OKU

5

Orthopaedic Knowledge Update

Spine

North American Spine Society

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AAOS
American Academy of Orthopaedic Surgeons

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Preface

This fifth edition of *Orthopaedic Knowledge Update Spine* (*OKU Spine 5*) seeks to maintain the tradition of excellence fostered by previous editors and authors and recognize the rapidly changing world of spine care. Not only have the sources of data greatly increased in the 5 years since the publication of the prior edition of this work, but so have the means of accessing this information. Excellent research has emerged from throughout the world, including rapidly growing input from Asia. This research is often published in a host of new journals, and much of it is directly available on the Internet.

For both learners and specialists working to maintain up-to-date knowledge, the challenge is not finding information, but rather sifting through the mountains of available data. The editors of *OKU Spine 5* sought to address that challenge by assembling more than 80 experts from diverse backgrounds and regions and representing various disciplines and subspecialty interests. Together, we seek to provide concise answers to the questions “where are we in spine care?” and “where are we going”? Toward this end, the powerful OKU format allowed us to organize this information. Most topics begin with a review of critical background information, followed by an update of the literature from the past 5 years. Each chapter offers an annotated bibliography to guide the readers’ further exploration of a topic.

Our thanks go to the project manager, Kim Hooker, and editorial team at the American Academy of Orthopaedic Surgeons (AAOS), including Lisa Claxton Moore, Kathleen Anderson, Laura Goetz, Steven Kellert, Genevieve Charet, and Rachel Winokur. To ensure timeliness, this book had very tight deadlines. The AAOS staff was instrumental in moving the project forward. They also hosted many conference calls during which the editors and section editors discussed concepts around section organization and author selection. These initial discussions led to a particularly engaged author group and strong content offering broad coverage of spine care with minimal redundancy.

Today, optimal spine care requires an interdisciplinary approach with invaluable input from our colleagues in physical medicine, rehabilitation, anesthesiology, radiology, neurology, neurosurgery, rheumatology, and internal medicine. That spectrum of caregivers is reflected in our selection of contributors to this work. As with previous editions of *OKU Spine*, this balance began with two book editors with different practices and training backgrounds and continued with a diverse group of section editors. We are indebted to the section editors—Chris Chaput, Charlie Cho, Mitchel Harris, Scott Laker, Ronald Lehman Jr, Charlie Reitman, Andrew Schoenfeld, and Jeffrey Wang—each a recognized expert in the field, for helping select topics and authors and for shepherding those chapters through to completion.

Although each chapter stands on its own, the book also is organized with a logic that allows it to be read cover to cover or section by section. *OKU Spine 5* begins with an overview of spine anatomy and physiology. This section is followed by a review of the assessment tools most useful to spine care providers. Approaches to management are grouped by type and disease state and include sections on medical and surgical management of spine disorders, spine deformity, spine trauma, neoplastic and inflammatory conditions, and the special populations affected by spine disorders.

For the first time, an *OKU Spine* update will be accompanied by section commentaries written by international spine experts; these commentaries will be available with the digital version of this work. The editors are indebted to these contributors for providing an international perspective that further emphasizes the wide-ranging approaches and viewpoints in current spine care.

We thank the North American Spine Society (NASS) and the AAOS for the honor of editing this book. We acknowledge our practices and our partners who have been very patient with our volunteer efforts and the time required for their completion. Finally, we thank our families for their patience while we attended those evening conference calls and weekends spent tapping away at the keyboard. With this done, we expect an increase in our exposure to those loved ones, the sun, and improvement in our vitamin D levels.

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Chapter 1

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Abstract

The vertebral column is a complex three-dimensional structure whose function in health and disease is determined by the anatomy and physiology of the spine at its supporting structures, including the vertebrae, the disks, and the intimate connections with the surrounding soft tissues. To understand, diagnose, and safely treat patients with spinal pathology, it is helpful for surgeons to review the basic anatomy of the spine and be aware of recent developments in understanding how the anatomy of the vertebrae and the surrounding tissues affect function.

Keywords: anatomy; applied anatomy; vertebrae

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Introduction

A detailed knowledge of spine anatomy is a prerequisite for safe and effective nonsurgical and surgical treatment of patients with spine pathology. The vertebrae, intervertebral disks, and surrounding ligaments and muscles are important determinants of spinal function, both in health and disease. The evolving body of knowledge on spine anatomy, function, and the complex interactions between the various elements that make up the spine allows a deeper understanding of the pathogenesis of disease and the potential development of future novel treatments.

Basic Anatomy

The spinal column consists of 24 vertebral segments. Except for the first cervical level, all individual vertebrae share similar basic morphologic characteristics, including a vertebral body, pedicles, a lamina, and a variety of bony projections that serve as attachments for ligaments and muscles. The mobile spine is traditionally divided into three regions consisting of 7 cervical vertebrae, 12 thoracic vertebrae, and 5 lumbar vertebrae. The sacrum consists of five fused vertebrae, with no motion between the vertebrae. Despite important similarities, substantial anatomic variation exists between the vertebrae of each region, with the vertebrae being adapted to the varying functional demands throughout the spine. A thorough understanding of these variations is essential for the safe and effective management of spinal pathology.

The functional spinal unit consists of two adjacent vertebrae and their intervening intervertebral disk and facet joints. The facet joints are true synovial joints with characteristics similar to those of other synovial articulations in the body. The intervertebral disk, however, is the major load-bearing structure of the spine and has unique characteristics. Each intervertebral disk is composed of an inner gelatinous nucleus pulposus consisting primarily of type II collagen and proteoglycans and surrounded by a highly organized collagenous anulus fibrosus, which primarily consists of type I collagen in concentric lamellae, with fibers lying in alternating directions (**Figure 1**). These components are confined cranially and caudally by the vertebral end plates, resulting in a confined hydraulic system with biphasic viscoelastic biomechanical properties capable of withstanding considerable compressive loads.

Ligaments

The spine is stabilized by several ligamentous structures. The anterior longitudinal ligament (ALL) is found on the ventral aspect of the vertebral body, extending from the skull to the sacrum. The ALL has several layers, with its deepest and strongest attachments being to the articular lip at the margins of each vertebra and its more superficial layers spanning multiple vertebrae. The posterior longitudinal ligament (PLL) also spans from the skull to the sacrum, but runs within the spinal canal on the dorsal aspect of the vertebral body. Unlike the ALL, the PLL has attachments only at the disk level, and it is bowstrung across the concavity of the vertebral bodies. The PLL can be elevated by pathologic processes, including disk herniations, hematomas, infections, and tumors. The location of the PLL reinforces the central anulus fibrosus, with most posterior disk herniations occurring at the lateral margin of the PLL. Because the ALL and PLL are innervated by the sinuvertebral nerves, which are branches from the spinal nerves near the origin of the anterior and posterior rami, they may be contributors to back pain.

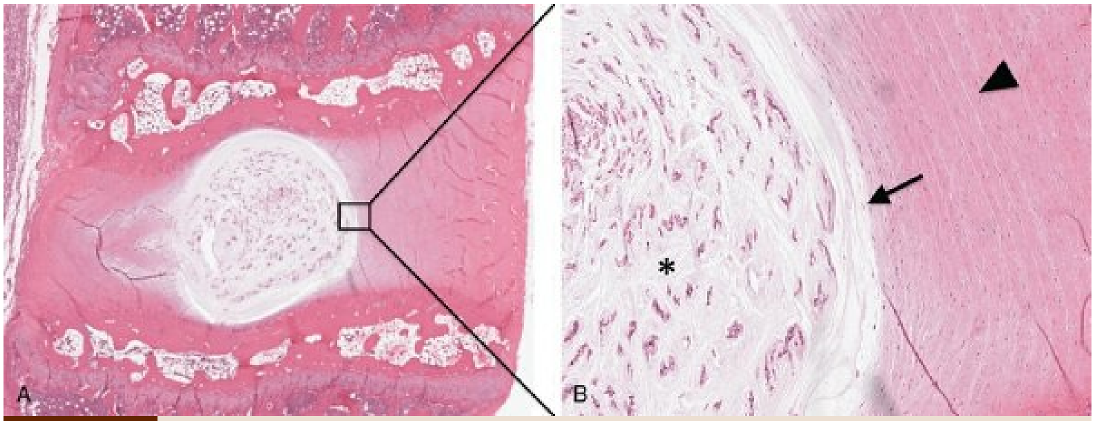

Figure 1 Hematoxylin and eosin-stained histologic section of an intervertebral disk at low (**A**) and high (**B**) power. The nucleus pulposus (*) is populated by clusters of cells within a gelatinous matrix. A clear border (arrow) between the nucleus pulposus and the anulus fibrosus is evident. The anulus fibrosus demonstrates organized fibrocartilage lamellae (arrow head). (Reproduced from Moss IL, An HS: Form and function of the intervertebral disc, in O'Keefe R, Jacobs JJ, Chu CR, Einhorn TA: *AAOS Orthopaedic Basic Science*, ed 4. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2013, pp 253-260.)

The ligamentum flavum is an important anatomic structure to consider during surgical decompression because it is a major contributor to spinal canal stenosis. In contrast with the ALL and PLL, the ligamentum flavum is a noncontiguous structure, with attachments to the ventral surface of the cranial lamina and superior surface of the caudal lamina of each individual functional spinal unit. When entering the canal with a Kerrison rongeur or burr, surgeons often exploit the fact that the ligamentum flavum extends halfway to two-thirds up the ventral surface of the cephalad lamina because this natural anatomic barrier can help prevent inadvertent durotomy.[1]

Development

The spinal column is formed from the paraxial mesoderm in a process called somatogenesis.[2] As the body axis elongates, individual somites are added on either ventral portion of the somite, which becomes the mesenchymal sclerotome and is responsible for the formation of the vertebrae and the anulus fibrosus. The nucleus pulposus is formed from the remnant of the notochord and is populated by cells of notochordal origin in early life. These cells are subsequently replaced by chondrocyte-like cells by the end of the first decade of life. Each vertebra is formed by three primary ossification centers—the centrum, neural arch, and a costal element. Failure of one or more of these ossification centers to develop can result in the formation of a hemivertebra, which often causes substantial deformity (referred to as congenital deformity).[3] Failure of the somite to fully segment results in the formation of block vertebrae or unsegmented bars. The combination of a hemivertebra and a contralateral unsegmented bar leads to the most progressive form of congenital scoliosis.

Muscles

The paraspinal musculature plays an important role in stabilizing the spine and maintaining upright posture. In the cervical spine, the paraspinal muscles are divided into deep and superficial groups, with the deep musculature mainly responsible for spinal stability and the superficial musculature mainly responsible for movement (**Figure 2**). An increased cross-sectional area in the deep cervical extensor muscles is associated with a higher rate of bony union after anterior cervical fusion.[4] In the thoracolumbar spine, the paraspinal musculature is generally divided into the deep multifidus muscles and the more superficial erector spinae muscles. The multifidus is considered the major posterior stabilizing muscle of the spine. Its large cross-sectional area and sarcomere orientation allow it to generate large forces with small changes in length.[5] The multifidus muscle originates from the spinous process of a single level and typically inserts three levels caudal (on the mammillary process in the lumbar spine). At each level, the multifidus is innervated by the medial branch nerve of the posterior ramus of the spinal nerve, which exits the spinal canal superolateral to the facet joint. Multifidus atrophy is seen after traditional open approaches to the spine and results from a combination of denervation, thermal injury, and pressure necrosis caused by prolonged retraction.[5] Medial branch nerve ablations, which are often performed to treat back pain, may lead to multifidus atrophy as well.[6]

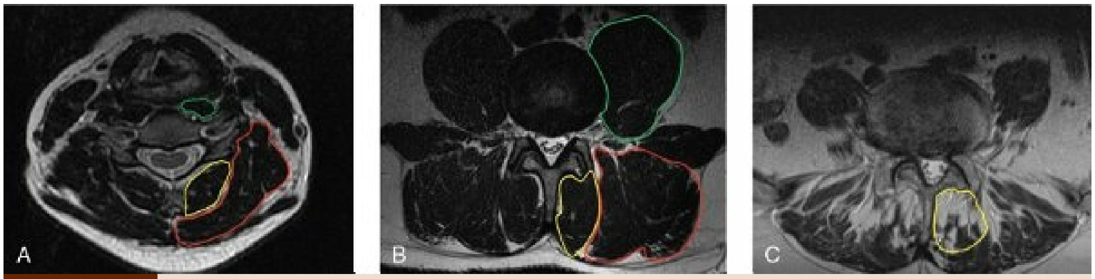

Figure 2 Axial T2-weighted magnetic resonance images of normal midcervical spine muscular. **A,** The anterior flexor longus collis (green), the deep extensors semispinalis cervicis and multifidus muscle (yellow), and the superficial extensors semispinalis capitus, splenius capitus, and longissimus muscles (red). **B,** Normal lumbar spine musculature at the L4-L5 disk space demonstrating the psoas muscle (green), the deep extensor multifidus muscle (yellow), and superficial erector spinae muscle (red). **C,** Lumbar spine musculature after open decompression shows substantial fatty atrophy of the multifidus muscle (yellow).

Recently, the health and function of the paraspinal musculature has been investigated as it relates to back pain and surgical success.[7-9]Paraspinal muscle atrophy and fatty infiltration, most prominently affecting the multifidus, has been associated with chronic low back pain; however, it is unclear if this change is causative or related to disuse in patients with long-term pain.[7] Paraspinal atrophy and fatty infiltration also have been associated with an increased risk of adjacent-segment degeneration after lumbar fusion.[8] Many minimally invasive approaches to the lumbar spine have been designed to preserve the medial branch nerve and minimize trauma to the multifidus.[9]

Spinal Balance

Positioning of the C7 vertebrae over the sacrum is essential for the maintenance of upright posture and efficient locomotion. Proper positioning is achieved by balancing the curvatures of the various anatomic regions of the spine, including lordosis of approximately 60° in the lumbar region and approximately 20° in the cervical region, and kyphosis of approximately 40° in the thoracic and sacral regions[10] (**Figure 3**).

The sagittal vertical axis is measured as the distance between the posterior corner of the S1 superior end plate and a vertical plumb line from the midpoint the C7 vertebral body. Increase in the sagittal vertical axis is linearly correlated with more pronounced symptoms and disability.[11] Lumbar lordosis is not evenly distributed, with two-thirds of overall lumbar lordosis contributed by L4-S1. Optimal lumbar lordosis is closely related to an individual's pelvic incidence, which is an important parameter to consider when planning corrective surgery for spine deformity. Recent evidence has shown that an individual's cervical lordosis is related to his or her cranial incidence, an anatomic parameter specific to an individual's skull[12] (**Figure 4**). Variation occurs in both sagittal balance and pelvic parameters as a result of shifting from a standing to a sitting position, with a reduction in both lumbar lordosis and thoracic kyphosis and a forward shift in the sagittal vertical axis.[13] The relevance of this information when planning spine deformity correction has yet to be determined. With aging, the regional curvatures often change, often with an increase in thoracic kyphosis. However, asymptomatic individuals may maintain a stable global balance by compensation in other areas of the spine.[14]

Applied Anatomy by Region

Cervical Spine

Occipitocervical Stability

The occipitocervical complex, which extends from the occiput to the C2-3 disk space, consists of specialized bony and ligamentous structures to stabilize this area of vital anatomy while also acting as the major contributor to cervical range of motion. The tectorial membrane, once thought to be the primary stabilizer of the occipitoatlantal articulation, is an extension of the PLL and runs from the anterolateral edge of the foramen magnum to the posterior surface of the C2 body and odontoid process. A recent study performed using modern biomechanical techniques demonstrated that the primary stabilizers of the craniocervical junction are the transverse and alar ligaments.[15]

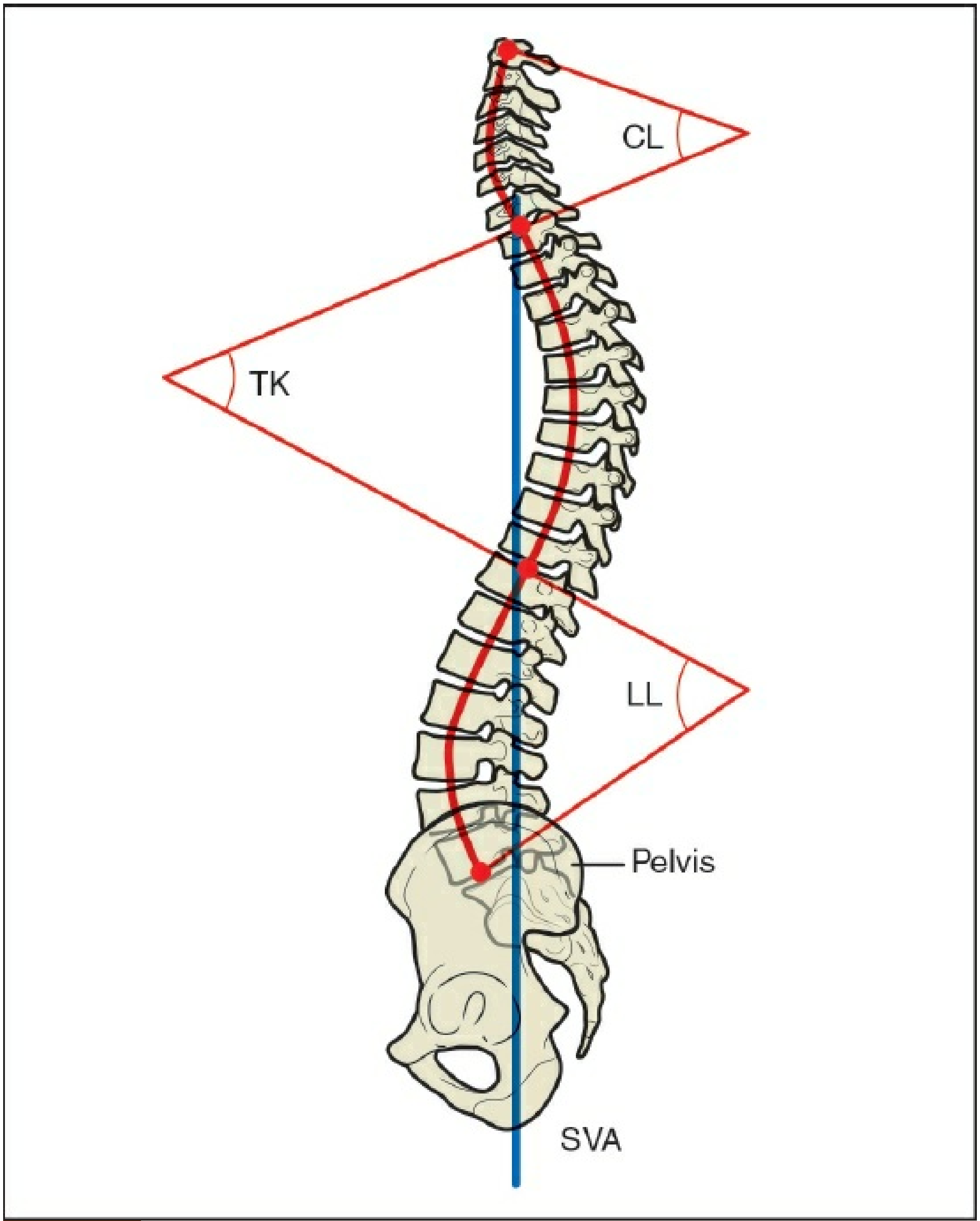

Figure 3 Illustration shows normal global sagittal balance measured by the sagittal vertical axis (SVA), a line drawn vertically from the center of the C7 vertebral body. Normal balance results from a balanced combination of cervical lordosis (CL), thoracic kyphosis (TK), and lumbar lordosis (LL).

The cruciate ligament, the key structure in atlantoaxial stability, consists of vertical and transverse components, which stabilize the odontoid to the occiput and atlas, respectively (**Figure 5**). Disruption of the occipitocervical complex, which can result from high-energy trauma, can lead to occipitoatlantal or atlantoaxial dissociation. The sensitivity of plain radiography to detect these often-fatal injuries has been questioned. Efforts have been undertaken to define parameters predictive of ligamentous injury based on CT and MRI, which are commonly obtained imaging studies in trauma settings. On CT, a basion-dens interval of greater than 10 mm and a C1-C2 lateral mass interval of 4 mm or greater are highly sensitive measurements for the detection of occipitocervical complex instability.[16] MRI studies have defined two patterns of occipitocervical complex injury based on the integrity of the occipitoatlantal capsular ligaments.[17] Atlantoaxial dissociation occurs when occipitoatlantal capsular ligaments are preserved but the cruciate ligament is disrupted. In patients with combined occipitoatlantal and atlantoaxial dissociation, both the occipitoatlantal capsular ligaments and the cruciate ligaments are disrupted.[17] It may be easier to recognize a true dissociation by evaluating not only the midline structures (eg, basion-dens interval), but also the congruency and the displacement of the occiput-C1 articular surfaces.

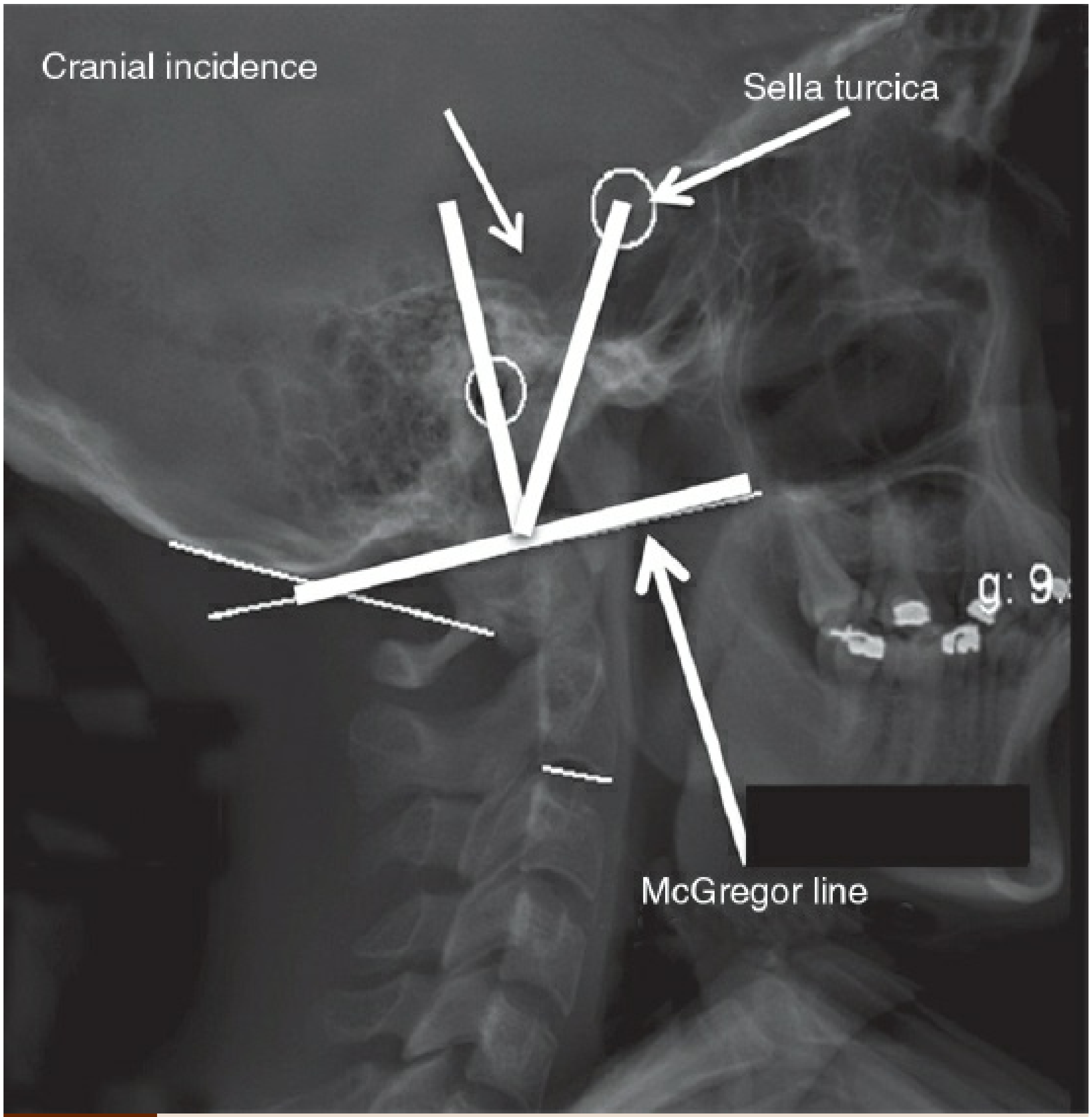

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Figure 4 EOS (EOS Imaging) image of the head and cervical spine demonstrating the cervical incidence as the angle between a line drawn perpendicular to the center of the McGregor line and a line from the sella turcica (approximate center of rotation of the skull) to the center of the McGregor line. (Reproduced with permission from Le Huec JC Demezon H, Aunoble S: Sagittal parameters of global cervical balance using EOS imaging: Normative values from a prospective cohort of asymptomatic volunteers. *Eur Spine J* 2015;24[1]:63-71.)

Vertebral Artery

The foramen transversarium is a key distinguishing anatomic feature of the cervical vertebrae from C2-C7. The vertebral artery, which is a branch of the subclavian artery, usually enters the foramen of C6, runs cranially to exit at

C2, and then proceeds around the lateral mass of C1 to the superior surface of the posterior C1 arch and enters the foramen magnum (**Figure 6**). Frequent variations exist in the size and position of the foramen transversarium and the artery contained within.[18] In rare instances, the artery can run through the lateral aspect of the vertebral body and entirely outside the foramen. Thus, a careful review of axial imaging studies is essential when planning cervical instrumentation. The vertebral artery can be injured when using a burr to remove the uncovertebral joint. Fibrous bands, which connect the nerve root to the vertebral artery, can tear this vessel even when the burr remains medial. The vertebral artery is most at risk for injury during the posterior instrumentation of C1 and C2. In addition, a fine-cut CT scan or CT angiogram is helpful when planning instrumentation at C1 and C2. The C2 pedicle has substantial anatomic variation in up to 18% of individuals, which can put the vertebral artery at risk for injury.[19] The Harms technique for C1-C2 fixation (with C1 lateral mass and C2 pedicle screws) has gained popularity over the Magerl transarticular screw technique because it provides greater freedom for screw trajectory and potentially reduces the risk of vertebral artery injury.[20]

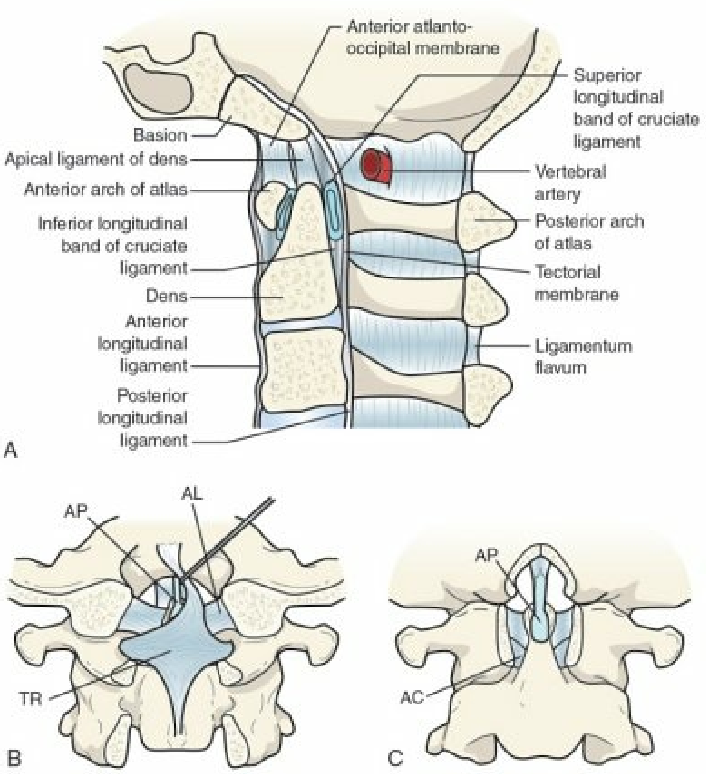

Figure 5 **A**, Illustration demonstrating the sagittal view of the occipitocervical articulation. Posterior (**B**) and anterior (**C**) illustrations of the atlantoaxial articulation. AC = accessory ligament, AL = alar ligament, AP = apical ligament, TR = transverse atlantal ligament.

Subaxial Cervical Spine

The subaxial cervical spine is most commonly instrumented from an anterior approach that takes advantage of an anatomic corridor to the spine and osseous anatomy for safe instrumentation. The cervical vertebrae and neural foramina of males are typically larger than those of females.[21] With advancing age, cervical vertebrae become wider and more elongated.[19] The average depth of the cervical vertebral bodies ranges from 15 to 17 mm and increases caudally. Subaxial cervical vertebrae have uncinate processes extending from the edges of the superior end plates, which form lateral borders of the intervertebral disk. The uncinate processes form an important landmark for the lateral extent of anterior decompression procedures. Posteriorly, the cervical vertebrae are characterized by bifid spinous processes and large lateral masses, but not the elongated transverse processes found in the thoracic and lumbar regions. Lateral mass instrumentation is most commonly used for posterior fixation from C3 through C6 because of its technical ease and safety.[22] The starting point for these screws is 1 mm medial to the center of the lateral mass. The screws are angulated approximately 15° cephalad and 30° lateral to limit the risk of injury to the vertebral artery and exiting nerve roots, although these parameters may change somewhat depending on the level instrumented and the amount of spinal degeneration.[23] Posterior instrumentation of subaxial cervical pedicles is possible; however, this is associated with a higher risk of neurologic and vascular complications compared with lateral mass fixation.[24] Many surgeons limit the use of this technique to C7, where lateral mass fixation is poor and there is less risk of injury to the vertebral artery. The starting point for C7 pedicle screw instrumentation is the upper outer quadrant of the lateral mass. The screw trajectory angles medially 25° to 45°. A laminoforaminotomy to palpate the pedicle may improve the accuracy and safety of this procedure.

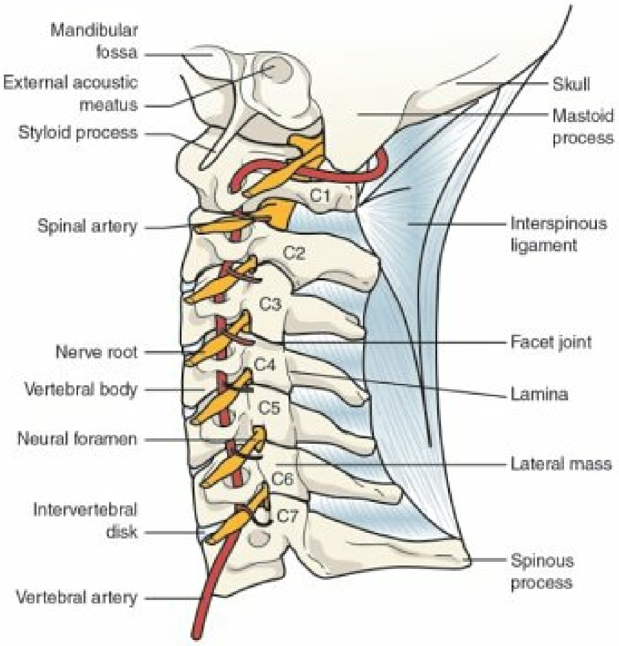

Figure 6 The relationship of the vertebral artery to the bony and neurologic anatomy of the cervical spine.

Thoracic Spine

Several unique anatomic characteristics are important to understand when