebrae bear the least weight, their bodies are relatively small and thin with respect to the size of the vertebral arch and vertebral foramen. In addition, their diameter is greater transversely than in the anteroposterior direction. The lateral edges of the superior surface of each body are sharply turned upward to form the uncinate processes that are characteristic of the cervical region. The most obvious diagnostic feature of the cervical vertebrae is the transverse foramina that perforate the transverse processes and transmit the vertebral arteries. The anterior part of the transverse processes represents fused costal elements that arise from the sides of the body. The lateral extremities of the transverse processes bear two projections, the anterior and posterior tubercles. The former serve as origins of anterior cervical muscles; the latter provide origins and insertions for posterior cervical muscles. A deep groove between the upper aspects of the tubercles holds the cervical spinal nerves.

The cervical pedicles connect the posterior vertebral arch to the vertebral body. Anatomic studies have shown that the cervical pedicle height ranges from 5.1 to 9.5 mm, and width ranges from 3 to 7.5 mm.[6,7] The pedicle is angled medially between 90 and 110 degrees.[7]

The superior and inferior articular processes appear as obliquely sectioned surfaces of short cylinders of bone that, when united with the adjacent vertebrae, form two osseous shafts posterolateral to the stacked vertebral bodies. The

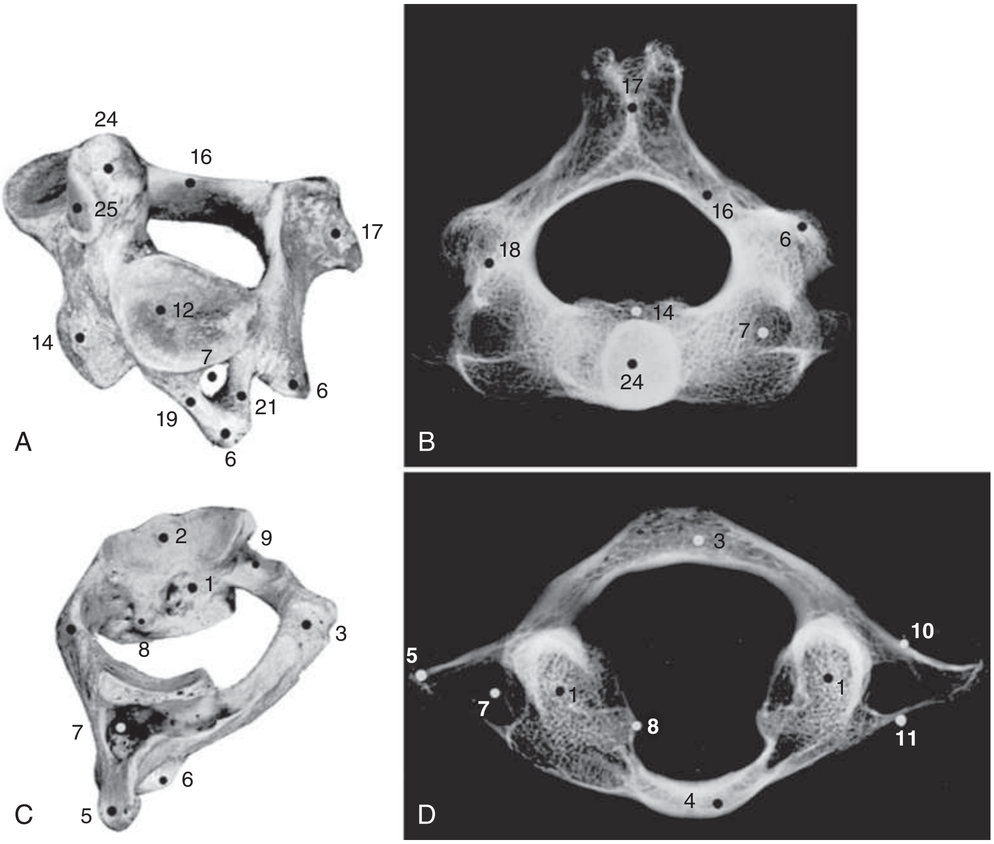

FIG. 2.4 Atlas, axis, and a typical vertebra of each region are illustrated photographically and radiographically. The following numerical key is applicable to all subdivisions of this figure. (A) Oblique view of atlas. (B) Ventral radiographic view of atlas. (C) Oblique view of axis. (D) Vertical radiographic view of axis. *1*, Lateral mass of atlas. *2*, Superior articulating process. *3*, Posterior arch. *4*, Anterior arch. *5*, Transverse process. *6*, Inferior articulating process. *7*, Transverse foramen. *8*, Alar tubercle. *9*, Groove for vertebral artery. *10*, Neural arch element of transverse process. *11*, Costal element of transverse process. *12*, Superior articulating process. *13*, Pedicle. *14*, Body. *15*, Uncinate process. *16*, Lamina. *17*, Spinous process. *18*, Articular pillar. *19*, Anterior tubercle of transverse process. *20*, Neural sulcus. *21*, Posterior tubercle of transverse process. *22*, Superior demifacet for head of rib. *23*, Inferior demifacet for head of rib. *24*, Odontoid process. *25*, Articular facet for anterior arch of atlas.

Continued

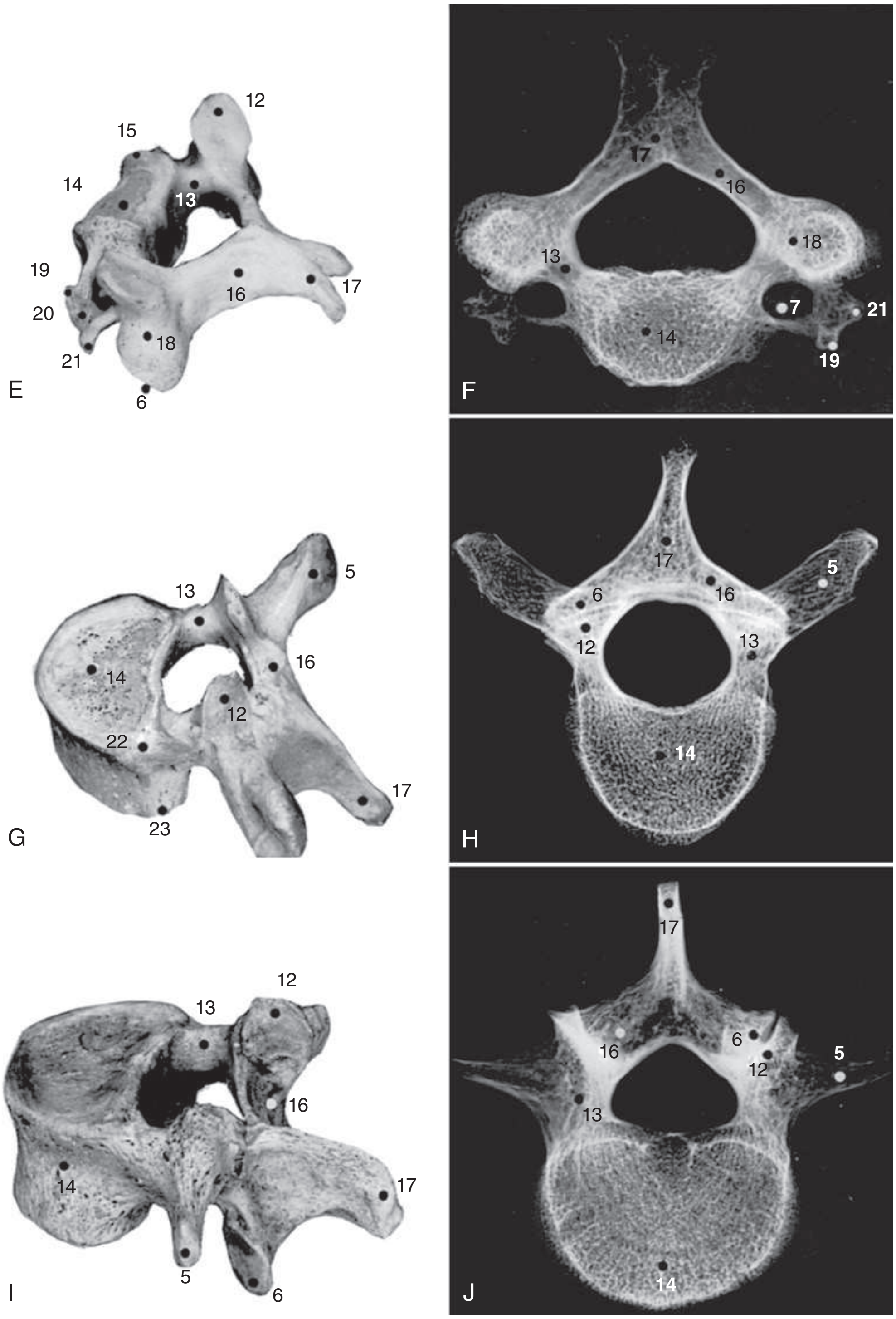

FIG. 2.4, cont'd (E) Oblique view of typical (fourth) cervical vertebra. (F) Vertical radiographic view of typical cervical vertebra. (G) Oblique view of typical (fifth) thoracic vertebra. (H) Vertical radiographic view of thoracic vertebra. The plane of the articular facets would readily permit rotation. (I) Oblique view of typical (third) lumbar vertebra. (J) Vertical radiographic view of lumbar vertebra. The plane of the articular facets is situated to lock the lumbar vertebrae against rotation.

cervical vertebrae present a tripod of flexible columns for the support of the head. As in the upper cervical spine, the combination of the articular processes and the intervening bone is often referred to as the lateral mass in the subaxial region. It is a common site for screw insertion during internal fixation of the cervical spine.[8]

The laminae are narrow and have a thinner superior edge. At their mid-dorsal junction, they bear a bifid spinous process that receives the insertions of the semispinalis cervicis muscles. The height of the lamina of C4 is 10 to 11 mm, whereas the lamina thickness at C5 is about 2 mm.[9] The lamina is thickest at T2, where it measures an average of 5 mm.

Atlantoaxial Complex

The first two cervical vertebrae are structurally and developmentally different. Together, they form a complex articular system that permits the nutational (i.e., nodding) and rotational movements of the head. The first cervical vertebra, or atlas, is a bony ring consisting of an anterior and a posterior arch, which are connected by the two lateral masses. It has all the homologous features of a typical vertebra with the exception of the body. The lateral masses correspond to the combined pedicles and articular pillars of the lower cervical vertebrae, but the superior and inferior articular facets are concave. The superior articular surfaces face upward and internally to receive the occipital condyles of the skull, whereas the inferior articulating surfaces face downward and internally to rotate on the sloped “shoulders” of the axis. This slope helps prevent lateral translation while permitting rotation.

The posterior arch consists of modified laminae that are more round than flat in their sectional aspect and a posterior tubercle that represents an attenuated spinous process that gives origin to suboccipital muscles. Immediately behind the lateral masses on the superior surface of the posterior arch of C1, two smooth grooves house the vertebral arteries as they penetrate the posterior atlanto-occipital membrane. These arteries take a tortuous course from the transverse processes of the atlas, making an almost 90-degree turn medially as they exit the foramen and a subsequent 90-degree turn superiorly to enter the dura and subsequently the foramen magnum. The vertebral artery courses over the posterior ring of the atlas 10 to 15 mm from the midline in adults and, although the arteries are closer to the midline in the pediatric population, 97% are located at least 1 cm from the midline.[10] Dissection further lateral risks injury to these vessels.

The transverse foramen also houses a venous system. In an anatomic and radiologic study to characterize the venous system within the transverse foramen, Magro and colleagues[11] found ventral longitudinal veins that may also exist in a plexus arrangement. Anastomosis between the plexus transverse veins and vertebral veins can be present. An understanding of venous anatomy in the transverse foramen may help contextualize false-positive diagnoses of vertebral artery dissection from magnetic resonance angiography caused by slow flow vertebral veins.

The anterior arch forms a short bridge between the anterior aspects of the lateral masses. It bears an anterior tubercle that is the site of insertion of the longus colli muscle. On the posterior surface of the anterior arch, a semicircular depression marks the synovial articulation of the odontoid process. Internal tubercles on the adjacent lateral masses are the attachment sites of the transverse atlantal ligaments that hold the odontoid against this articular area. Cadaveric studies have shown that the right-sided tubercles tend to be of larger caliber and that the mean angle formed between both tubercles and the dental facet is 75 degrees.[12]

The second cervical vertebra, or axis, provides a bearing surface on which the atlas may rotate. Its most distinctive characteristic is the vertically projecting odontoid process that serves as a pivotal restraint against horizontal displacements of the atlas. This bony prominence represents the phyletically purloined centrum of the first cervical vertebra. It exhibits a slight constriction at its neck and an anterior facet for its articulation with the anterior arch of the atlas. Posteriorly, a groove in the neck of the odontoid marks the position of the strong transverse atlantal ligament.

The apex of the odontoid process is slightly pointed. It is the attachment site of the apical ligament. Posterior to the apex, two lateral roughened prominences indicate the attachments of the alar ligaments. These structures and the apical ligament connect the odontoid process to the base of the skull at the basion, the anterior aspect of the foramen magnum. The occipital attachments of the alar ligaments are on the medial surface of the occipital condyles, adjacent to the atlanto-occipital joints. Atlantal attachments of the alar ligaments have also been described, but these are more likely to be anatomic variants and not essential components of craniovertebral junction stability.[13] The superior articulating surfaces of the axis are convex and are directed laterally to receive the lateral masses of the atlas. The inferior articulating surfaces are typical of those of the cervical vertebrae and serve as the start of the articular columns. The transverse processes of the axis are directed downward. Anteriorly, the inferior aspect of the body of the axis forms a liplike process that descends over the first intervertebral disc and the body of the third cervical vertebra.

The seventh cervical vertebra is transitional. The inferior surface of its body is proportionately larger than the superior surface. It has a long, distinct spinous process that is usually easily palpable (the vertebra prominens). The superior and inferior articulating facets are more steeply inclined and presage the form of these structures in the thoracic region. Blunt transverse processes have heavy posterior struts and much lighter anterior struts that surround transverse foramina that are often bilaterally unequal and seldom pass the vertebral arteries. Frequently, one or both of the anterior struts realize their true potential as a costal element and develop into a cervical rib.

Thoracic Vertebrae

All 12 thoracic vertebrae support ribs and have facets for the diarthrodial articulations of these structures. The first and last four have specific peculiarities in the manner of costal articulations, but the second to the eighth are similar (Fig. 2.4G–H).

The body of a mid-thoracic vertebra is heart-shaped. Its length and width are roughly halfway between that of the cervical and lumbar bodies. Often a flattening of the left side of the body indicates its contact with the descending aorta. In the mid-thorax, the heads of the ribs form a joint that spans the intervertebral disc, so that the inferior lip of the body of one vertebra and the corresponding site of the superior lip of the infrajacent element share in the formation of a single articular facet for the costal capitulum. The typical thoracic vertebra bears two demifacets on each side of its body. The thoracic vertebral arch encloses a small, round vertebral foramen that would not admit the tip of an index finger, even when the specimen is from a large adult. This limited space for the spinal cord predisposes to severe spinal cord injury with minimal dimensional compromise.

Because the pedicles arise more superiorly on the dorsum of the body than they do in the cervical region, the inferior vertebral notch forms an even greater contribution to the intervertebral foramen. The pedicle height increases from T1 to T12, but the transverse pedicle width (which is more critical for transpedicular screw containment) does not follow this same craniocaudal pattern.[14] Cinotti and colleagues[15] found that the pedicles in the T4 to T8 region had the smallest transverse diameter. Scoles and colleagues[16] documented similar findings in 50 cadaveric human spines, with the smallest diameters measured at T3 to T6. On average, the transverse pedicle diameter at T3 is 3.4 mm in women and 3.9 mm in men. At T6, it averages 3 mm in women and 3.5 mm in men. At T1, however, the mean diameter is 6.4 mm in women and 7.3 mm in men. Lehman and colleagues described key morphologic characteristics to facilitate safe medial-lateral starting points for placement of thoracic pedicle screws.[17] The ventral lamina is an anatomically reproducible structure consistently located medial to the superior articular facet in the thoracic spine. They also noted the center of the pedicle lays 2 to 3 mm lateral to the midline of the superior articular facet.

The superior articular facets form a stout shelflike projection from the junction of the laminae and the pedicles. Their ovoid surfaces are slightly convex, are almost vertical, and are coronal in their plane of articulation. They face dorsally and slightly superolaterally, and in bilateral combination they present the segment of an arc whose center of radius lies at the anterior edge of the vertebral body. They permit a slight rotation around the axis of this radius. The inferior articular facets are borne by the inferior edges of the laminae. The geometry of their articular surfaces is complementary to the superior processes.

On the ventral side of the tip of the strong transverse processes, another concave facet receives the tuberculum of the rib whose capitulum articulates with the superior demifacet of the same vertebra. The spinous processes of the thoracic vertebrae are long and triangular in section. The spinous processes of the upper four thoracic vertebrae are more bladelike and are directed downward at an angle of about 40 degrees from the horizontal. The middle four thoracic spinous processes are longer but directed downward at an angle of 60 degrees, so that they completely overlap the adjacent lower segment. The lower four resemble the upper four in direction and shape.

The first thoracic vertebra has a complete facet on the side of its body for the capitulum of the first rib and an inferior demifacet for the capitulum of the second rib. The costal articulations of the 9th to 12th thoracic vertebrae are confined to the sides of the bodies of their respective segments. On the last two thoracic vertebrae, transitional characteristics are evident in the diminution of the transverse processes and their failure to buttress the last two ribs. Because the ribs are disconnected from the sternum, they are frequently referred to as "floating ribs."

Lumbar Vertebrae

The lumbar vertebrae are the lowest five vertebrae of the presacral column (see Fig. 2.4I–J). All their features are expressed in more massive proportions. They are easily distinguished from other regional elements by their lack of a transverse foramen or costal articular facets. The body is large, having a width greater than its anteroposterior diameter, and is slightly thicker anteriorly than posteriorly. All structures associated with the vertebral arch are blunt and stout. The thick pedicles are widely placed on the dorsolaterosuperior aspects of the body, and with their laminae they enclose a triangular vertebral foramen. Although the inferior vertebral notch is deeper than the superior, both make substantial contributions to the intervertebral foramen. The transverse processes are flat and winglike in the upper three lumbar segments, but in the fifth segment they are thick, rounded stumps. The fourth transverse process is usually the smallest.

Aside from their relative size, the lumbar vertebrae can be recognized by their articular processes. The superior pair arise in the usual manner from the junction of the pedicles and laminae, but their articular facets are concave and directed dorsomedially, so that they almost face each other. The inferior processes are extensions of the laminae that direct the articulating surfaces ventrolaterally and lock themselves between the superior facets of the next inferior vertebra in an almost mortise-and-tenon fashion. This arrangement restricts rotation and translation in the lumbar region. The lumbar segments also have pronounced mammillary processes, which are points of origin and insertion of the thick lower divisions of the deep paraspinal muscles.

Sacral Vertebrae

The sacrum consists of five fused vertebrae that form a single triangular complex of bone that supports the spine and forms the posterior part of the pelvis (Figs. 2.5 and 2.6). It is markedly curved and tilted backward, so that its first element articulates with the fifth lumbar vertebra at a pronounced angle (the sacrovertebral angle).

Close inspection of the flat, concave ventral surface and the rough, ridged convex dorsal surface reveals that, despite their fusion, all the homologous elements of typical vertebrae are still evident in the sacrum. The heavy, laterally projecting alae that bear the articular surfaces for articulation with the pelvis are fused anterior costal and posterior transverse processes of the first three sacral vertebrae. These lateral fusions require that separate dorsal and ventral foramina provide egress for the anterior and posterior divisions of the sacral nerves. The ventral four pairs of sacral foramina are larger than their dorsal counterparts because they must pass the thick sacral contributions to the sciatic nerve. The ventral surface of the sacrum is relatively smooth. There are four transverse ridges that mark the fusions of the vertebral bodies and enclose remnants of the intervertebral discs. Lateral to the bodies of the second, third, and fourth elements, the ridges of bone that

FIG. 2.5 Composite anteroposterior view of sacrum. The roughened crests on the dorsum (*left side*) indicate longitudinal fusions of vertebral arch structures. The articular process is directed backward to buttress the vertebral arch of the fifth lumbar vertebra. *Art crest,* articular crest; *Art pro,* articular process; *Cost proc,* costal process; *Lat crest,* lateral crest; *Sarc tub,* superior articulating tubercle; SC, sacral comua; *Spin crest,* spinous crest.

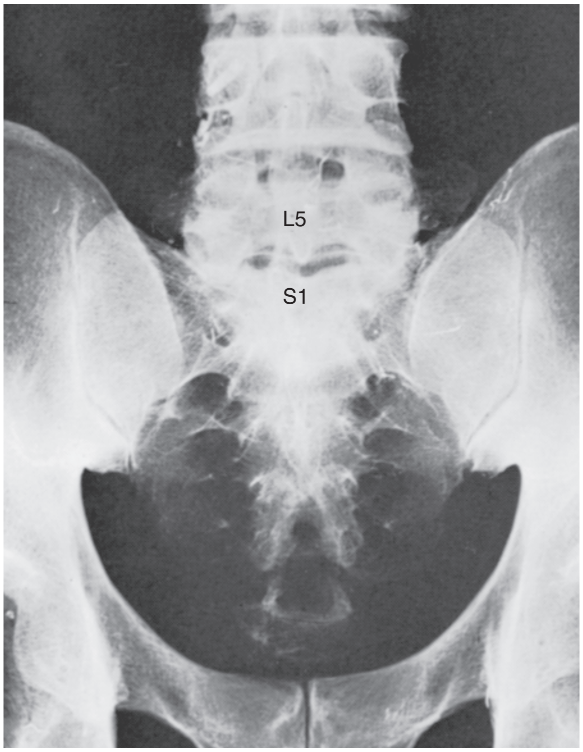

FIG. 2.6 Anterior radiographic view of lumbosacral and sacroiliac articulations. Load transfer from the lumbar spine to the iliac bones via the costal processes of the first and second sacral segments is obvious.

separate the anterior sacral foramina are quite prominent and give origin to the piriformis muscle.

The dorsal aspect of the sacrum is convex, rough, and conspicuously marked by five longitudinal ridges. The central one, the middle sacral crest, is formed by the fusion of the spinous processes of the sacral vertebrae. On either side, a sacral groove separates it from the medial sacral articular crest that represents the fused articular process. The superior ends of these crests form the functional superior articular processes of the first sacral vertebra, which articulate with the inferior processes of the fifth lumbar vertebra. They are very strong, and their facets are directed dorsally to resist the tendency of the fifth lumbar vertebra to be displaced forward. Inferiorly, the articular crests terminate as the sacral cornua, two rounded projections that bracket the inferior hiatus where it gives access to the sacral vertebral canal. More laterally, the lateral crests and sacral tuberosities form uneven elevations for the attachments of the dorsal sacroiliac ligaments.

The sacrum and its posterior ligaments lie ventral to the posterior iliac spines and form a deep depression that accommodates, and gives origin to, the inferior parts of the paraspinal muscles. The grooves between the central spinous crest and the articular crests are occupied by the origins of the multifidus muscles. Dorsal and lateral to these are attached the origins of the iliocostal and iliolumbar muscles.

Coccyx

The coccyx is usually composed of four vertebral rudiments, but one fewer or one greater than this number is not uncommon. The coccyx is the vestigial representation of the tail. The first coccygeal segment is larger than the succeeding members and resembles to some extent the inferior sacral element. It has an obvious body that articulates with the homologous component of the inferior sacrum, and it bears two cornua, which may be regarded as vestiges of superior articulating processes. The three inferior coccygeal members are most frequently fused and present a curved profile continuous with that of the sacrum. They incorporate the rudiments of a body and transverse processes but possess no components of the vertebral arch.

The coccyx contributes no supportive function to the spine. It serves as an origin for the gluteus maximus posteriorly and the muscles of the pelvic diaphragm anteriorly.

Arthrology of the Spine

The articulations of the spine include the three major types of joints: synarthroses, diarthroses, and amphiarthroses (Figs. 2.7 to 2.9). The *synarthroses* are found during development and the first decade of life. The best examples are the neurocentral joints of the immature spine, which are the two unions between the centers of ossification for the two halves of the vertebral arch and that of the centrum. Until they are obliterated during the 2nd decade, they possess a thin plate cartilage between the two apposed bony surfaces. Another example is

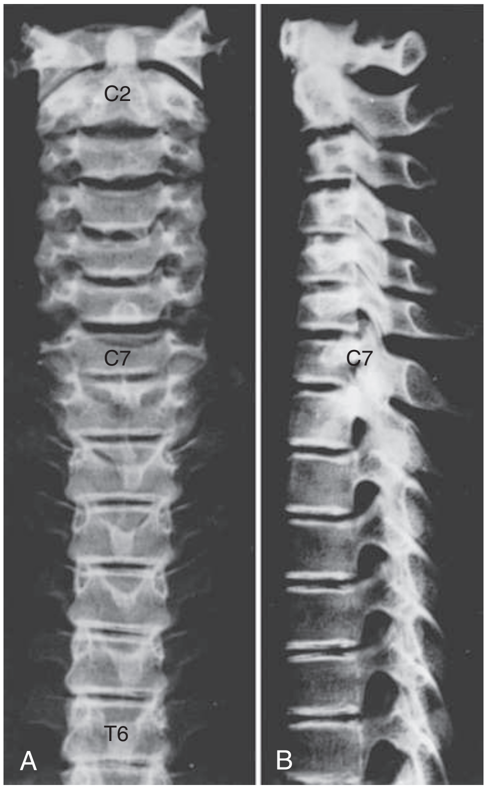

FIG. 2.7 (A) Anteroposterior radiograph of dried preparation of cervical and upper thoracic spine. Note greater relative thickness of cervical discs and more lateral disposition of cervical articular pillars. (B) Lateral view of preceding specimen. The normal curvatures did not survive the preparation, but the gradual increase in size of the bodies and the intervertebral foramina is well illustrated.

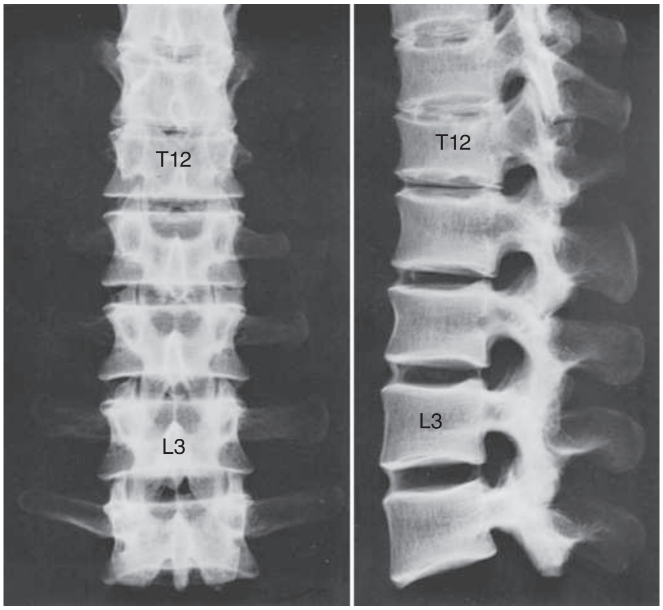

FIG. 2.8 Anteroposterior *(left)* and lateral *(right)* radiographs of lower thoracic and upper lumbar region of articulated dried preparation.

the early union between the articular processes of the sacral vertebrae, known as *ephemeral synchondroses*.

The *diarthroses* are true synovial joints, formed mostly by the facet joints and costovertebral joints, but also include the atlantoaxial and sacroiliac articulations. All the spinal diarthroses are of the arthrodial or gliding type, with the exception of the trochoid or pivot joint of the atlantodens articulation.

The *amphiarthroses* are nonsynovial, slightly movable connective tissue joints. They are of two types: the symphysis, as exemplified by the fibrocartilage of the intervertebral disc, and the syndesmosis, as represented by all the ligamentous connections between the adjacent bodies and the adjacent arches.

Articulations of the Vertebral Arches

The synovial facet joints formed by the articular processes of the vertebral arches possess a true joint capsule and are capable of a limited gliding articulation. The capsules are thin and lax and are attached to the bases of the engaging superior and inferior articulating processes of opposing vertebrae. Because it is mostly the plane of articulation of these joints that determines the types of motion characteristic of the various regions of the spine, it would be expected that the fibers of the articular capsules would be longest and loosest in the cervical region and become increasingly taut in an inferior progression.

The syndesmoses between the vertebral arches are formed by the paired sets of ligamenta flava, the intertransverse ligaments, the interspinous ligaments, and the unpaired supraspinous ligament. The ligamenta flava bridge the spaces between the laminae of adjacent vertebrae from the second cervical to the lumbosacral interval. The lateral extent of each half of a paired set begins around the bases of the articulating processes and can be traced medially where they nearly join in the midline. This longitudinal central deficiency serves to transmit small vessels and facilitates the passage of a needle during lumbar punctures. The fibers of the ligamenta flava are almost vertical in their disposition, but are attached to the ventral surface of the cephalad lamina and to the superior lip of the subjacent lamina.

This shinglelike arrangement conceals the true length of the ligaments because of the overlapping of the superior lamina. Their morphology is best appreciated from the ventral aspect as in Fig. 2.9B. The yellow elastic fibers that give the ligamenta flava their name maintain their elasticity even in embalmed specimens. It has been stated in some texts that the elasticity of the ligamenta flava serves to assist in the maintenance of the erect posture. A more probable reason for this property is simply to keep the ligament taut during extension, where any laxity would permit redundancy and infolding toward the ventrally related nervous structures, as occurs in degenerative lumbar spinal stenosis.

There are two separable layers of the ligamentum flavum, one superficial and one deep, that have distinct attachments to the inferior lamina.[18] The superficial component inserts at the classically described location along the posterosuperior aspect of the lamina. The deep component inserts along the anterosuperior surface of the lamina.[18] This attachment can have significance during surgical removal of the ligamentum flavum for exposure of the neural elements.

The intertransverse ligaments are fibrous connections between the transverse processes. They are difficult to distinguish from extensions of the tendinous insertions of the segmental muscles and in reality may be just that in some regions.

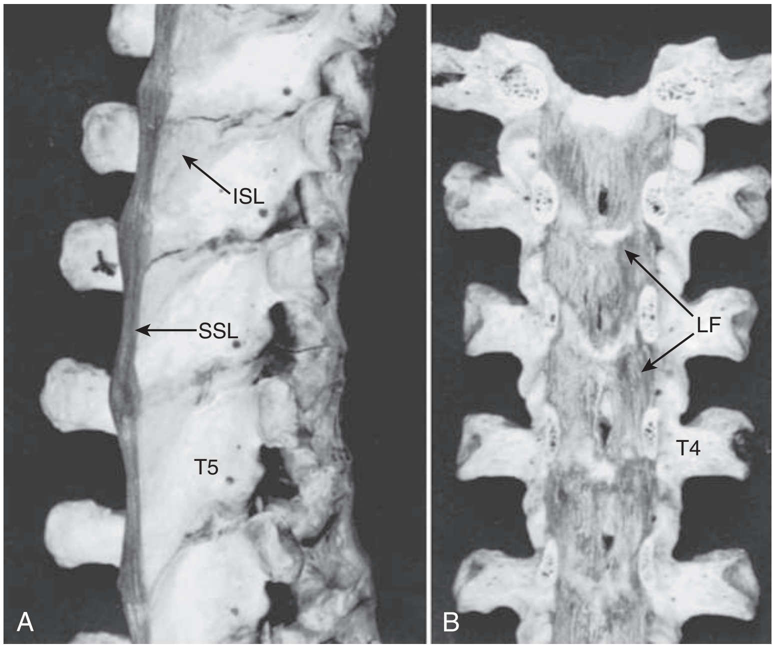

FIG. 2.9 (A) Dried preparation of thoracic vertebrae showing the supraspinous ligament (SSL) and interspinous ligaments (ISL). (B) Anterior view of upper thoracic vertebral arches showing the disposition of the ligamenta flava (LF).

They appear as a few tough, thin fibers between the cervical transverse processes, and in the thoracic area they blend with the intercostal ligaments. Being most distinct between the lumbar transverse processes, the intertransverse ligaments may be isolated here as membranous bands.

The interspinous ligaments (see Fig. 2.9A) are membranous sets of fibers that connect adjoining spinous processes. They are situated medial to the thin pairs of interspinal muscles that bridge the apices of the spine. The fibers of the ligaments are arranged obliquely as they connect the base of the superior spine with the superior ridge and apex of the next most inferior spinous process. These midline ligaments are found in pairs with a distinct dissectible cleft between them.

The supraspinous ligament (see Fig. 2.9A) is a continuous fibrous cord that runs along the apices of the spinous processes from the seventh cervical to the end of the sacral spinous crest. Similar to the longitudinal ligaments of the vertebra, the more superficial fibers of the ligament extend over several spinal segments, whereas the deeper, shorter fibers bridge only two or three segments. In the cervical region the supraspinous ligament assumes a distinctive character and a specific name, the *ligamentum nuchae*. This structure is bowstrung across the cervical lordosis from the external occipital protuberance to the spine of the seventh cervical vertebra. Its anterior border forms a sagittal fibrous sheet that divides the posterior nuchal muscles and attaches to the spinous processes of all cervical vertebrae. The ligamentum nuchae contains an abundance of elastic fibers. In quadrupeds, it forms a strong truss that supports the cantilevered position of the head.

Special Articulations

The atlanto-occipital articulation consists of the diarthrosis between the lateral masses of the atlas and the occipital condyles of the skull and the syndesmoses formed by the atlanto-occipital membranes. The articular capsules around the condyles are thin and loose and permit a gliding motion between the condylar convexity and the concavity of the lateral masses. The capsules blend laterally with ligaments that connect the transverse processes of the atlas with the jugular processes of the skull. Although the lateral ligaments and the capsules are sufficiently lax to permit nodding, they do not permit rotation.

The anterior atlanto-occipital membrane is a structural extension of the anterior longitudinal ligament that connects the forward rim of the foramen magnum, also known as the *basion,* to the anterior arch of the atlas and blends with the joint capsules laterally. It is dense, tough, and virtually cordlike in its central portion.

The posterior atlanto-occipital membrane is homologous to the ligamenta flava and unites the posterior arch of the atlas. It is deficient laterally where it arches over the groove on the superior surface of the arch. Through this aperture, the vertebral artery enters the neural canal to penetrate the dura. Occasionally, the free edge of this membrane is ossified to form a true bony foramen (called the *ponticulus posticus*) around the artery.

The median atlantoaxial articulation is a pivot (trochoid) joint (Figs. 2.10 and 2.11). The essential features of the articulation are the odontoid process (dens) of the axis and the internal surface of the anterior arch of the atlas. The opposition of the two bones is maintained by the thick, straplike transverse atlantal ligament. The ligament and the arch of the atlas have true synovial cavities intervening between them and the odontoid process. Alar expansions of the transverse ligament attach to tubercles on the lateral rims of the anterior foramen magnum, and a single, unpaired cord, the apical odontoid ligament, attaches the apex of the process to the

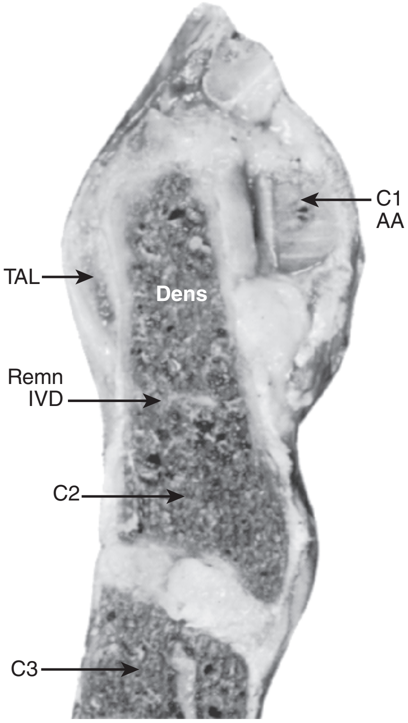

FIG. 2.10 Sagittal section through adult odontoid process showing articular relationships with anterior arch of the atlas (AA) and transverse atlantal ligament (TAL). Despite the fact this patient was older than 50 years, a cartilaginous remnant of the homologue of an intervertebral disc (Remn IVD) may be discerned. Radiologically, this might be confused with fracture or a nonunion status.

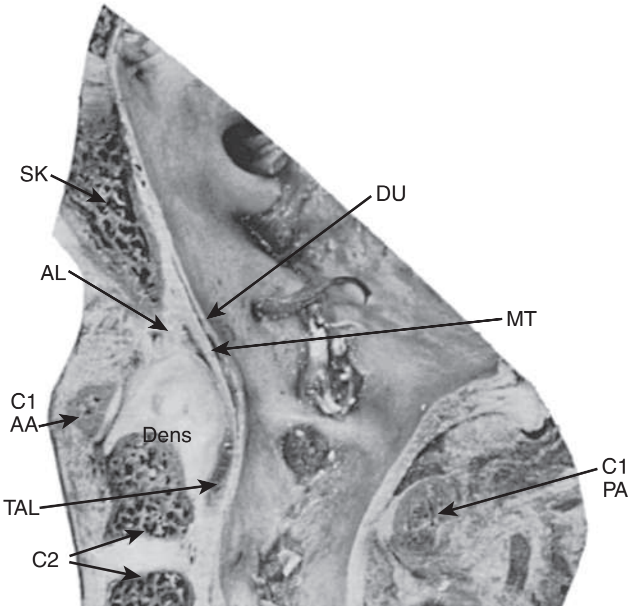

FIG. 2.11 Sagittal section through atlanto-occipital articulation of a 4-year-old child. The major ossification centers of the odontoid process are still separated from the body of C2 by a well-differentiated disc. The cartilaginous apex of the process shows a condensation marking the apical ossific center. C1 AA and C1 PA mark the anterior and posterior atlantal arches. The dura (DU) overlies the membrana tectoria (MT), which is a superior extension of the posterior longitudinal ligament. The transverse atlantal ligament (TAL) and apical ligament (AL) are also indicated. SK, skull.

basion. The entire joint is covered posteriorly by a cranial extension of the posterior longitudinal ligament, which is named *tectorial membrane* in this region. Because the atlas freely glides over the superior articulating facets of C2, the atlantoaxial pivot is essential for preventing horizontal displacements between C1 and C2. Fracture of the odontoid or, less likely, rupture of the transverse ligament produces a very unstable articulation.

Articulations of the Vertebral Bodies

The vertebral bodies are connected by the two forms of amphiarthroses. Symphyses are represented by the intervertebral discs, and syndesmoses are formed by the anterior and posterior longitudinal ligaments.

Intervertebral Disc

In view of the semiliquid nature of the nucleus pulposus and the vacuities that may be shown in the nucleus of aging specimens, von Luschka[19] attempted to classify the intervertebral disc as a diarthrosis, in which the vertebral chondral plates were the articular cartilages, the anulus provided the articular capsule, and the fluid and ephemeral spaces within the nucleus corresponded to the synovia and the joint cavity. Although the intervertebral disc forms a joint that should be classified in its own exclusive category because its development, structure, and function are generally different from those of any other joint, it most closely conforms to an amphiarthrosis of the symphysis type.

The intervertebral disc is the fibrocartilaginous complex that forms the articulation between the bodies of the vertebrae. Although it provides a very strong union, ensuring the degree of intervertebral fixation that is necessary for effective action and the protective alignment of the neural canal, the summation of the limited movements allowed by each disc imparts to the spinal column as a whole its characteristic mobility. The discs of the various spinal regions may differ considerably in size and in some detail, but they are basically identical in their structural organization. Each consists of two components: the internal semifluid mass, called the *nucleus pulposus,* and its laminar fibrous container, known as the *anulus fibrosus*.

Nucleus Pulposus

Typically, the nucleus pulposus occupies an eccentric position within the confines of the anulus, usually being closer to the posterior margin of the disc. Its most essential character becomes obvious in either transverse or sagittal preparations of the disc in which, as evidence of internal pressure, it bulges beyond the plane of section. Palpation of a dissected nucleus from a young adult shows that it responds as a viscid fluid under applied pressure, but it also exhibits considerable elastic rebound and assumes its original physical state on release. These properties may still be shown in the spine of a cadaver that has been embalmed for many months.

Histologic analysis provides a partial explanation for the characteristics of the nucleus. As the definitive remnant of the embryonic notochord, it is similarly composed of loose, delicate fibrous strands embedded in a gelatinous matrix. In the center of the mass, these fibers show no geometric preference in their arrangement but form a felted mesh of undulating bundles. Only the fibers that are in approximation to the vertebral chondral plates display a definite orientation. These approach the cartilage at an angle and become embedded in its substance to afford an attachment for the nucleus. Numerous cells are suspended in the fibrous network. Many of these are fusiform and resemble typical reticulocytes, but vacuolar and darkly nucleated chondrocytes are also interspersed in the matrix. Even in the absence of vascular elements, the profusion of cells should accentuate the fact that the nucleus pulposus is composed of vital tissue. There is no definite structural interface between the nucleus and the anulus. Rather, the composition of the two tissues blends imperceptibly.

Anulus Fibrosus

The anulus is a concentric series of fibrous lamellae that encase the nucleus and strongly unite the vertebral bodies (Fig. 2.12). The essential function of the nucleus is to resist and redistribute compressive forces within the spine, whereas one of the major functions of the anulus is to withstand tension, whether the tensile forces be from the horizontal extensions of the compressed nucleus, from the torsional stress of the column, or from the separation of the vertebral bodies on the convex side of a spinal flexure. Without optical aid, simple dissection and discernment reveals how well the anulus is constructed for the performance of this function.

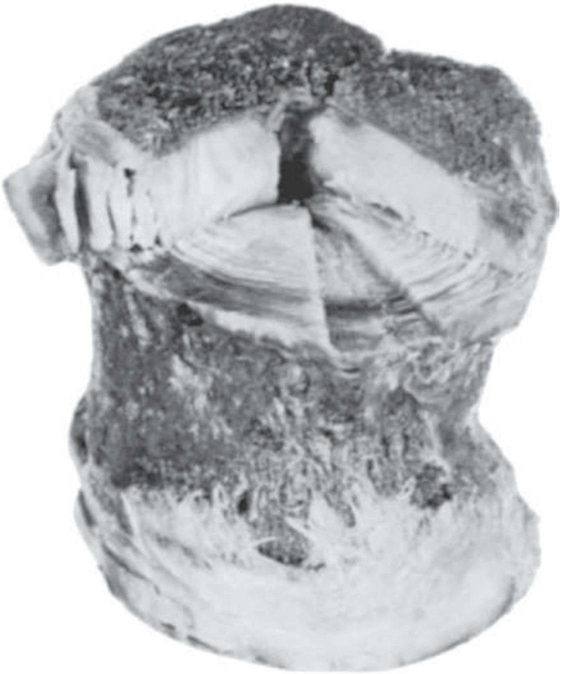

FIG. 2.12 A dissected third lumbar disc. Lamellar bands are still visible when the section is cut deep into bony apophyseal ring. A layer of spongiosa was left attached to the superior surface of the disc to show that only a thin chondral plate intervenes between the vascular trabeculae and the disc. The inward buckling of the lamellae near the cavity of the extirpated nuclear material is well shown. The specimen is from a 52-year-old man.

On horizontal section, it is noted that an individual lamella encircling the disc is composed of glistening fibers that run an oblique or spiral course in relation to the axis of the vertebral column. Because the disc presents a kidney-shaped or heart-shaped horizontal section, and the nucleus is displaced posteriorly, these lamellae are thinner and more closely packed between the nucleus and the dorsal aspect of the disc. The bands are stoutest and individually more distinct in the anterior third of the disc, and here when transected they may give the impression that they are of varying composition because every other ring presents a difference in color and elevation with reference to the plane of section. Teasing and inspection at an oblique angle shows in the freed lamellae, however, that this difference is due to an abrupt change in the direction of the fibers of adjacent rings. Previous descriptions of the anulus have claimed that the alternating appearance of the banding is the result of the interposition of a chondrous layer between each fibrous ring.[20] In reality, the alternations of glistening white lamellae with translucent rings result from differences in the incidence of light with regard to the direction of the fiber bundles. This repeated reversal of fiber arrangement within the anulus has implications in the biomechanics of the disc, which are discussed later.

The disposition of the lamellae on sagittal section is not consistently vertical. In the regions of the anulus approximating the nucleus pulposus, the first distinct bands curve inward, with their convexity facing the nuclear substance. As one follows the successive layers outward, a true vertical profile is assumed, but as the external laminae of the disc are approached, they may again become bowed, with their convexity facing the periphery of the disc.[21,22]

The attachment of the anulus to its respective vertebral bodies warrants particular mention. This attachment is best understood when a dried preparation of a thoracic or lumbar vertebra is examined first. In the adult, the articular surface of the body presents two aspects: a concave central depression that is quite porous and an elevated ring of compact bone that appears to be rolled over the edge of the vertebral body. Often a demarcating fissure falsely suggests that the ring is a true epiphysis of the body, but postnatal studies of ossification have indicated that it is a traction apophysis for the attachment of the anulus and associated longitudinal ligaments.[23]

In life, the depth of the central concavity is filled to the level of the marginal ring by the presence of a cribriform cartilaginous plate. In contrast to other articular surfaces, there is no closing plate of compact osseous material intervening between this cartilage and the cancellous medullary part of the bone. The trabeculations of the spongiosa blend into the internal face of the chondrous plate, whereas fibers from the nucleus and inner lamellae of the anulus penetrate its outer surface. As intimate as this union between the central disc and vertebra may appear, the outer bony ring affords the disc its firmest attachment because the stoutest external lamellar bands of fibers actually penetrate the ring as Sharpey fibers. Scraping the disc to the bone shows the concentric arrangements reflecting the different angles at which the fibers insert (see