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Chapter 32

Functional anatomy of the spine

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Abstract

Among other important features of the functional anatomy of the spine, described in this chapter, is the remarkable difference between the design and function of the cervical spine and that of the lumbar spine. In the cervical spine, the atlas serves to transmit the load of the head to the typical cervical vertebrae. The axis adapts the suboccipital region to the typical cervical spine. In cervical intervertebrtal discs the anulus fibrosus is not circumferential but is crescentic, and serves as an interosseous ligament in the saddle joint between vertebral bodies. Cervical vertebrae rotate and translate in the sagittal plane, and rotate in the manner of an inverted cone, across an oblique coronal plane. The cervical zygapophysial joints are the most common source of chronic neck pain. By contrast, lumbar discs are well designed to sustain compression loads, but rely on posterior elements to limit axial rotation. Internal disc disruption is the most common basis for chronic low-back pain. Spinal muscles are arranged systematically in prevertebral and postvertebral groups. The intrinsic elements of the spine are innervated by the dorsal rami of the spinal nerves, and by the sinuvertebral nerves. Little modern research has been conducted into the structure of the thoracic spine, or the causes of thoracic spinal pain.

INTRODUCTION

In writing a chapter on anatomy for neurologists the risk arises of being arcane or banal. Neurologists will already be familiar with the precepts of classic anatomy, and would not be inclined to read a chapter that repeats boring, undergraduate material. For these reasons, the present chapter has been cast in a different manner. Although conventional elements of anatomy are reprised, they are permeated by several themes. New facts are provided, stemming from modern research into the structure of the spine, along with new perceptions about design and function. Throughout, the focus is on clinical relevance, particularly with respect to the mechanisms of spinal injury and spinal pain. In that regard, certain structures – ignored in conventional undergraduate curricula – are promoted to epidemiologically significant, clinical importance.

CERVICAL SPINE

The cervical spine serves as a mobile support for the sensory platform of the head. It allows the sensory apparatus for vision, hearing, and smell to be elevated or depressed in the sagittal plane, and to scan the environment in the horizontal plane. In order to subserve these functions, the cervical spine has to be mobile, yet sufficiently strong to support the weight of the head. Its vulnerability, to either minor or major injuries, lies in being long, slender, and carrying the large mass of the head at its summit.

Both for descriptive purposes and functionally, the cervical spine can be divided into three zones: the suboccipital zone, centered on the C1 vertebra; a transitional zone formed by the C2 vertebra; and the typical zone, encompassing the C–7 vertebrae (Bogduk and Mercer, 2000) (Fig. 32.1). These zones differ both in structure and in function.

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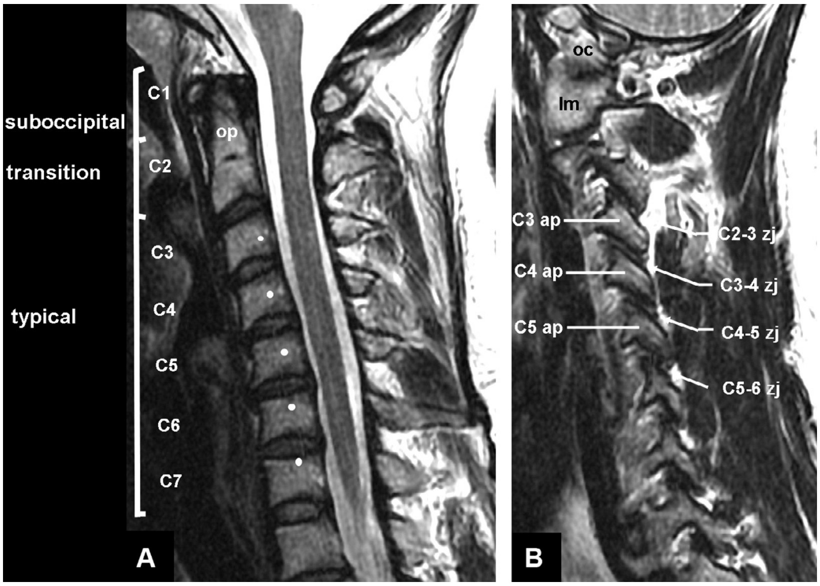

Fig. 32.1. Sagittal magnetic resonance images of the cervical spine, showing its structure and zones. (**A**) Median scan, showing the vertebral bodies and interverterbral discs. The white dots mark the mean location of the axes of rotation for flexion-extension of the vertebra above. The odontoid process (op) projects rostrally from the body of C2, to lie behind the anterior arch of the atlas (C1). (**B**) Lateral scan, showing the occipital condyle (oc), the lateral mass (lm) of the atlas (C1), the articular pillars (ap), and the zygapophysial joints (zj) that they form, at the segments labeled. (Courtesy of Dr. Tim Maus, Mayo Clinic, Rochester, MN.)

Suboccipital zone

The C1 vertebra (the atlas) shares none of the features of typical cervical vertebrae, and should never have been considered cervical. In structure and in function it is more like an occipital vertebra. In structure it resembles the occipital bone, as can be seen in axial scans. In function, it more closely operates with the head, rather than with the remainder of the cervical spine.

The classic description of the atlas as a ring vertebra belies its design and function. The critical components of the atlas are its two lateral masses (Fig. 32.2). Superiorly, these present superior articular processes that receive the occipital condyles, and thereby cradle the skull. Inferiorly, the lateral masses present inferior articular processes that rest on the C2 vertebra, and thereby transmit the load of the head to the remainder of the cervical spine. The anterior and posterior arches of the atlas serve little function other than holding the two lateral masses both apart and together, while the latter do the mechanical work of the atlas.

Upon receiving the occipital condyles into their deep sockets, the superior articular processes of each lateral mass form the atlanto-occipital joints (Figs 32.2 and 32.3). These synovial joints constitute the only direct connection between the skull and C1. They allow a small range of flexion-extension, but the depth of their sockets precludes axial rotation. Therefore, as the head rotates (in the transverse plane) the atlas is obliged to move with it. In that respect, the atlas behaves like a passive washer, between the skull and C2.

Upper transition zone

The upper half of the C2 vertebra (the axis) is designed to support the atlas. Superiorly and laterally, it presents superior articular processes that slope caudally and laterally, and act like sloping shoulders on which the lateral masses of the atlas rest (Fig. 32.2). The inferior articular processes of the atlas have a reciprocal, caudal and lateral slope. The apposed articular processes on each side form the lateral atlantoaxial joint (Figs 32.2 and 32.3).

The caudolateral slope of the lateral atlantoaxial joint helps stabilize the atlas in the coronal plane, but also underlies the mechanism of Jefferson fractures. Severe axial loads, applied to the skull, will drive the atlas caudally, but its lateral masses will also spread laterally down the lateral slope of the lateral atlantoaxial joints, resulting in burst fractures of the anterior and posterior arches.

Centrally, the axis presents a long odontoid process (the dens) that projects behind the anterior arch of the atlas, with which it forms the median atlantoaxial joint (Figs 32.1, 32.3, and 32.4). The anterior arch is held against the odontoid process by the transverse ligament, which spans like a belt between the two lateral masses of the atlas, behind the odontoid process (Figs 32.4 and 32.5).

Posterior displacement of the atlas is prevented by impaction of the anterior arch against the odontoid process, at the median atlantoaxial joint. Anterior displacement is prevented by tension in the transverse ligament (Fielding et al., 1974). The ligament allows up to 3 mm normal range of separation between the odontoid

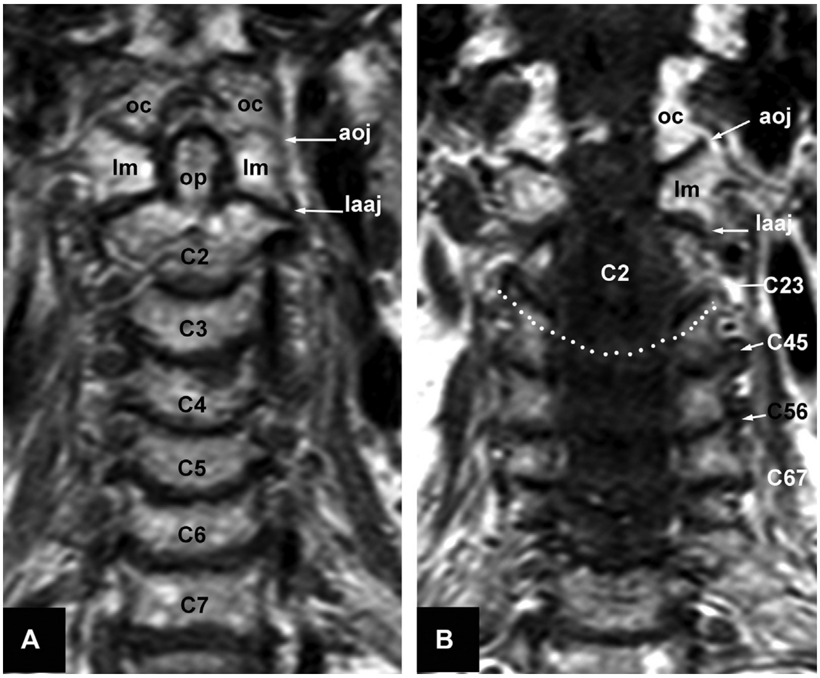

Fig. 32.2. Coronal magnetic resonance images of the cervical spine, showing the structure of its components. (**A**) Anterior scan, showing the occipital condyles (oc) resting in the sockets of the lateral masses (lm) of the atlas, and forming the atlanto-occipital joints (aoj); and the lateral masses bracketing the odontoid process (op), and resting on the "shoulders" of the axis (C2), where they form the lateral atlantoaxial joints (laaj). The vertebral bodies of C2–7 form the anterior column of the cervical spine. (**B**) Posterior scan, through the synovial joints of the cervical spine. Note the wedge shape of the lateral mass (lm) between the atlanto-occipital joint (aoj) and the lateral atlantoaxial joint (laaj). The zygapophysial joint at C2–3 slopes caudally and medially, but those at successive levels are essentially horizontal. The dotted line illustrates the ellipsoid shape depicted by the C2–3 zygapophysial joints and the C2–3 disc, into which the atlas (C2) nestles on to the typical cervical spine.

process and the anterior arch in adults, and 5 mm in children. In the past, the magnitude of the interval between the anterior arch and the odontoid process has been used as a measure of atlantoaxial instability, but as a predictor of neurologic compromise the posterior atlantodental interval (Fig. 32.3) has greater sensitivity and specificity (Wasserman et al., 2011).

Severe forces delivered anteriorly to the head can fracture the odontoid process. Such fractures threaten the sagittal stability of the atlas. In turn, anterior or posterior displacement of the atlas can threaten the spinal cord. Rheumatoid arthritis of the atlantoaxial joints can weaken the transverse ligament of the atlas, resulting in anterior subluxation of the atlas (Wasserman et al., 2011).

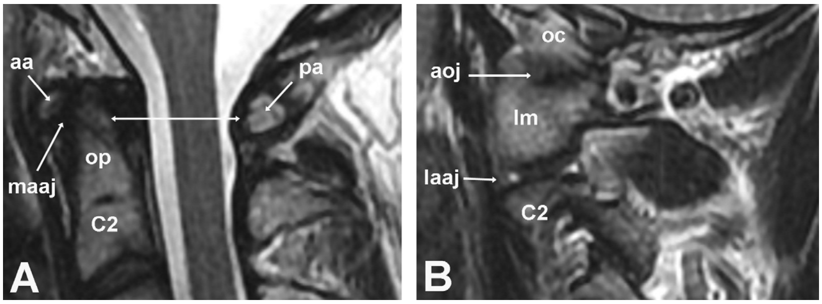

Fig. 32.3. Close-up views of sagittal magnetic resonance images of the suboccipital joints. (**A**) Median scan through the odontoid process (op) and vertebral body of C2. With the front of the odontoid process, the anterior arch (aa) of the atlas forms the median atlantoaxial joint (maaj). The transverse arrow marks the posterior atlantodental (pa) interval. (**B**) Lateral scan through the lateral mass (lm) of the atlas. With the superior sockets of the lateral mass of the atlas, the occipital condyle (oc) forms the atlanto-occipital joint (aoj). With C2, the lateral mass forms the lateral atlantoaxial joint (laaj). Note the bi-convex shape of the lateral atlantoaxial joint. The triangular, white signals anteriorly and posteriorly within the joint are the fibroadipose meniscoids that it contains. (Courtesy of Dr. Tim Maus, Mayo Clinic, Rochester MN.)

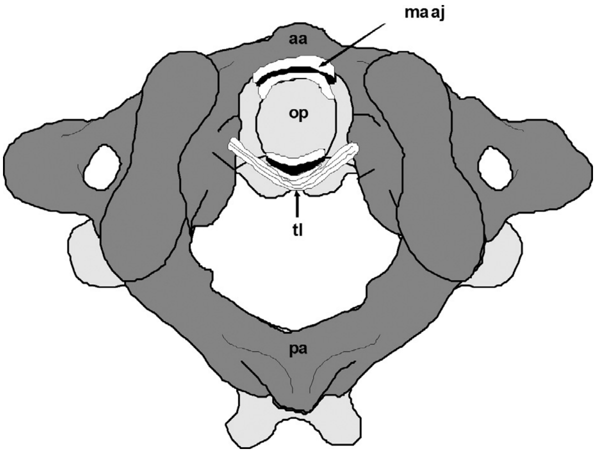

Fig. 32.4. A sketch of an axial (top) view of the atlas sitting on the axis. The lateral masses of the atlas bracket the odontoid process (op) of the axis, and are themselves joined by the anterior (aa) and posterior (pa) arches of the atlas. With the anterior arch, the odontoid process forms the median atlantoaxial joint (maaj). The transverse ligament (tl) spans like a belt behind the odontoid processes, between the two lateral masses.

Although the osseous articular processes of the lateral atlantoaxial joint are flat, their articular cartilages are convex (along the sagittal plane) (Koebke and Brade, 1982) (Fig. 32.3). As a result, the atlas perches somewhat precariously on the axis, with its convex inferior articular cartilages balancing on the convexities of the superior articular cartilages of the axis. The spaces anteriorly and posteriorly between the convex cartilages are filled by wedge-shaped fibrocartilaginous meniscoids (Mercer and Bogduk, 1993).

Although a small degree of flexion and extension is possible between the atlas and the axis (Bogduk and Mercer, 2000), the cardinal movement between these two vertebrae is axial rotation. During this movement the atlas pivots at the median atlantoaxial joint, while its lateral masses slide backwards or forwards, circumferentially, at the lateral atlantoaxial joints. However, because of the convexity of the articular cartilages in these joints, the lateral masses also descend, down the posterior or anterior slope of the cartilages, as they move backwards or forwards, respectively. As a result, the atlas settles (lowers or screws down) during axial rotation, and rises when the movement is reversed (Bogduk and Mercer, 2000). During these displacements, the meniscoids of the joints cover the exposed surfaces of the subluxating articular cartilages.

The total range of axial rotation of the atlas is considerably large. It has been measured as 43 ± 5.5° which effectively amounts to 50% of the range of axial rotation of the head and neck (Bogduk and Mercer, 2000). At the extremes of this range, very little of the articular cartilages of the lateral atlantoaxial joints remain opposed; the joint is almost dislocated.

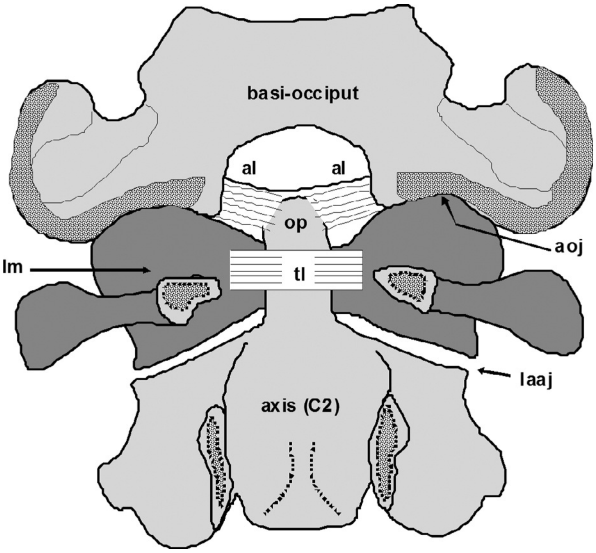

Fig. 32.5. A sketch of the suboccipital joints and ligaments, as view from behind with the posterior arch of the atlas resected. The lateral mass (lm) of the atlas supports the occipital bone, and rests of the axis, forming the atlanto-occipital joint (aoj) above, and the lateral atlantoaxial joint (laaj) below. The transverse ligament (tl) holds the atlas (al) against the odontoid process (op). The alar ligaments bind the odontoid process to the margins of the foramen magnum, thereby connecting the skull to C2 but bypassing C1.

In order to accommodate this large range of motion, the capsules of the lateral atlantoaxial joint are loose, and serve little to hold the atlas on the axis. That service is provided by the alar ligaments. On each side, these ligaments pass essentially transversely from the upper end of the odontoid process to the margin of the foramen magnum (Fig. 32.5). In doing so, they bypass the atlas, and lock the head into place on the axis, effectively clamping the atlas between the skull and C2. The alar ligaments are the cardinal restraint to axial rotation of the head (Dvorak et al., 1987). They are sufficiently strong to prevent anterior dislocation of the head even if the transverse ligament is completely severed (Fielding et al., 1974). Disruption of an alar ligament can result in rotatory instability of the head and atlas (Dvorak et al., 1987).

Excessive axial rotation of the atlas can result in a lateral mass dislocating at the lateral atlantoaxial joint, causing fixed atlantoaxial deformity (Wortzman and Dewar, 1968). A less dramatic form of torticollis can arise if, after rotation of the head and atlas, a meniscoid of the lateral atlantoaxial joint fails to re-enter the joint space, catches under the capsule of the joint, and acts like a loose body to prevent derotation of the joint (Mercer and Bogduk, 1993).

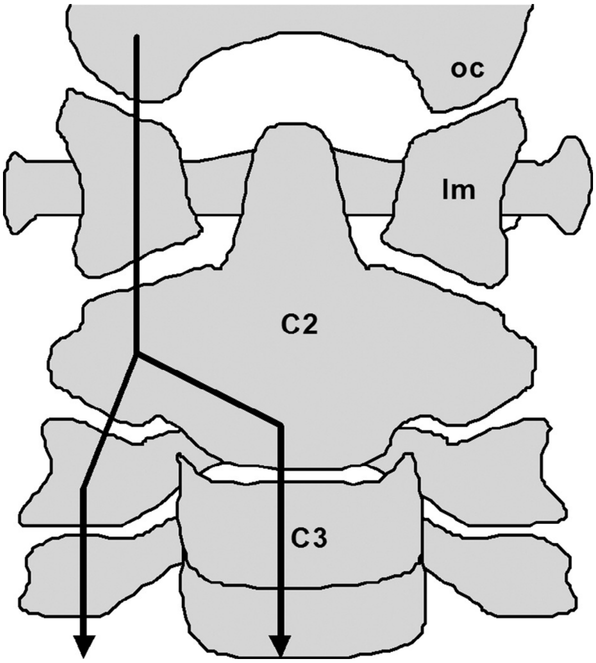

Fig. 32.6. A sketch of a coronal view of how forces from the head are transmitted into the cervical spine. On each side, the weight of the head passes through the occipital condyle (oc), into the lateral mass (lm) of the atlas, and into the axis (C2) through the lateral atlantoaxial joint. From there, the forces diverge, partly into the posterior column of zygapophysial joints, and partly into the anterior column of vertebral bodies and discs. Half the load passes anteriorly and half posteriorly.

Increasing interest has been focused on the lateral atlantoaxial joints as a possible source of cervicogenic headache. This contention can be tested by controlled, intra-articular, diagnostic blocks of the putatively painful joint (Bogduk and Bartsch, 2008; Bogduk and Govind, 2009; Bogduk, 2014).

Lower transition zone

The lower half of the C2 vertebra has the structure of a typical cervical vertebra (Figs 32.1 and 32.2). Centrally it presents a vertebral body, and laterally it presents paired inferior articular processes. Having received the lateral masses of the atlas, the axis transmits the load of the head along an anterior channel, through its vertebral body to the vertebral bodies below, and along paired posterior channels, through the zygapophysial joints (Fig. 32.6). Approximately half of the axial load is transmitted through the anterior channel, and half through the two posterior channels.

Typical cervical vertebrae

The cardinal elements of a typical cervical vertebra are its vertebral body and two articular pillars (Figs 32.1 and 32.2). Secondarily, transverse processes project laterally from the articular pillars, and posteriorly the two pillars are united by a pair of laminae, which support a midline spinous process at their junction. The transverse processes and spinous processes serve as levers upon which act the muscles that control the position of the cervical vertebrae. Along its superior, posterolateral margin on each side, each vertebral body bears uncinate processes. Previously enigmatic, the uncinate processes underlie the nature of the joints between the cervical vertebral bodies and how they operate.

Consecutive articular pillars are united by the zygapophysial joints (Figs 32.1 and 32.2), which are synovial joints formed by the inferior articular process of the vertebra above and the superior articular process of the vertebra below. Fibroadipose meniscoids intervene between the articular cartilages of these joints (Mercer and Bogduk, 1993). The zygapophysial joints are planar, and at typical cervical levels are oriented at about 40° to the coronal and transverse planes, so that they face backwards and upwards (Nowitzke et al., 1994). At the C2–3 level, however, the joints also face medially, such that the pair of joints depict an ellipsoid socket into which nestles the weight of the axis, and the load that it carries from the head (Figs 32.2 and 32.6).

Consecutive vertebral bodies are united by intervertebral discs, and by the anterior and posterior longitudinal ligaments (Mercer and Bogduk, 1999). The anterior ligament connects only the typical cervical vertebrae, from C2 caudally. The posterior longitudinal ligament forms a carpet along the floor of the vertebral canal at typical cervical levels, but expands into the membrana tectoria to cover the back of the atlantoaxial region. In doing so, the ligament separates the dural sac and spinal cord from the mechanics of the median atlantoaxial joint.

Posterior ligaments are lacking in the cervical spine. Interspinous ligaments are represented by only a sagittal layer of fascia (Mercer and Bogduk, 2003). The ligamentum nuchae lacks the structure of a ligament. It consists largely of a narrow, coronal raphe, anchored to the C7 spinous process, and formed by interlacing tendons of the splenius muscles and trapezius (Mercer and Bogduk, 2003).

The intrinsic structure of the cervical intervertebral discs is unlike that of lumbar discs, and differs with age (Oda et al., 1988; Mercer and Bogduk, 1999). The nucleus pulposus of cervical discs is gelatinous only in children and young adults. By the age of 30 it dries out to form a fibrocartilaginous plate (Oda et al., 1988). Moreover, the nucleus is not surrounded by concentric lamellae of the anulus fibrosus (Mercer and Bogduk, 1999). The anulus fibrosus is largely deficient posteriorly, and consists of a thin, paramedian band of collagen fibers that run longitudinally between the

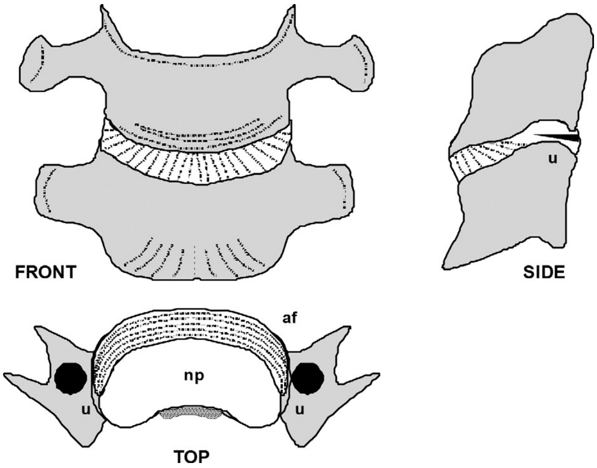

Fig. 32.7. Sketches of various views of the internal structure of the cervical disc. In a front view, all fibers of the anterior anulus fibrosus pass towards a point on the inferior anterior surface of the vertebral body above. In a top view, the anulus fibrosus (af) is crescentic in shape, thick anteriorly but tapering at the uncinate processes (u). The nucleus pulposus (np) is a fibrocartilaginous plate. Posteriorly the anulus is restricted to a small bundle of paramedian, longitudinal fibers. A side view shows the fibers of the anulus fibrosus passing upwards and forwards. A transverse cleft runs from one uncinate process to the other.

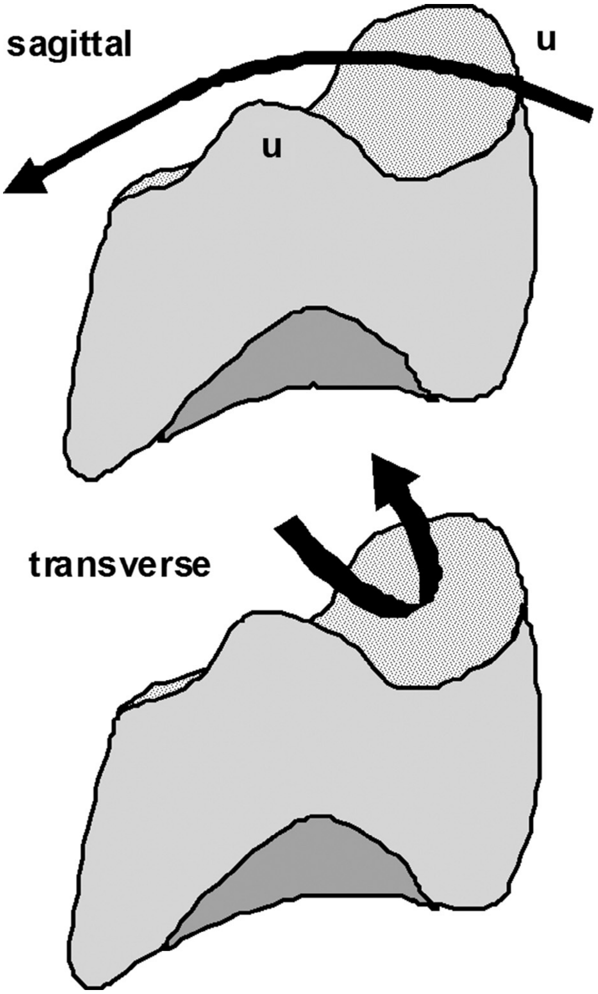

Fig. 32.8. Sketches of a posterolateral view of a typical cervical vertebral body, showing the two curvatures of its superior surface: a downward concavity along the sagittal plane, and a second concavity, facing upwards and forwards, between the uncinate processes (u). These two concavities endow the intervertebral disc with the features of a saddle joint.

vertebral bodies (Fig. 32.7). Posterolaterally, the nucleus is covered by the posterior longitudinal ligament, rather than by anulus fibrosus. Anteriorly, the anulus fibrosus is crescentic in shape, thin posteriorly near the uncinate processes, but thicker anteriorly towards the midline. All of its collagen fibers pass in a similar direction, effectively aiming to a median point on the lower anterior surface of the vertebral body above. This configuration endows the anulus fibrosus with the structure of a thick interosseous ligament that binds the anterior edges of consecutive vertebral bodies.

The superior surface of each cervical vertebral body presents two curvatures: a slight convex curvature along the sagittal plane, and a deep concave curvature transversely between the uncinate processes (Fig. 32.8). These curvatures endow the vertebral body with the configuration of a saddle joint (Bogduk and Mercer, 2000). Consequently, the cervical interbody joints operate like a saddle joint, with motion restricted to two planes: the sagittal plane and an oblique coronal plane.

In the sagittal plane, the vertebral bodies can rock and slide (rotate and translate), to provide for flexion and extension of the neck. From above downwards, the typical cervical vertebrae exhibit progressively less translation for each degree of rotation, during flexion or extension. This is reflected by the different locations of their axes of movement. At higher levels the axes lie in the vertebral body below the moving vertebra, but are progressively closer to their intervertebral disc at lower levels (Amevo et al., 1991) (Fig. 32.1). These differences correlate strongly with the height of the articular pillar at each segment (Nowitzke et al., 1994). Taller pillars provide less space into which the vertebra can translate once it has commenced sagittal rotation. Conversely, at segments with shorter pillars, sagittal rotation lifts the inferior articular processes of the moving vertebra off the supporting articular pillar, and provides a greater gap into which it can translate (Nowitzke et al., 1994).

The second plane of movement of typical cervical vertebrae is set at 40° forwards of the coronal plane, and lies parallel to the plane of the zygapophysial joints

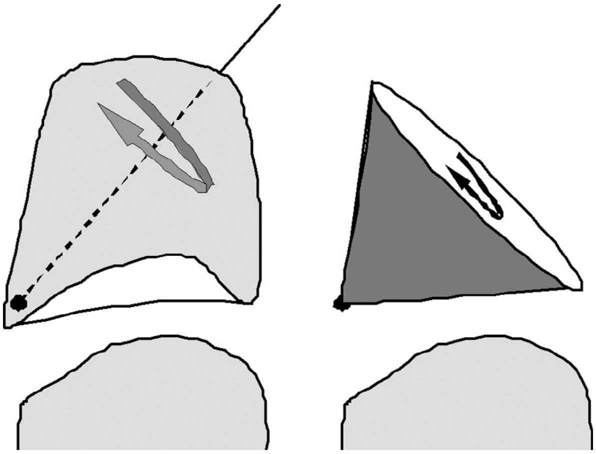

Fig. 32.9. A sketch of a typical cervical intervertebral joint, illustrating the mechanics of rotation of the vertebral body, across the oblique concavity of the uncinate processes, and around an oblique axis through the vertebral body. The motion is like that of a cone whose apex is fixed but whose bases nevertheless free to twist and spin, in the direction and plane indicated by the arrow.

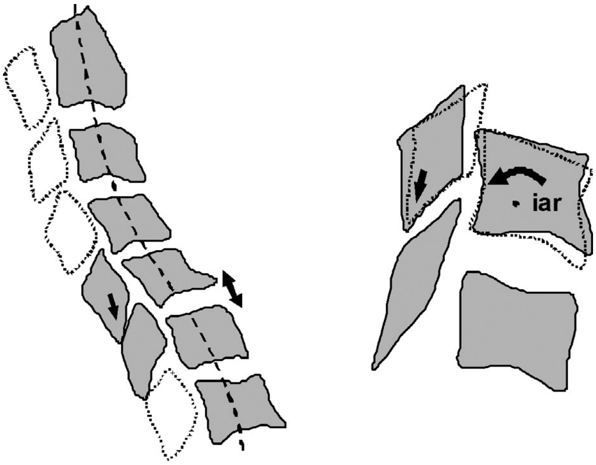

Fig. 32.10. The mechanics of the early phase of whiplash injury. As a result of a thrust from below, the cervical spine undergoes a sigmoid deformation. Lowe segments, e.g., C5–6, undergo a posterior sagittal rotation around an abnormally high instantaneous axis of rotation (iar), which results in posterior elements being impacted and anterior elements being stretched.

(Bogduk and Mercer, 2000). Across this plane, each vertebra rotates like an inverted cone whose apex is fixed, but whose base can twist (Fig. 32.9). The apex of the cone corresponds to the anterior, median point on the vertebral body to which the fibers of the anulus fibrosus are directed; and the anulus fibrosus serves to hold this apex in place. Meanwhile the posterior, inferior edge of the vertebral body presents a convex surface that is cupped by the concave surface between the uncinate processes of the vertebra below. This latter geometry is that of an ellipsoid joint, and the posterior inferior margin of the vertebral body is free to spin, or swing, across this ellipsoid surface. Thus, while the anterior end of the vertebral body is fixed, its posterior end and its posterior elements are free to spin clockwise or counterclockwise across the oblique coronal plane. During this motion, the inferior articular processes of the zygapophysial joints simply glide laterally across the surfaces of their supporting superior articular processes.

A consequence of this mode of operation is that the interbody joints of typical cervical vertebrae cannot tolerate a posterolateral anulus fibrosus, for it would impede the spin of the posterior vertebral body across the oblique coronal plane. Consequently, although a posterior anulus is present at birth and in young children, it gradually disappears as neck movements increase (Tondury, 1972). By about the age of 9 years, the posterolateral anulus tears, and clefts appear in the region of the uncinate processes. Progressively these clefts enlarge centrally, until they meet in the midline, at about the age of 30, to form a transverse cleft from one uncinate process to the other. This cleft is not a degenerative change but a normal age change. The cleft effectively forms the "joint space" across the posterior intervertebral disc that allows axial rotation of the head to be accommodated and amplified in range by the typical cervical vertebrae.

This structure and mechanics of the cervical spine are of relevance to the mechanisms of injury in whiplash. The early phase of whiplash injury involves a thrust from below (Bogduk and Yoganandan, 2001; Bogduk, 2006). This upward thrust deforms the cervical spine into a sigmoid shape, within which the lower cervical vertebrae – typically C5 and C6 – undergo an abnormal extension (Fig. 32.10). The vertebra rocks backwards but without translating. As a result, it rotates about an abnormally high axis of rotation (Kaneoka et al., 1999). During this motion, anterior elements are stretched while posterior elements are impacted. The anterior anulus fibrosus can be torn or avulsed, resulting in so-called rim lesions. Impaction in the zygapophysial joints can cause impaction fractures of the articular cartilages, or contusions of the intra-articular meniscoids. During later phases, the cervical spine rebounds into flexion, which can excessively strain the capsules of the zygapophysial joints (Curatolo et al., 2011).

Physiologic studies in laboratory animals have shown that the capsule strains induced by whiplash injury result in persistent nociception from the injured joint, and persistent changes within the central nervous system characteristic of chronic pain (Winkelstein, 2011). Clinical studies have shown that the cervical zygapophysial joints are the single most common source of chronic neck pain after whiplash, accounting for between 50% and 60% of cases (Bogduk, 2011). Most commonly, neck pain – with referred pain to the shoulder girdle – stems from the C5–6 joint, while headache stems from the C2–3 zygapophysial joint.

Less well understood is pain from the cervical intervertebral discs. Conspicuously, degenerative disc disease is not associated with neck pain. Furthermore, discogenic pain appears to be uncommon, once zygapophysial joint pain is taken into account (Yin and Bogduk, 2008). Perhaps discogenic pain is caused by strains of the interosseous ligament formed by the anterior anulus fibrosus, but diagnostic techniques by which to test this proposition have not been developed.

LUMBAR SPINE

The cardinal role of the lumbar spine is to support the thorax and upper limbs – and any loads that they carry – and to transmit those loads to the pelvis and lower limbs (Bogduk, 2012a). Secondarily, the lumbar spine accommodates a modest range of movement between the thorax and pelvis.

In order to subserve these functions, the essential elements of the lumbar spine are the vertebral bodies of the five lumbar vertebrae (Fig. 32.11). These are stacked into a strong column, and are united by intervertebral discs and by the anterior and posterior longitudinal ligaments (Bogduk, 2012a). Bowing the column into a lordosis endows the lumbar spine with the ability to absorb dynamic axial loads (bouncing). Axial impulses deform the lordotic curve; the energy is absorbed by the elastic discs and longitudinal ligaments; and is returned to restore the more upright curve, once the axial impulse has passed (Bogduk, 2012a).

The lumbar intervertebral discs are well designed to accommodate compression loads (Hickey and Hukins, 1980). Each consists of hydrated nucleus pulposus, surrounded by an anulus fibrosus, and capped superiorly and inferiorly by a vertebral endplate that joins the disc to the adjacent vertebral body (Fig. 32.12). The anulus fibrosus is formed by concentric layers of collagen fibers, in which the fibers in any one layer run in parallel, at about 60° to the long axis of the spine, but in successive layers that orientation alternates.

Axial compression is resisted primarily by the concentric layers of the anulus fibrosus (Markolf and Morris, 1974) (Fig. 32.12). However, the tendency of the anulus under load is to buckle, both outwards and inwards. This buckling is resisted by the hydrostatic nucleus pulposus. When the nucleus is compressed it exerts a radial pressure that braces, and stiffens, the anulus, thereby preventing it from buckling. A small range of flexion-extension is accommodated by the discs (about 13° per segment), during which the anulus fibrosus on the side to which

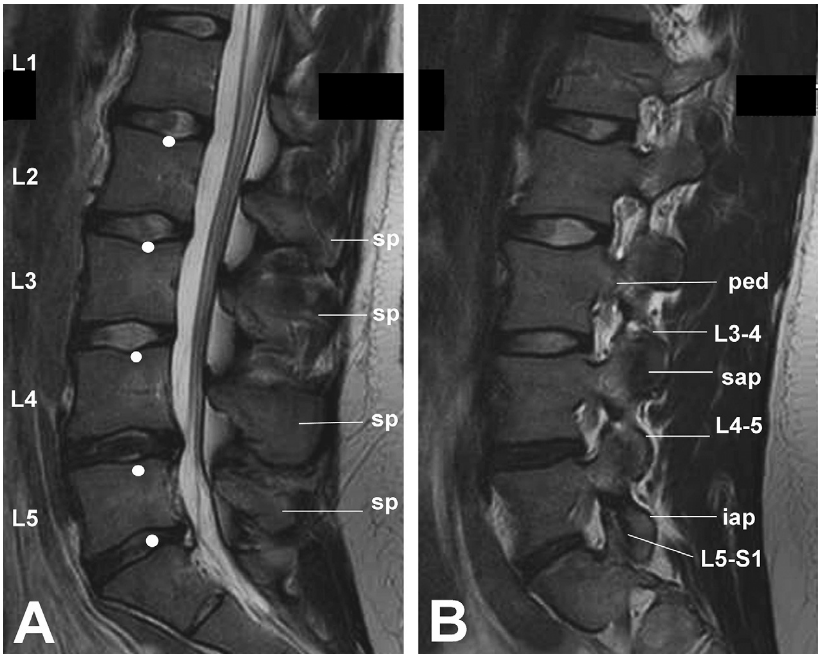

Fig. 32.11. Sagittal magnetic resonance images of the lumbar spine. (**A**) Median scan showing the vertebral bodies and spinous processes (sp). The white dots mark the location of the axes of rotation of the vertebra above. (**B**) Lateral scan through the intervertebral foramina and the L3–4 to L5–S1 zygapophysial joints. ped, pedicle of L3; sap, superior articular process of L4; iap, inferior articular process of L5.

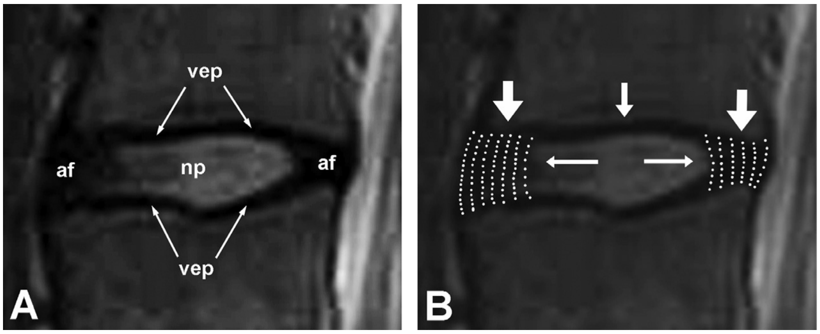

Fig. 32.12. Close-up views of a sagittal magnetic resonance image of an L3–4 intervertebral disc. (**A**) The components of the disc. np, nucleus pulposus; af, anulus fibrosus; vep, vertebral endplate. (**B**) The mechanics of the disc. Axial compression loads are primarily borne by the lamellae of collagen in the anulus fibrosus. When compressed, the nucleus pulposus exerts radial pressure to brace the anulus, and prevent it from buckling under load.

movement occurs is compressed slightly, while the anulus on the opposite side is stretched (Bogduk, 2012a).

While strongly designed to resist compression, the lumbar discs are poorly designed to resist axial rotation. Because the collagen fibers of the anulus fibrosus alternate in direction in successive layers, only half are available to resist axial rotation in one direction or the other. For stability in axial rotation, the lumbar vertebral bodies and intervertebral discs rely on the posterior elements of the lumbar vertebrae (Bogduk, 2012a).

The posterior elements are based on an arch (Bogduk, 2012a) (Fig. 32.13). The arch is supported by stout pedicles that emanate from the upper posterior surface of each vertebral body. The pedicles serve to transmit forces from the succeeding posterior elements to the vertebral bodies, which control the position or movements of the vertebral bodies. The arch is completed by left and right laminae that join in the midline. From the junction of the two laminae springs a large spinous process, and from the junction between the pedicle and lamina on each side arises a long transverse process. These processes serve as levers to which attach the muscles that control the movements of the lumbar vertebrae.

At its superior and inferior lateral corners respectively, each lamina bears a superior and inferior articular process. Like large mittens, the paired superior articular processes reach cranially to grasp the inferior articular processes of the vertebra above, and form the zygapophysial joints. The plane of these joints is parallel to the longitudinal axis of the lumbar spine. Consequently, during flexion of the vertebral bodies, the inferior articular processes glide freely out of the sockets formed by the superior articular processes, until movement is arrested by tension in the joint capsules (Bogduk, 2012a). The axis of this movement typically lies in the disc below the moving vertebra (Pearcy and Bogduk, 1988) (Fig. 32.11A), which indicates only a small amount of translation for every degree of rotation of the moving vertebra. As the inferior articular processes move, they lift away from the superior articular process, tantamount to partially subluxating the joint. Fibroadipose meniscoids protect the exposed surfaces of the articular cartilages during this displacement (Engel and Bogduk, 1982; Bogduk and Engel, 1984).

In axial views, the lumbar zygapophysial joints variously present flat, C-shaped, or J-shaped appearances, which correspond to the primary functions of these joints (Horwitz and Smith, 1940). Flat joints essentially face medially and posteriorly. C-shaped joints have an anterior end that faces posteriorly, and a posterior end that faces medially. J-shaped joints have a small anterior lip facing posteriorly, and a larger surface facing medially. The medially facing surfaces serve to resist axial rotation of the vertebrae. Attempted axial rotation swings the inferior articular process laterally, but this movement is arrested by the opposing superior articular process. The range of motion is limited to about 2° or less per segment (Pearcy and Tibrewal, 1984), and is accommodated only by compression of the articular cartilage. The surfaces that face posteriorly serve to resist forward displacement (listhesis) of the vertebra.

Impaction of an inferior articular process against its superior articular process tends to force the inferior process backwards, and lift the lamina from which it arises (like opening a hatchback). In turn this tendency stresses the junction between the lamina and its pedicle. Repeated impactions – particularly during repeated axial rotation – can cause stress fractures at this point, resulting in pars interarticularis defects.

The lumbar zygapophysial joints can be a source of low-back pain, but its prevalence is uncertain. It appears to be uncommon or rare in injured workers, but is common in elderly patients (Bogduk, 2008, 2012b).

The most common cause of chronic low-back pain is internal disc disruption (Bogduk et al., 2013). This condition is characterized by degradation of the nucleus

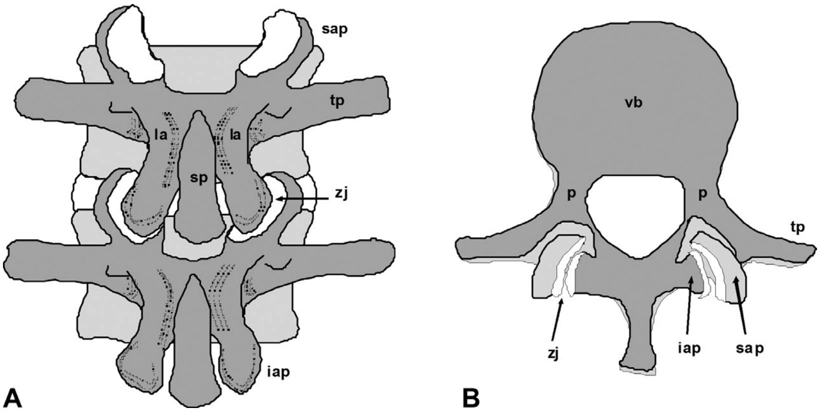

Fig. 32.13. Sketches of the posterior elements of a lumbar vertebra. (**A**) Posterior view. The two laminae (la) form a quadrangular plate, from whose corners project the superior (sap) and inferior (iap) processes. From the junction of the two laminae projects the spinous process (sp). On each side, the inferior and superior articular processes of consecutive vertebrae form the zygapophysial joint (zj) (**B**) Axial (top) view. The posterior elements are connected to the vertebral body (vb) by the pedicles (p). The transverse process (tp) projects from the junction of the pedicle and lamina, on each side.

pulposus of the affected disc and the development of radial fissures into the posterior or posterolateral anulus. The condition has been produced in laboratory animals, and pursued in numerous clinical studies. Its cause is compression injuries that produce small fractures of the vertebral endplate. These result in degradation of the matrix of the nucleus pulposus. As the nucleus becomes less able to retain water, it is no longer able to pressurize and brace the anulus. Pressures in the nucleus drop, but rise in the posterior anulus. The unbraced anulus progressively delaminates, particularly in regions of high stress where the laminae are curved: at the posterolateral corners or the posterior paramedian sector. Pain arises as a result of chemical irritation of nociceptors in the anulus by degradation products from the nucleus, and as a result of the increased mechanical stresses on the surviving, intact laminae of anulus (Bogduk et al., 2013). To various degrees of certainty the condition can be diagnosed by characteristic features on magnetic resonance imaging, such as Modic lesions in the vertebral body or high-intensity zones in the anulus fibrosus, and by provocation discography (Bogduk et al., 2013). No treatment has been vindicated, but several minimally invasive interventions are being pursued, which encompass ablating nociceptors in the disc, injecting restorative agents such as stem cells, or injecting antagonists of inflammation.

MUSCLES

The anatomy of muscles of the cervical and lumbar spine is made complex by the diversity of their numerous attachments. If those specifics are ignored, the anatomy becomes simpler.

Small muscles connect consecutive spinous processes and transverse processes. Too small to move their vertebrae effectively, these muscles serve as proprioceptors for the spine (Bastide et al., 1989).

Prevertebral muscles are represented only in the cervical spine (Standring, 2008). The longus cervicis connects the vertebral bodies and transverse processes of the cervical vertebrae. It is covered by the longus capitis which anchors the skull to the cervical vertebrae. These muscles are weak flexors of the head and neck.

Various suboccipital muscles control movements of the head in relation to the atlas and the axis. They are the rectus anterior and rectus lateralis anteriorly, and the rectus capitis posterior major and minor accompanied by obliquus inferior and obliquus superior, posteriorly (Standring, 2008). Collectively these muscles control the orientation of the head on the atlas and axis.

The postvertebral muscles are aligned systematically, side by side and by layers (Standring, 2008). Multifidus is the deepest and most medial muscle. Its fascicles arise from a spinous process and descend to various insertions on articular processes and transverses processes one to several segments caudally. It is flanked by the longissimus system of muscles, which attach to transverse processes near their bases, and whose components are large at lumbar levels, but virtually miniscule at cervical levels. Further laterally runs the iliocostalis system, which attaches to transverse processes near their tips, and whose components are, likewise, large at lumbar levels but miniscule at cervical levels. A semispinalis system is vestigial at lumbar levels but well developed at cervical levels. Semispinalis cervicis arises from the cervical spinous processes, and covers the multifidus with fascicles longer than those of the latter muscle. Semispinalis capitis arises from the occiput, and is anchored to the cervical transverse processes. It is the largest of the posterior neck muscles. It is covered by the splenius muscle, which passes cranially and laterally from the raphe of the ligamentum nuchae to wrap around all the other posterior muscles of the neck. Splenius cervicis reaches the upper cervical transverse processes, while splenius capitis reaches the superior nuchal line. Variously and collectively, the cervical postvertebral muscles act to extend the head and the cervical spine.

Other muscles use the vertebral column adventitiously, as a base from which to act on nonspinal structures. In the neck, these include the scalene muscles, which act on the ribs; and levator scapulae and trapezius, which act on the shoulder girdle. Sternocleidomastoid is the principal flexor and rotator of the head and neck, but passes directly from the manubrium and clavicle to the head, with no connection to the cervical spine. Being locked to the skull through the atlanto-occipital joints, the atlas is rotated when the sternocleidomastoid rotates the head.

In the lumbar spine, psoas major arises from the vertebral bodies, discs, and transverse processes to act on the femur, but does not move the lumbar spine (Bogduk et al., 1992). Quadratus lumborum attaches to the lumbar transverse processes but acts principally on the 12th rib; its actions on the lumbar vertebrae are effectively trivial (Phillips et al., 2008). Transversus abdominis stems from the lumbar transverse processes, and has virtually no effect on the lumbar vertebrae (Macintosh et al., 1987). Likewise, latissimus dorsi gains some anchorage to the lumbar spinous processes but has a negligible action on the lumbar spine (Bogduk et al., 1998).

INNERVATION

The C1 spinal nerve is unlike other spinal nerves, which reinforces the atlas being suboccipital rather than cervical in nature. This nerve lacks a typical dorsal root ganglion, but ganglion cells can be found amongst the rootlets of the spinal accessory nerve. The C1 dorsal ramus appears amongst the posterior suboccipital muscles (Lazorthes and Gaubert, 1956). Sometimes it can have a cutaneous branch. The C1 ventral ramus crosses the posterior arch of the atlas, behind the superior articular process. It innervates the atlanto-occipital joint before entering the cervical plexus (Lazorthes and Gaubert, 1956).

The C2 spinal nerve lies behind the lateral atlantoaxial joint, and forms a large dorsal ramus that supplies the more superficial posterior neck muscles, and becomes cutaneous as the greater occipital nerve, over the occiput (Bogduk, 1982). The C2 ventral ramus supplies the lateral atlantoaxial joint before joining the cervical plexus (Lazorthes and Gaubert, 1956).

The C3–7 cervical spinal nerves lie above their like-numbered vertebrae, enclosed in their respective intervertebral foramina. They are joined by the C8 spinal nerve, which lies in the C7–T1 intervertebral foramen. The ventral rami of C3 and C4 join the cervical plexus, and the lower cervical ventral rami join the brachial plexus. The dorsal rami of the typical cervical spinal nerves form lateral branches that supply the splenius, longissimus, and iliocostalis; and medial branches that supply the deeper and medial posterior neck muscles, and the cervical zygapophysial joints (Bogduk, 1982). The cervical medial branches have constant locations on the cervical articular pillars, which allow them to be targeted for fluoroscopy-guided diagnostic blocks, by which pain from the zygapophysial joints can be diagnosed (Bogduk, 1982, 2011).

Gray rami communicantes, from the stellate ganglion and from the cervical ventral rami, form a plexus – called the vertebral nerve – that accompanies the vertebral artery through the foramina transversaria of the neck, and into the posterior cranial fossa (Bogduk et al., 1981a). Although *migraine cervicale*, or the Barré–Lieou syndrome, has been attributed to irritation of these nerves, and spasm of the vertebral artery, laboratory studies have shown the vertebrobasilar system to be remarkable unresponsive to stimulation of the vertebral nerve (Bogduk et al., 1981a; Lambert et al., 1984).

The cervical sinuvertebral nerves are formed by somatic roots from the ventral rami and autonomic roots from the rami communicantes in the vertebral nerve. As recurrent meningeal branches they innervate the cervical dural sac, but also innervate the cervical discs and the posterior longitudinal ligament (Bogduk et al., 1988). The C1–3 sinuvertebral nerves innervate the ligaments of the median atlantoaxial joint before passing through foramen magnum to supply the dura mater over the clivus (Kimmel, 1960).

The lumbar spinal nerves lie obliquely in their intervertebral foramina, each below the like-numbered vertebra. Their ventral rami enter the lumbar or lumbosacral plexus. Their dorsal rami form lateral and intermediate branches that innervate the iliocostalis and longissimus muscles respectively (Bogduk et al., 1982; Bogduk, 1983). Medial branches innervate the lumbar zygapophysial joints and the multifidus (Bogduk et al., 1982; Bogduk, 1983). Where the medial branches cross the root of the superior articular process they can be targeted for fluoroscopy-guided diagnostic blocks, by which pain from the lumbar zygapophysial joints can be diagnosed (Bogduk, 1983, 2008, 2012b).

At each segmental level, the lumbar sinuvertebral nerves arise from the ventral ramus and gray ramus

Fig. 32.14. Sagittal magnetic resonance images of the thoracic spine. (**A**) Median section, through the vertebral bodies, spinal cord (sc), and spinous processes (sp) cord. (**B**) Paramedian section through the zygapophysial joints (zj). Intervertebral discs (ivd) are evidence in both sections. (Courtesy of Dr. Tim Maus, Mayo Clinic, Rochester MN.)

communicans. Each passes back into the intervertebral foramen to supply the dural sac, the posterior longitudinal ligament, and the posterior anulus fibrosus (Bogduk et al., 1981b; Bogduk, 1983). These nerves provide the sensory pathway for lumbar discogenic pain.

THORACIC SPINE

There have been no substantial advances in the description of the anatomy of the thoracic spine since editions of anatomy textbooks of the 19th and 18th century. In parallel, there has been little advance in the understanding of thoracic spinal pain and its sources, let alone causes. No diagnostic or treatment procedures have been validated. Thoracic spinal pain essentially remains a mystery.

Like cervical and lumbar vertebrae, the thoracic vertebrae have vertebral bodies that are connected by intervertebral discs and longitudinal ligaments, and posterior elements that are connected by zygapophysial joints (Fig. 32.14). The distinction of the thoracic spine is that it suspends the ribs. At typical thoracic levels, the head of the rib articulates with the intervertebral disc and demifacets on the edges of the vertebrae that bind that disc, and the articular tubercle of the rib articulates with the transverse process of the upper of the two vertebrae (Fig. 32.15). Exceptions to this arrangement occur at T1 and at T11 and T12, where the head of the rib fully articulates with the like-numbered vertebrae.

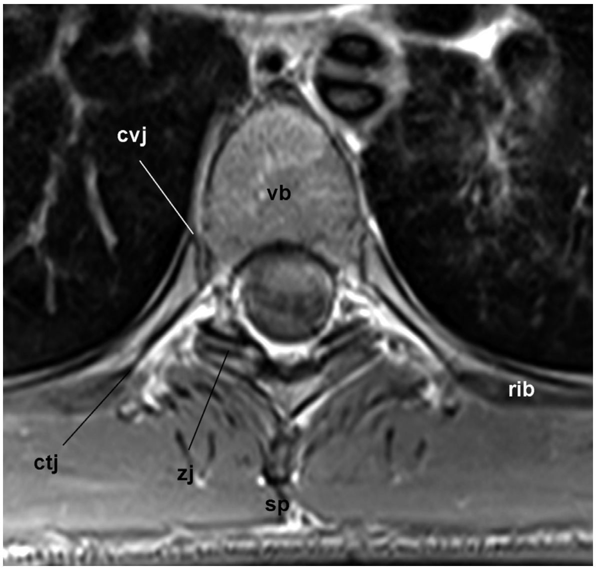

Fig. 32.15. Axial magnetic resonance image of a typical thoracic spinal segment. vb, vertebral body; zj, zygapophysial joint; sp, spinous process; cvj, costovertebral joint; ctj, costotransverse joint. (Courtesy of Dr. Tim Maus, Mayo Clinic, Rochester, MN.)

Few studies have explored the innervation of the thoracic spine (Bogduk, 2002). The thoracic sinuvertebral nerves are assumed to be homologous to those at cervical or lumbar levels. The courses of the thoracic dorsal rami appear to differ from those at cervical and lumbar levels, but are nevertheless homologous (Chua and Bogduk, 1995). Whereas the medial branches at cervical and lumbar levels wind around the base of the superior articular process at each segmental level, at thoracic levels the dorsal ramus stretches to the tip of the transverse process before dividing into medial and lateral branches. This difference is reconciled once it is realized that what are called the transverse processes at cervical and lumbar levels are embryologically costal elements (rudimentary ribs), whereas the embryologic transverse elements (or true transverse processes) are absorbed into the base of the superior articular process. Consequently, at cervical and lumbar levels, the medial branches cross the superior articular process because the true transverse processes also lie there. This distinction becomes pertinent for minimally invasive, diagnostic, and treatment procedures that target thoracic medial branches. The target lies on the transverse process, not on the superior articular process (Chua and Bogduk, 1995).

A persisting curiosity pertains to the structure of thoracic intervertebral discs. Cervical discs differ greatly from lumbar discs, but undiscovered is the transition zone. Are thoracic discs like cervical discs, or do they have the structure of lumbar discs? Given that cervical uncinate processes are homologous to the heads of the ribs, unpublished observations suggest that discs change their structure where uncinate processes or their rib equivalent cease. Thoracic discs become lumbar in nature at T11, where the rib no longer articulates with the disc.

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