Clinical Anatomy of the Trunk and Central Neuraxis

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Contents

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13.1 Spinal Nerves and the Vertebral Column

13.1.1 Origin of Spinal Nerves

Spinal nerves arise from the spinal cord and are part of the peripheral nervous system, along with the cranial and autonomic nerves and their ganglia. Spinal nerves supply somatic or body wall structures, in other words, structures derived embryologically from somites and somatic mesoderm. They also supply parietal membranes, namely, the parietal pleura, pericardium, and peritoneum, as well as the periosteum. There are 31 pairs of spinal nerves – 8 cervical (C1–C8), 12 thoracic (T1–12), 5 lumbar (L1–L5), 5 sacral (S1–S5), and 1 coccygeal (Co1). These spinal nerves are formed by the union of the ventral (anterior) and dorsal (posterior) spinal roots, each made up of smaller rootlets. The rootlets either converge to form the roots as they exit the cord if they are motor (efferent; ventral) or diverge from the roots as they enter the cord if they are sensory (afferent; dorsal). The dorsal roots bear sensory ganglia (dorsal root ganglia) containing the cell bodies of somatic and visceral sensory neurons.

Each typical spinal nerve is a mixed nerve containing somatic and visceral fibers, both efferent and afferent. The *motor (somatic efferent) fibers* supply skeletal muscle, while *sensory (somatic afferent) fibers* innervate skin and superficial fascia (subcutaneous tissues). The sensory fibers also supply receptors in joint capsules and ligaments, fasciae, and skeletal muscle (e.g., muscle spindles and Golgi tendon organs). In addition, all spinal nerves contain *sympathetic (visceral efferent) fibers* for supplying blood vessels, smooth muscle, and glands in the skin and blood vessels in skeletal muscle. The preganglionic sympathetic neurons arise from the lateral horn of the spinal gray matter (intermediolateral cell column) in the thoracic and upper two or three lumbar segments and synapse with postganglionic neurons in the *sympathetic trunk* (chain) at corresponding levels or track up and down the trunk to be distributed with spinal nerves at all levels. Some synapse with the postganglionics at higher or lower levels in the trunk to get into spinal nerves above T1 and below L2/3. Those destined for the head synapse mostly in the superior cervical ganglion. Finally, sacral spinal nerves from cord segments S2, S3, and S4 contain preganglionic *parasympathetic* fibers, which leave via the ventral rami of the sacral nerves and are destined for the pelvic viscera via pelvic plexuses and ganglia. These parasympathetic nerves are called the *pelvic splanchnic nerves* or the *nervi erigentes. Visceral afferent* fibers, carrying visceral sensation pain from the viscera, have their cell bodies in the spinal dorsal root ganglia with their peripheral processes passing through the sympathetic trunk via the rami communicantes without synapsing (without synapsing) and ending in the thoracic and abdominal viscera.

Soon after exiting the intervertebral (spinal) foramina, each spinal nerve in turn divides into a larger *ventral* and a smaller *dorsal* (*primary*) *ramus* (Fig. 13.1). The *ventral rami* course laterally and anteriorly to supply the muscles, subcutaneous tissues (superficial fascia), and skin of the neck, trunk, and upper and lower extremities. The *dorsal rami* course posteriorly and supply the paravertebral muscles, subcutaneous tissues, and skin of the back close to the midline. All dorsal rami are arranged and distributed segmentally, from C1 all the way down to coccyx 1 (Co1). The only ventral rami that are arranged and distributed segmentally are those of spinal nerves T1–T12. The ventral rami of T1–T11 are called the *intercostal nerves*, while the ventral ramus of T12 is the *subcostal nerve*. The intercostal nerves course through the 11 intercostal spaces beneath the intercostal vessels between the innermost and internal intercostal muscles, while the subcostal nerve runs along the posterior abdominal wall underneath the 12th pair of ribs. Ventral rami *not arranged segmentally* (C1 to C8 and L1 to Co1) fuse to form nerve plexuses. Thus, the neck, lower abdomen, pelvis, and extremities are supplied by nerve plexuses (cervical, brachial, lumbar, and sacral plexuses), while the thoracic and upper three quarters of the abdominal wall are supplied by the segmentally organized intercostal nerves.

It is important to realize that the first cervical (C1) nerve leaves the spinal cord and courses *above* the atlas (C1 vertebra); hence, the cervical nerves are numbered corresponding to the vertebrae inferior to them (e.g., the C6 nerve exits below C5 and above C6 vertebra; C8 nerve exits below C7 and above T1). From this point on, all the spinal nerves are named corresponding to the vertebral level above. For example, T3 and L4 spinal nerves exit below the T3 and L4 vertebrae, respectively.

13.1.2 Vertebral Column

This section reviews the developmental anatomy and growth of the vertebral column (spinal column or spine) and provides a basis for appreciating the improved visibility rendered when imaging the spine using ultrasound on the pediatric patient. It begins with the development of the vertebrae and vertebral column as a whole, followed by the growth and curves of the vertebral column and finally a brief description of the developmental anatomy of the thoracic and lumbar spine and sacrum.

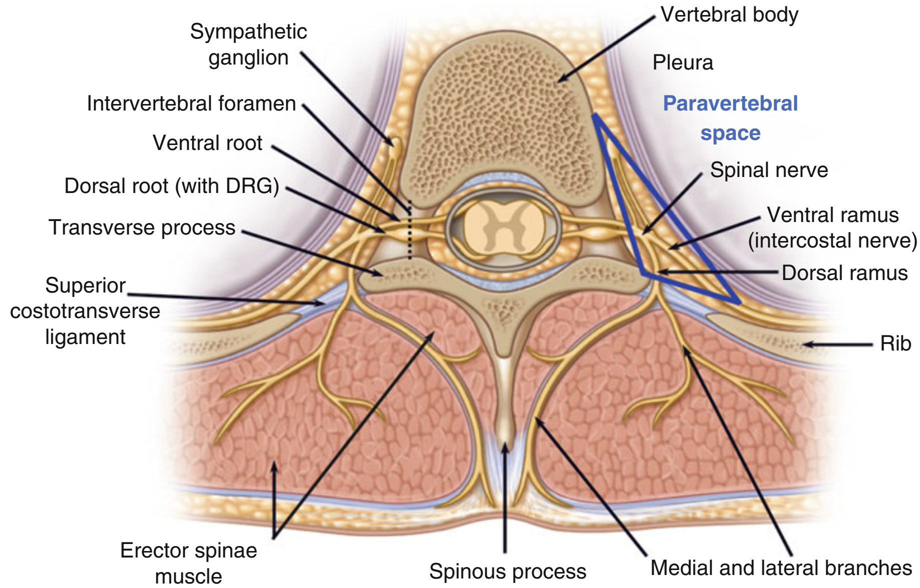

Fig. 13.1 Cross section of a thoracic vertebral segment with a simplified spinal nerve and paravertebral space shown (right side only). *DRG* dorsal root ganglion

13.2 Development of the Vertebral Column

As with most of the other bones of the human body, the development of the human vertebral column goes through three stages: mesenchymal (precartilaginous), chondrification (cartilaginous), and ossification (bony).

1. Mesenchymal (precartilaginous) stage
   During the fourth week of intrauterine life (IUL), sclerotomic mesenchymal cells of the somites (derived from the paraxial mesoderm) start to migrate toward the notochord which represents the primitive axial supporting structure. At this stage, the developing neural tube, notochord, and endoderm of the yolk sac are in close contact and are flanked by the paired dorsal aortae from which the *intersegmental arteries* branch off and course between the somites. In the thorax, these intersegmental arteries become the intercostal arteries; in the abdomen, they become the lumbar arteries. The mesenchymal tissue surrounding the notochord is subdivided by the intersegmental vessels into sclerotomic segments. The mesenchymal cells within the sclerotome become characterized by alternating regions of densely packed and loosely arranged cells between which an *intervertebral fissure* appears. This new segment forms the primitive vertebra consisting of a dense cranial zone separated by a loose caudal zone of cells by the intersegmental vessels.

   From the dense zone, three processes arise and extend dorsally, ventrally, and laterally. The dorsal extension is called the *neural process* and will form the vertebral neural arch. The ventral process will form the *centrum* (vertebral body), while the lateral process is related to the development of the vertebral *transverse process* and the attachment of the ribs. Therefore, the primordia of the definitive vertebrae are not formed from the mesenchymal cells of one somite but the recombination of the lesser and more condensed zones of mesenchyme derived from two adjacent somites. The intervertebral fissures fill with mesenchymal cells that migrate from the dense zone to form the *annulus fibrosus* of the intervertebral (IV) disk, whereas the notochord and inner cells of the annulus fibrosus degenerate to form the *nucleus pulposus*.
2. Chondrification (cartilaginous) stage
   During the sixth to seventh weeks of IUL, a pair of *chondrification centers* appears in each vertebral body followed by separate centers in each neural and transverse processes. The two centers in each vertebral body fuse at the end of the embryonic period (~9 weeks of IUL) to form a cartilaginous centrum or body. At the same time, the chondrification centers in the neural and transverse processes fuse with those in the centrum to form a cartilaginous model of the vertebra. The spinous and transverse processes arise from proliferation of chondrification centers in the vertebral neural arch and lateral process, respectively.
3. Ossification (bony) stage
   Ossification of the developing vertebrae commences during the embryonic period around the eighth to ninth weeks of IUL and is usually complete by the 25th year. Three *primary ossification centers* appear, one for the centrum and one for each half of the vertebral neural arch, followed by five *secondary (epiphyseal) ossification centers*. Centers for the vertebral arches appear classically first in the upper cervical vertebrae during the ninth to tenth weeks of IUL and then in successively lower vertebrae, reaching the lumbar vertebrae at around 12 weeks. Thus, at birth, each vertebra consists of three bony parts connected by cartilage. The vertebral neural arches usually fuse during the first 3–5 years of life, commencing in the lumbar region and progressing cranially. The vertebral arches articulate with the centrum at the cartilaginous neurocentral junctions (joints) or synchondroses, which permit the vertebral arches to grow and the vertebral canal to expand as the spinal cord enlarges. These neurocentral junctions disappear when the vertebral arches fuse with the centrum beginning in the cervical region during the third to sixth years of life. Until puberty, the superior and inferior surfaces of the bodies and tips of transverse and spinous processes are cartilaginous. Five *secondary centers of ossification* appear at the epiphyses of the vertebra around puberty: one for the tip of the spinous process, one each for the tips of the transverse processes and two annular ring-like epiphyses, one on the superior and one on the inferior rim of the vertebral body. The vertebral body is thus made up of two annular epiphyses with the mass of bone in between them which is derived from the centrum. It is important to point out that the adult vertebral body is not coextensive with the developmental centrum. Although the centrum will form the majority of the vertebral body, in the adult, the body includes parts of the neural arches posterolaterally. These secondary centers fuse with the rest of the vertebra around 25 years of age to form the definitive vertebra and the vertebral column. The atlas (C1), axis (C2), C7, sacrum, and coccyx are exceptions to this typical ossification pattern.

The majority of people have 7 cervical, 12 thoracic, 5 lumbar, 5 sacral (fused), and usually 4 (3 to 5) coccygeal (fused) vertebrae; however, about 2–3 % have one fewer or one or two additional vertebrae. When this occurs, there may be regional compensation (e.g., 11 thoracic and 6 lumbar vertebrae), so when determining the number of vertebrae, it is important to examine the entire vertebral column.

Growth and Curves of the Vertebral Column

The increase in length of the vertebral column is determined by the growth of its vertebral components. The various regions of the column and different parts of the vertebrae have differential rates of growth. The growth of the vertebral bodies begins in the thoracic and lumbar regions and extends craniocaudally. The lower part of the column grows faster than the upper as a functional prerequisite for providing better support. There are two periods of accelerated growth: the first between 2 and 7 years of age and the second between 9 and 15 years of age. The curves of the vertebral column become evident during the third month of IUL life. At first, there is only a slight curve, concave anteriorly, followed in the fifth month by the appearance of the sacrovertebral angle. Radiographic studies have shown, however, that 83 % of fetuses aged between 8 and 23 weeks already possess a cervical curve.

At birth, this embryonic anterior curvature is preserved in the thoracic and sacral regions. These areas of the column, concave anteriorly, are therefore referred to as the *primary curves*. The cervical curve is also present at birth although it becomes more accentuated when the baby starts supporting its head (around 3–4 months of life) and sitting upright (around 9 months of life). The lumbar curves appear later in response to the baby adopting the upright walking posture and walking unassisted (around 12 months of life). These are termed *secondary or compensatory curves* since they develop in response to biomechanical demands placed on the column and are convex anteriorly. Thus, the adult has four anteroposterior curves: cervical (secondary), thoracic (primary), lumbar (secondary), and sacrococcygeal or pelvic (primary), while the newborn has only three, cervical, thoracic, and sacral, the latter demarcated by the sacrovertebral angle. Between 3 and 9 months of life, the cervical curve becomes more marked in response to the biomechanical demands placed on it from the baby supporting its head and sitting upright, while after the first year, one sees the appearance of the lumbar curve in response to the need for supporting the baby's weight.

The cervical and lumbar curves in the adult are due mainly to the shapes of the intervertebral disks, while the thoracic curve is related more to the shapes of the thoracic vertebrae, which have a greater depth posteriorly. During intrauterine life, the vertebral column represents about three quarters of total body length, whereas at birth, it is reduced to two fifths due to the relatively rapid development of the lumbosacral region and lower extremities. This variation in the proportions of the vertebral column, head, trunk, and extremities causes the center of gravity of the body to shift caudally as the infant grows. In the newborn held in the upright erect posture, the center of gravity is at about the level of the xiphoid process and remains above the umbilicus throughout early childhood. At about 5–6 years, it is just below the umbilicus, and at around 13 years, it shifts to the level of the iliac crest. In the adult, the center of gravity lies at the level of the sacral promontory (the most forward projecting aspect of the upper edge of the first sacral vertebra).

13.2.1 Developmental Anatomy of the Thoracic and Lumbar Vertebral Column (Spine)

- At birth, the vertebrae of the thoracic and lumbar spine consist of three bony masses: a *centrum* anteriorly and two *vertebral neural arches* posteriorly, united by cartilage.
- Development of the *thoracic spine*:
  - The laminae typically unite in a caudo-cranial (upwards, T12 through T1) fashion, usually by the end of the first or beginning of the second year of life.
  - The centrum (body) fuses with the neural arches (neurocentral fusion), also in a caudal to cranial manner, generally by the end of the fifth year of life.
  - The transverse processes are present and prominent at birth; however, their tips, like the tips of the transverse processes, remain cartilaginous until puberty.
  - The three facets for articulation with the ribs at the costovertebral and costotransverse joints are present at birth.
  - The neurocentral and posterior synchondroses are not fused at birth; the posterior ones fuse within 2–3 months of postnatal life, and the neurocentral synchondroses close after 5–6 years of life.
- Development of the *lumbar spine*:
  - Fusion of the laminae of L1 through L4 occurs during the first year of life, with those of L5 fusing by 5 years of age.
  - Neurocentral fusion is generally complete by age 4.
  - Transverse processes begin to develop after the first year of life; however, their tips, like the tips of the spinous processes, are cartilaginous until puberty.
  - The lumbar secondary compensatory curve (through intervertebral disk modification) does not begin to develop until 6 or 8 months of age when the infant begins sitting upright and supporting its weight and becomes more apparent after the first year of life when the infant is able to adopt the upright posture and walk unassisted.
- The vertebral canal in young infants is quite small, with the thickness of the epidural space being as little as 1–2 mm.

- Secondary ossification centers in vertebral bodies and arches do not fuse with the rest of the vertebra until the early twenties, allowing continuing growth and development of the vertebral structures.
- In children, most vertebrae contain five secondary ossification centers (in the transverse and spinous processes as well as on the superior and inferior surfaces or rims of the vertebral bodies), which allow continual growth and remodeling of the vertebral column.
- In adults (early 20s), the vertebral column is essentially complete with the exception of fusion between the bodies of S1 and S2.
- In adults:
  – *The thoracic* vertebral bodies are of medium size and heart shaped (Fig. 13.1); vertebral (spinal) canals are small and nearly circular in shape; laminae are relatively small; spinous processes are long and oriented obliquely inferiorly (Figs. 13.2 and 13.3). Spinous processes overlap from T5–T8, the latter being the longest and most oblique, and their obliquity increases from T1–T9 then decreases in T10–T12. The transverse processes are relatively broad and robust for articulation with the ribs and generally face posterolaterally. The thoracic vertebrae are adapted mostly for articulation with the ribs and their role in movements of the chest wall during respiration; however, they also play a secondary role in supporting and transmitting the weight of the head and neck and the thorax to the lumbar segment of the column.
  – *The lumbar* vertebral bodies are large and kidney shaped; vertebral (spinal) canals are triangular in shape; laminae are thick; spinous processes are short and stout with a posterior (horizontal) orientation (Fig. 13.3); intervertebral disks are thickest with respect to the rest of the spine; within the lumbar spine itself, the disks are thicker anteriorly, contributing to the anterior lumbar curvature (lumbar lordosis). The transverse processes are long, slender, and directed laterally and are mostly for muscular attachments. The lumbar vertebrae are designed primarily for weight bearing and transmission, as reflected in the large size and robustness of their bodies, laminae, and IV disks.

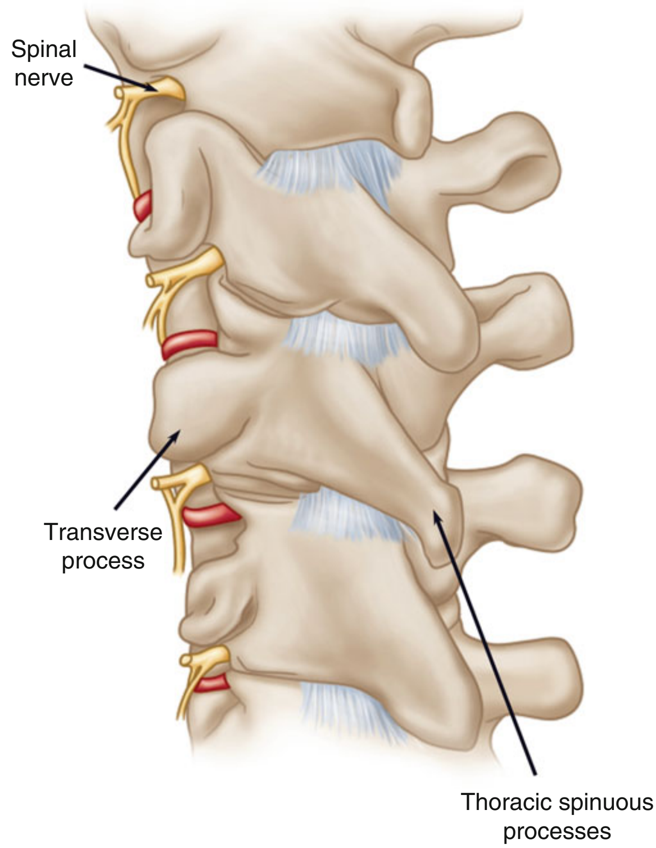

Fig. 13.2 Vertebrae of the thoracic spine, illustrating inferiorly oriented spinous processes

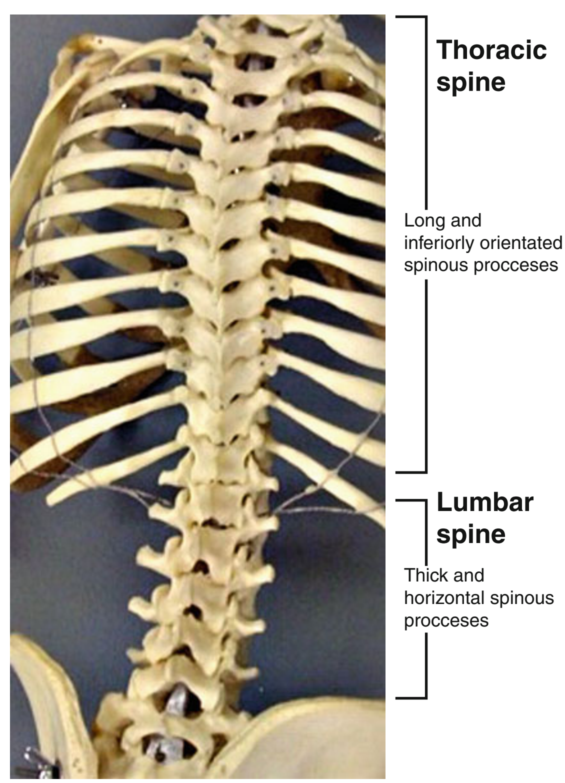

Fig. 13.3 Spinal column showing the thoracic and lumbar regions

13.2.2 Developmental Anatomy of the Sacrum

- In infancy and childhood, the sacrum is highly variable with respect to its shape and ossification and therefore also its visibility on ultrasound imaging (Fig. 13.4):
  - Like the lumbar spine, neonatal sacral vertebrae are composed of two half neural arches posteriorly and a centrum anteriorly.
  - S1 and S2 vertebrae contain lateral elements that will form the articular surfaces of the sacroiliac joints.
  - Compared to the lumbar spine, fusion and ossification are delayed in the sacrum; neurocentral fusion occurs between ages 2 and 6, and fusion of the neural arches to form spinous processes continues until age 15.
  - Ossification is a continual process that carries on until puberty with ventral fusion of S1–S2 occurring in the early 20s.
- Sacral vertebrae are oriented vertically until weight bearing around age 1.
- Beyond puberty, the *sacral hiatus* is an inferiorly placed opening into the caudal epidural space, below the fifth sacral vertebra and between it and its inferior "horns" or cornua (this is because the S5 laminae fail to fuse) (Fig. 13.4). In young infants, the sacral hiatus is generally lower, below the fifth sacral vertebra, and since there is much less ossification of the sacrum, ultrasound imaging in infants is generally rendered easier and generates superior image quality.
- The posterior sacrococcygeal ligament (membrane) has superficial and deep laminae and covers the sacral hiatus externally; this ligament requires penetration by the needle for epidural needle entry (see Fig. 13.5).

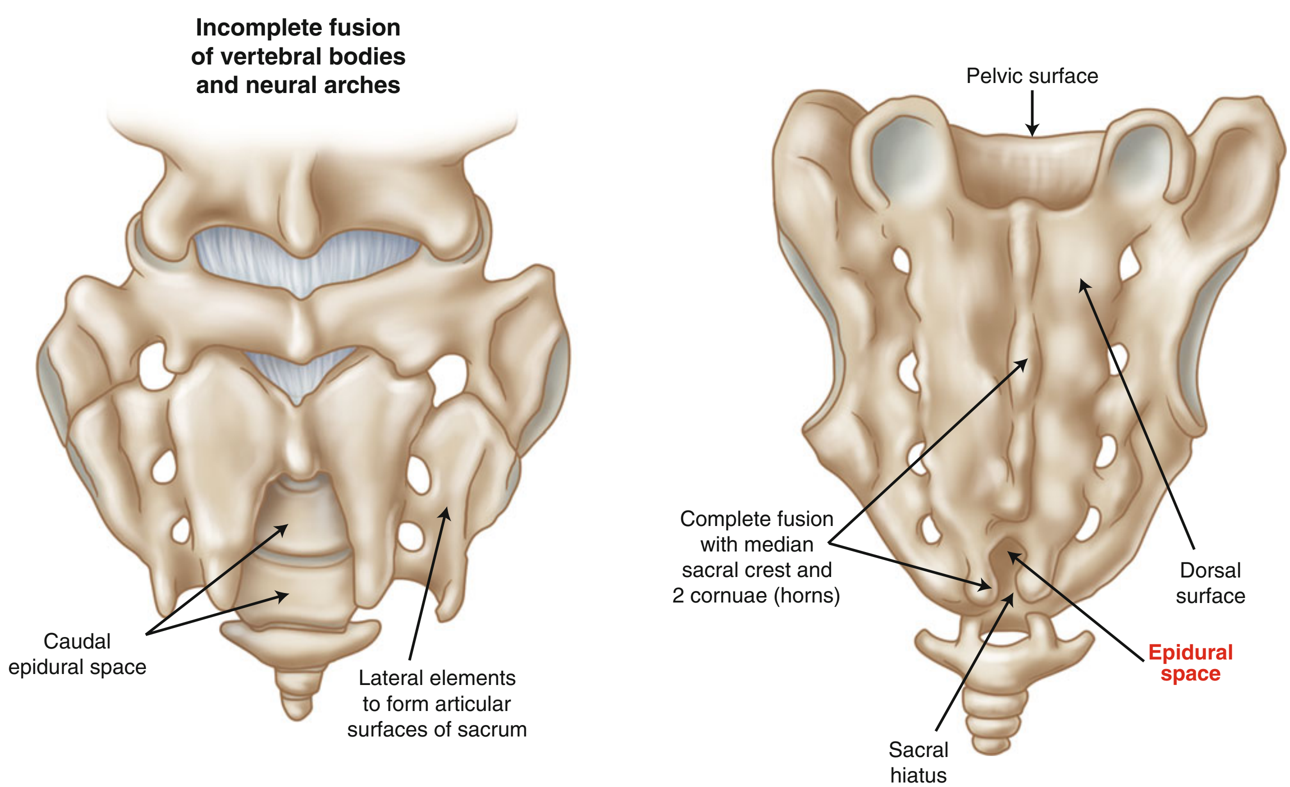

Fig. 13.4 Posterior view of infant (*left*) and adolescent (*right*) sacra, illustrating incomplete fusion of the sacral neural arches. Also shown is the incorporation of lateral elements which form the articular surfaces to form the sacroiliac joints

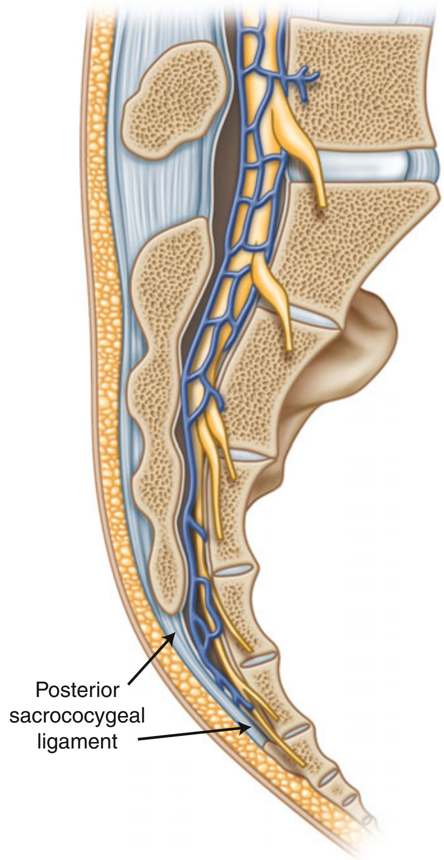

Fig. 13.5 The caudal epidural space. When performing epidural entry in this location, puncture of the posterior sacrococcygeal ligament minimizes the risk of potential needle trauma to the spinal cord

13.3 Costovertebral Articulations

The costovertebral articulations (Fig. 13.6) are relevant primarily for paravertebral and intercostal blockades, although practitioners will encounter these joints during ultrasound-guided epidurals as the imaging technique will incorporate these structures. The ribs articulate with the vertebral column through two synovial joints, one for the head of the rib (costovertebral) and the other for the tubercle (costotransverse):

- *Costovertebral joint:* the head of the rib articulates through a synovial joint with demi-facets on adjacent thoracic vertebral bodies and the corresponding intervertebral disk of the upper vertebral joint, e.g., 7th rib with bodies of T6, T7, and T6–T7 disk (except for the 1st and 10th–12th ribs, which articulate with a single vertebral facet through a simple synovial joint). The synovial joint cavities of the remaining costovertebral joints are bisected by an intra-articular ligament resulting in double synovial compartments. The joints are enclosed in fibrous capsules lined on the inside with synovial membrane and reinforced by capsular, radiate, and intra-articular ligaments.
- *Costotransverse joint:* articular facets on the tubercles of the ribs articulate through synovial joints with the transverse processes of the corresponding thoracic vertebrae (the 11th and 12th ribs lack this articulation since they do not possess tubercles). The joints are enclosed in thin fibrous capsules lined with synovial membrane and reinforced by ligaments. The ligaments are the superior and lateral costotransverse and the costotransverse ligament, the latter filling the interosseous gap (costotransverse foramen) between the neck of the rib and its adjacent vertebral transverse process. The primary purpose of these articulations is to facilitate movements of the ribs for respiratory excursions of the thorax.

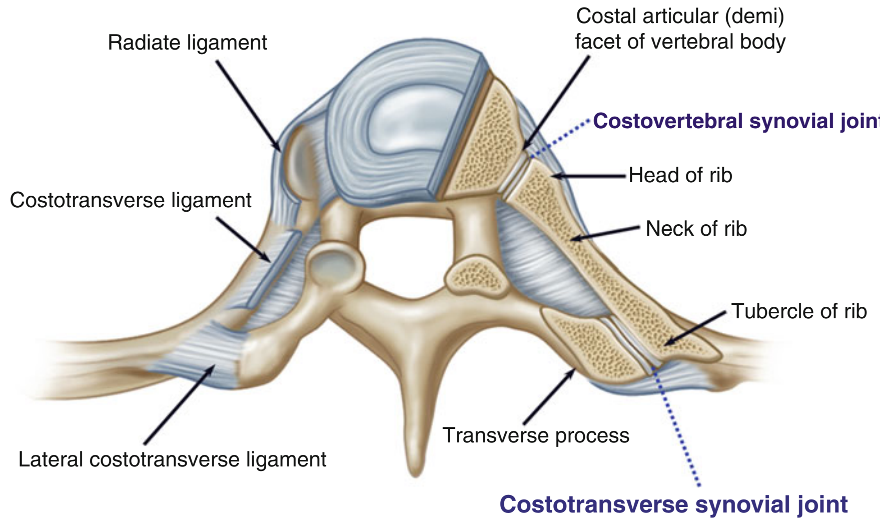

Fig. 13.6 Costovertebral articulations. *Left side*: costovertebral and costotransverse synovial joints, illustrating exterior surfaces with ligamentous coverings; *right side*: section through the synovial joints

13.4 Paravertebral Space

The paravertebral space is a bilateral wedge-shaped space on either side of the vertebral column and between the individual vertebrae, extending the column's entire length, through which the spinal nerves course after exiting from the intervertebral foramina. In the thoracic region, its boundaries are as follows (Fig. 13.1):

- Medially: vertebral body, intervertebral disk and foramen, and spinous process
- Anterolaterally: parietal pleura
- Posteriorly: costotransverse joint and the adjacent parts of the transverse process and the rib, approximately 2.5 cm (for adolescents) from the tip of the transverse process, often in a slightly caudal orientation

The paravertebral space communicates medially with the intervertebral foramen throughout the length of the column with the exception of the sacrum and coccyx. In the thoracic region, it is continuous laterally with the intercostal space, and adjacent levels of the paravertebral space communicate with each other. In the lumbar region, however, the paravertebral space is divided into segments by the attachments of the psoas major muscle.

13.5 Thoracic Spinal Nerves and Intercostal Nerves

- There are 12 pairs of thoracic spinal nerves: T1–T12.
- The intercostal nerves are the *ventral primary rami* of thoracic spinal nerves T1–T11.
- The ventral primary ramus of thoracic spinal nerve T12 is called the *subcostal nerve*, which courses beneath the 12th rib along the posterior abdominal wall.
- The thoracic spinal nerves arise from the thoracic segments of the cord from the union of dorsal and ventral roots and emerge from the *intervertebral (spinal)* foramina to course through the *paravertebral space* en route to the structures they supply in the thoracic and abdominal walls.
- The intervertebral foramina are found between adjoining neural arches near their junctions with the vertebral bodies, where adjacent *vertebral notches* on the pedicles of the vertebra above and below contribute to the formation of the foramen.
- As they course through the intervertebral foramina, the spinal nerves have clinically important relations with the boundaries of the foramina.
- Forming the complete perimeter of an intervertebral foramen, these boundaries are, *superiorly and inferiorly*, the vertebral notches of the pedicles of adjoining vertebrae; *anteriorly*, the posterolateral aspects of the adjacent vertebral bodies and intervening IV disk; and, *posteriorly*, the fibrous capsule of the synovial facet (zygapophyseal) joint between the superior and inferior articular processes of the vertebrae.
- Each spinal nerve, together with its spinal artery, a small venous plexus, and its own meningeal branch(es), traverses the intervertebral foramen.
- After exiting through the intervertebral foramen, each spinal nerve quickly divides into a small *dorsal (primary) ramus* (branch) to supply the paravertebral (paraspinal) muscles and skin of the back and a larger *ventral (primary) ramus* that swings around from posterolateral to anteromedial along the chest wall to supply the intercostal spaces, the adjacent thoracic wall, and the anterior abdominal wall (Fig. 13.1).
- The ventral (primary) rami of thoracic spinal nerves T1–T11 form the 11 pairs of *intercostal nerves* for the 11 intercostal spaces (see Fig. 11.6) and the *subcostal nerve* (T12), which courses just underneath the 12th rib.
- The intercostal nerves give off cutaneous branches at the lateral and anterior aspects of the thoracic and abdominal walls that supply the skin and superficial fascia (subcutaneous tissues) in these regions.
- Thoracic spinal nerves T2 through T12 (intercostal nerves and subcostal nerve) and lumbar spinal nerve L1

(iliohypogastric and ilioinguinal nerves) can be blocked for surgical intervention (Fig. 13.7).

Initially, the intercostal nerves course through the posterior aspects of the intercostal spaces, between the intercostal membrane and the parietal pleura, and then course laterally past the angles of their respective ribs between the innermost and internal intercostal muscles. Laterally, they give off both collateral branches (running adjacent to the nerve within the intercostal space) and lateral cutaneous branches, the latter of which divide into ventral and dorsal rami. The first intercostal nerve branches into two nerves; the first of which leaves the thorax near the neck of the first rib and contributes to the brachial plexus, while the second travels a path similar to those below it within the intercostal space. The lateral cutaneous branch of the second intercostal nerve is the *intercostobrachial nerve*, which pierces the second intercostal space and crosses the axilla to reach the medial and posterior aspects of the arm where it supplies the skin and subcutaneous tissues.

As the intercostal nerves travel laterally, anteriorly, and then medially to reach the anterior aspect of the thoracic wall, they contact the parietal pleura again before giving off the *anterior cutaneous nerves of the thorax*. The first to sixth intercostal nerves (T1–T6) proceed in their intercostal spaces between the innermost and internal intercostal muscles and beneath the intercostal vessels until they approach the sternum where they end as the *anterior cutaneous nerves of the thorax*. Intercostal nerves 7 (T7) through 11 (T11) and the subcostal nerve (T12) continue from their intercostal and subcostal spaces into the anterior abdominal wall, in which they supply and end as the *anterior cutaneous nerves of the abdomen* (T7–T12). As these nerves enter the anterolateral abdominal wall, they course in the plane between the transversus abdominis and internal oblique muscles, which corresponds to the plane between the innermost and internal intercostal muscles in the thorax. The tenth intercostal nerve, for example, the cutaneous branches of which supply the periumbilical skin, travels laterally between the transverse abdominis and internal oblique muscles; courses anteriorly and then medially around the abdominal wall; pierces the posterior rectus sheath; pierces through the rectus abdominis, supplying it; and then pierces the anterior rectus sheath to become the anterior cutaneous branch (Figs. 13.8, 13.9, and 13.10). Intercostal nerves T7 to T9 and T11 take a similar course through the anterior abdominal wall. They supply the muscles, skin, and subcutaneous tissues of the anterolateral abdominal walls, as well as the parietal peritoneum lining the abdominal walls. Cutaneous innervation to the anterolateral thoracic and abdominal walls by cutaneous branches of the intercostal nerves and subcostal nerve is organized segmentally (Fig. 13.7). Landmark dermatomes on the anterior thoracic and abdominal walls in the adult are the sternal angle (of Louis), T2; nipple, T4; xiphoid process, T7; umbilicus, T10; and suprapubic region, L1.

Innervation:	*Motor:* rectus abdominis; transversus abdominis; internal and external oblique; innermost, internal, and external intercostals; subcostales; transversus thoracis; serratus posterior (superior and inferior); and levatores costarum
	Sensory: skin and subcutaneous tissues on anterior and posterior thoracic and abdominal walls, parietal pleura, parietal peritoneum, skin and subcutaneous tissues on medial and posterior aspects of the arm (via brachial plexus and intercostobrachial nerve), and peripheral portions of the diaphragm

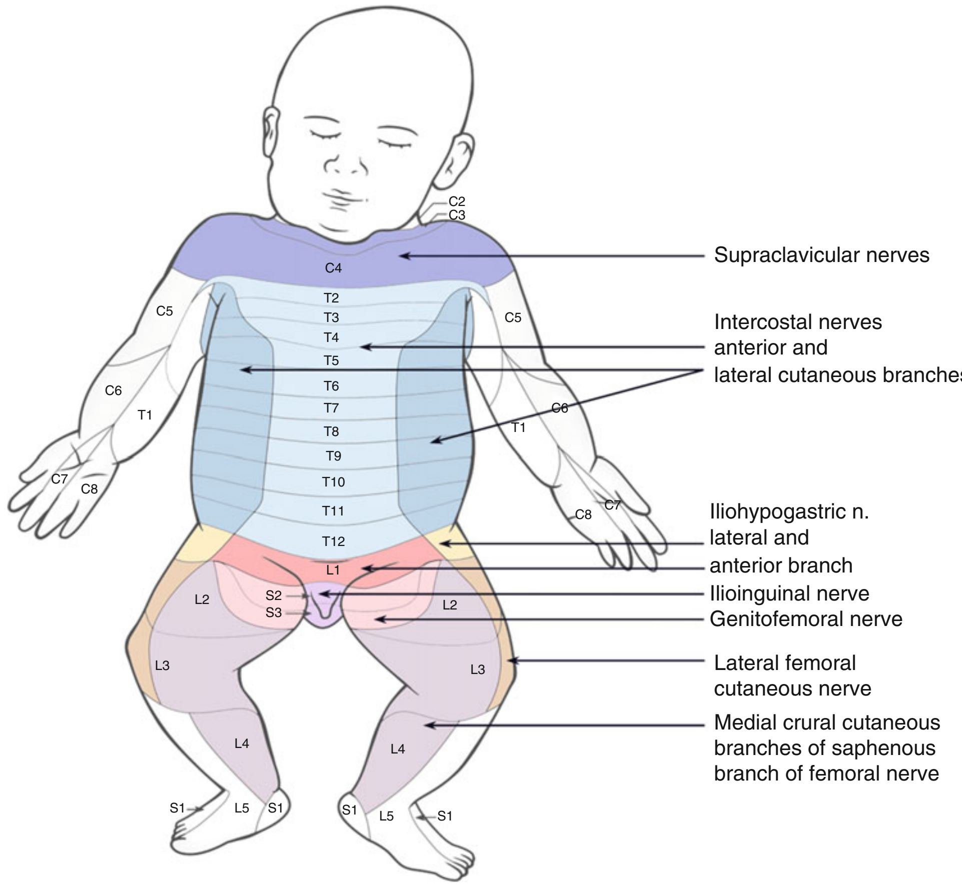

Fig. 13.7 Cutaneous innervation of the anterior trunk

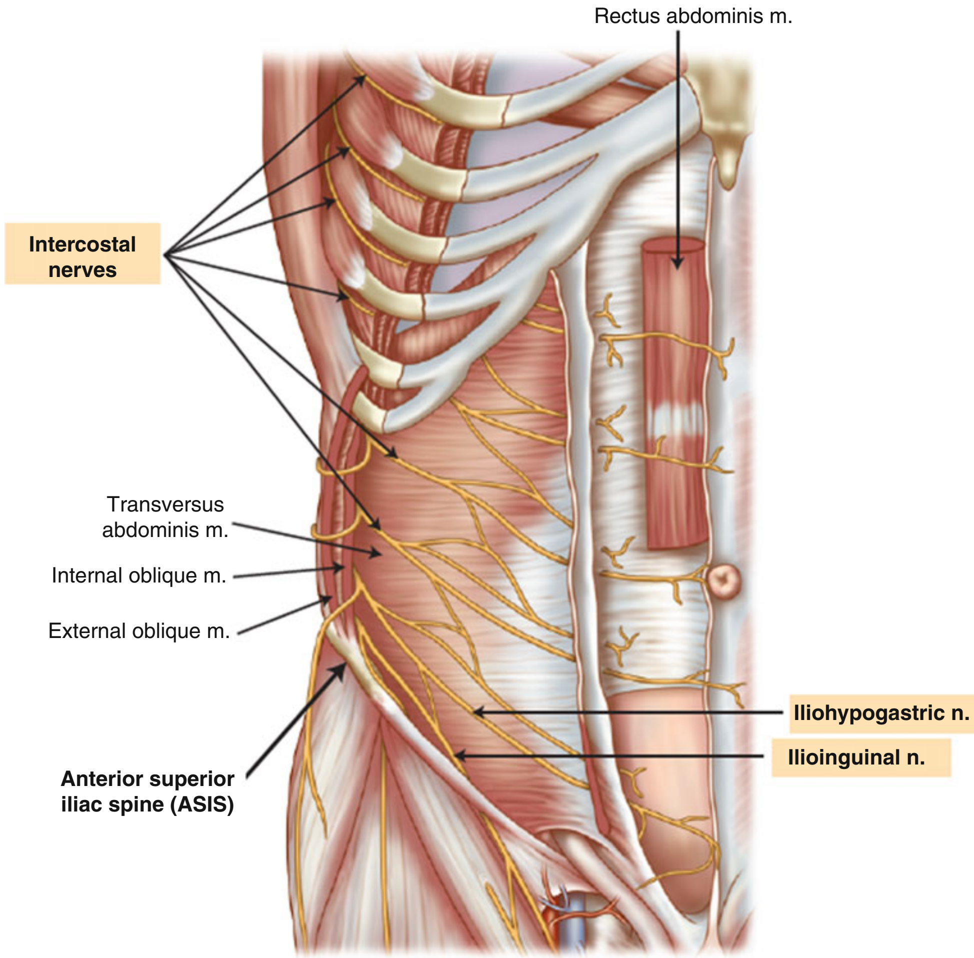

Fig. 13.8 Anterior view of the abdomen

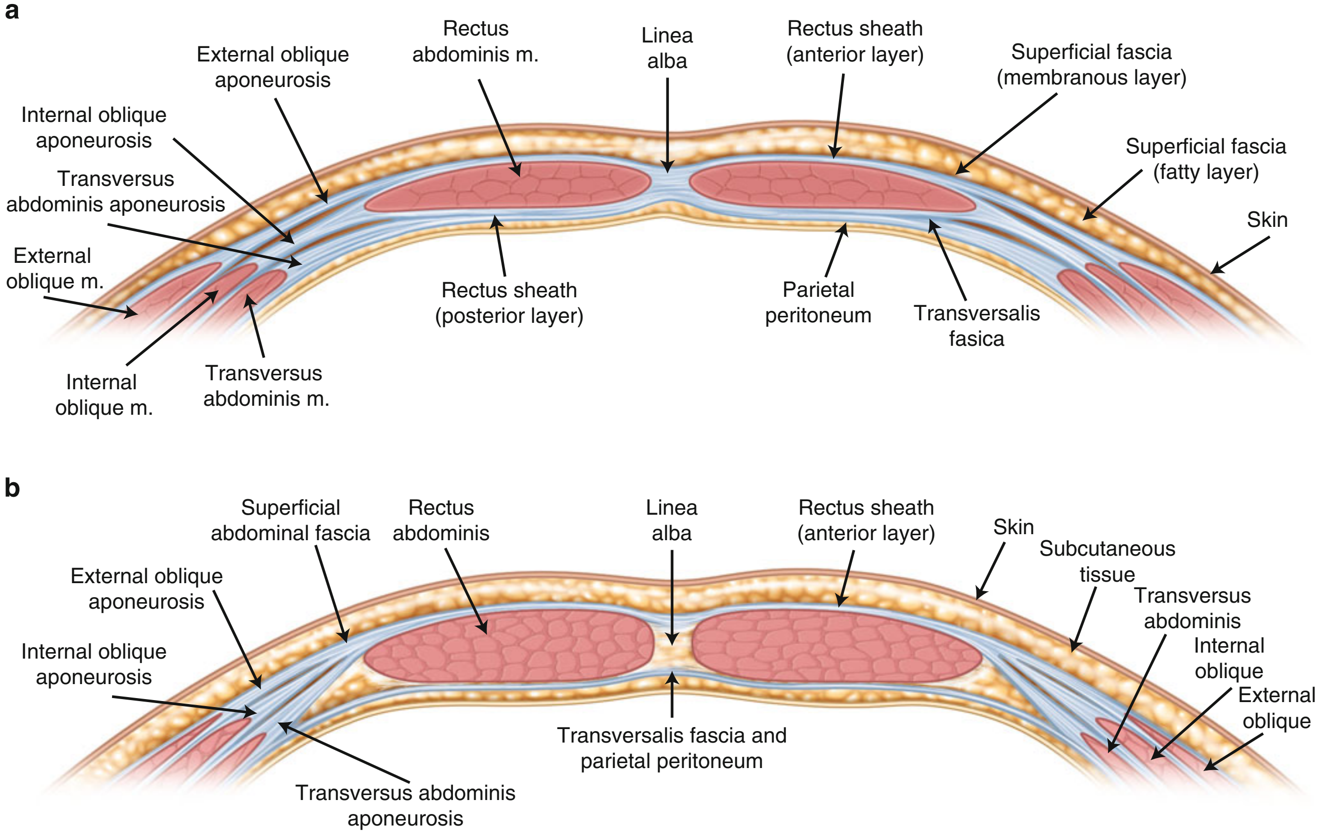

Fig. 13.9 Transverse view of the abdomen above (**a**) and below (**b**) the arcuate line of the abdomen (Douglas' line)

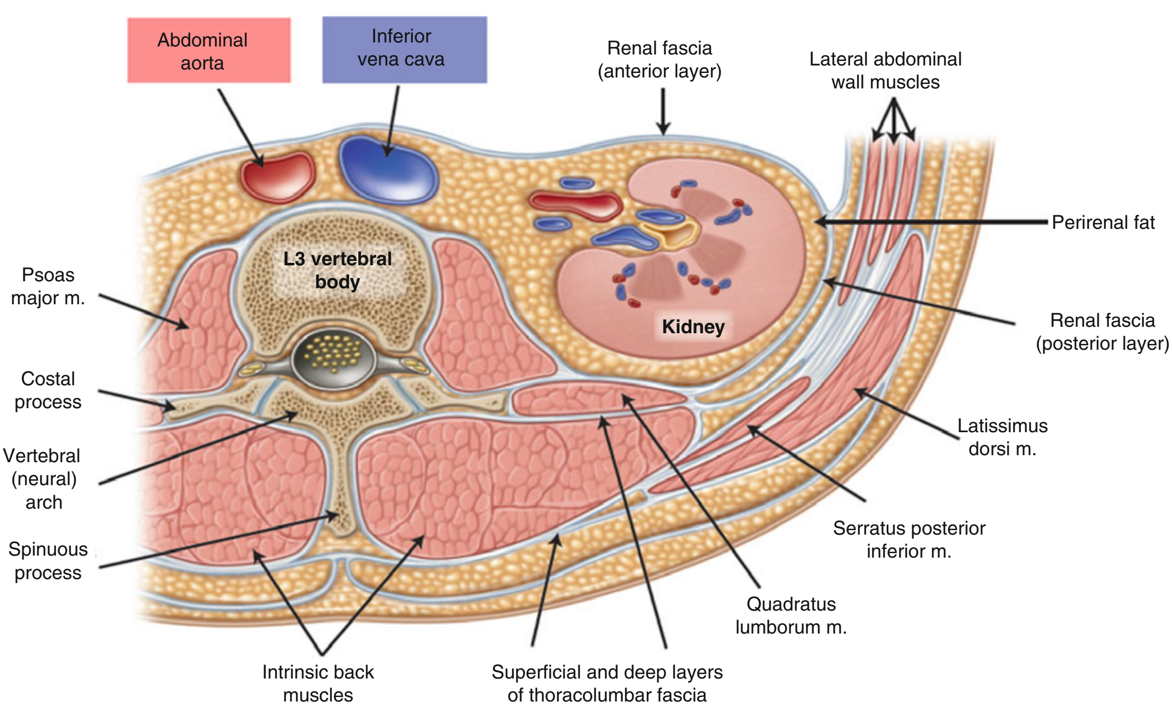

Fig. 13.10 Transverse view of the lumbar torso (L3 level)

13.6 Vertebral (Spinal) Canal

In order to safely and proficiently administer a spinal anesthetic in children, it is crucial to understand the anatomy of the vertebral (spinal) canal, including the level of termination of the spinal cord and dural sac, the relationship between vertebral levels and spinal cord segments, as well as the age-dependent variation in the volume of cerebrospinal fluid (CSF). This section reviews the gross and developmental anatomy of the vertebral column in order to provide a basis for appreciating the improved visibility when imaging the spine in the pediatric patient, followed by a brief segment explaining the relationship between vertebral levels and spinal cord segments.

The spinal cord and its nerve roots lie within the bony central canal of the vertebral column. The vertebral column consists of 7 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 4 (3 to 5) coccygeal vertebrae. The developmental anatomy of the lumbar and sacral regions is of particular relevance to spinal anesthesia in infants and children.

- The vertebral (spinal) canal is the longitudinal, cylindrical space within the vertebral column created by successive vertebral foramina superimposed upon one another and extends from C1 vertebra to the bottom of the sacrum (sacral canal). Superiorly, it is continuous with the foramen magnum which transmits the spinomedullary junction. The vertebral canal houses the spinal cord with its blood vessels and surrounding meninges; the proximal portions of the spinal nerves within their dural sheaths, epidural fat, loose connective tissue, lymphatics, and small arterial branches; and the internal vertebral venous plexus. The latter five structures are found within the epidural space, a real space between the dura and the bony margins of the vertebral canal.
- The vertebral canal's anterior border is formed by posterior aspects of the vertebral bodies and the posterior longitudinal ligament; laterally, it is bordered by the pedicles, while posterolaterally and posteriorly, its boundaries are formed by the laminae, the ligamenta flava, and the posterior aspects of the vertebral neural arches, respectively.
- The lumbar segment of the vertebral (spinal) canal has been described as having a shape similar to that of an hourglass, with narrowing at the third and fourth lumbar levels. This feature is already present at age 3. Furthermore, the sagittal (anteroposterior) diameter of the vertebral canal does not differ significantly between the ages of 3–14 inclusive.
- The major structure within the vertebral canal is the spinal cord with its blood vessels, its cerebrospinal fluid, and its three meningeal coverings. The meninges are three concentric membranes surrounding the brain and spinal cord and providing support and protection to these delicate structures. The cranial and spinal meninges are continuous at the foramen magnum.

From superficial to deep, the three meninges surrounding the spinal cord are:

1. The *dura mater* (pachymeninx) which is the outermost fibrous and toughest layer of the meninges. Between the dura and the walls of the vertebral canal is the spinal epidural space, a real space containing epidural fat within loose connective tissue, lymphatics, small arterial vessels, and the internal vertebral venous plexus (see below).
2. The *arachnoid mater*, a much thinner and more delicate, mostly translucent spider web-like membrane which lines the inside of the dura and is separated from the next deep layer, the *pia mater*, by a real space, the *subarachnoid space*, through which it sends delicate trabeculae down to the pia mater. The spinal subarachnoid space contains cerebrospinal fluid (CSF) and the anterior and posterior spinal vessels. There is a potential *subdural space* within the vertebral canal since the dura and arachnoid are closely applied; however, accidental subdural penetration may occur during epidural injections.
3. The *pia mater*, the transparent innermost single-cell layered membrane tightly adherent to the surface of the spinal cord and inseparable from it. The pia mater intimately follows and dips into all the grooves and fissures on the surface of the cord. The arachnoid and pia together are sometimes referred to as the leptomeninges. Deep to the pia is a thick *subpial collagenous layer* which is continuous with the collagenous core of the *denticulate ligaments*. The latter, which are flat, triangular fibrous sheets on either side of the cord between the ventral and dorsal roots anchor the cord via their apices to the inside of the dura mater at regular intervals and provide it with structural support.

Intermediate layer: In addition to the three classically described layers of meninges surrounding the cord, there is an additional so-called intermediate layer of leptomeninges found just deep to the arachnoid but superficial to the pia and concentrated mostly around the posterior and anterior regions of the cord. This layer is perforated and lacelike in appearance and thickened focally to form the posterior, posterolateral, and anterior ligaments of the cord and provide it with additional support to that provided by the denticulate ligaments. Structurally, it is similar to the trabeculae crossing the cranial subarachnoid space and may play a role in dampening fluid waves in the CSF within the subarachnoid space.

13.6.1 Vertebral Levels, Spinal Nerve Roots, and Spinal Cord Segments

An appreciation of the clinical anatomy of the spinal cord as it relates to the vertebral column and the relationship between spinal cord segments and vertebral levels is important for the anesthesiologist. Since, due to differential growth rates, the spinal cord is shorter than the vertebral column, the more caudal spinal roots descend almost vertically for varying distances beyond the termination of the cord (conus medullaris) to reach their corresponding intervertebral foramina. As they do so, they form a divergent bundle of spinal roots resembling a horse's tail, the *cauda equina*, beyond the conus medullaris and surrounding the filum terminale. This sheaf of nerve roots is suspended within the cerebrospinal fluid in an expanded subarachnoid space, the lumbar cistern, the preferred site for performing a lumbar puncture.

With regard to the relationship between spinal cord segments and vertebral levels, the following estimation is helpful: at the cervical level, the tip of the vertebral spinous process corresponds to the succeeding spinal cord segment (i.e., the tip of the fifth cervical spine is opposite the sixth cervical spinal cord segment). At upper thoracic levels, this difference corresponds to two cord segments (i.e., the tip of the third thoracic spine is opposite the fifth thoracic cord segment); in the lower thoracic region, this difference increases to three segments (i.e., the tenth thoracic spine is opposite the first lumbar cord segment); the 12th thoracic spine lies opposite the first sacral cord segment; thus, there is a progressively increasing discrepancy between spinal cord segments and vertebral levels craniocaudally.

The adult spinal cord terminates in most cases at the level of the intervertebral disk between the first and second lumbar vertebrae (L1 and L2); however, there is some variation (see also Sect. 13.2.2). The neonatal spinal cord extends to the upper border of the third lumbar vertebra (L3), this level rising during the first 2 months after birth. There is marked variation however; the cord may terminate between L1–L3/4 at birth and between L1–L3 in children between the ages of 3 months to 15 years [1].

13.6.2 Spinal Nerves Above the Sacrum

- The *ventral* and *dorsal* roots (dorsal roots containing the dorsal root ganglia at this location) of the spinal nerves join as they leave the spinal cord, forming the mixed *spinal nerve*, which exits the vertebral canal through the intervertebral (spinal, neural) foramen.
- The ventral and dorsal roots as well as the proximal portions of the spinal nerves are enclosed within a sleeve of *dura mater*, which is an extension of the dura from that surrounding the cord. Deep to this sheath of dura mater is the arachnoid mater. The dural/arachnoid sleeve extends onto the spinal nerves for a short distance before blending with the epineurium surrounding the nerves.
- The *spinal epidural space* (Fig. 13.11) is a "real" space between the dura mater and the periosteum lining the vertebral (spinal) canal. This space is richly vascularized (internal vertebral venous plexus, small arterial branches, and lymphatics) and filled with epidural fat and loose connective tissue which surrounds the dura mater. It is bordered posteriorly by the *ligamentum flavum* (*interlaminar ligament*), laterally by the pedicles, and anteriorly by the *posterior longitudinal ligament* which lies on posterior aspects of the vertebral bodies within the vertebral canal.
- *Gray* and *white rami communicantes* (Fig. 13.1) connect the spinal nerves to the sympathetic trunk (chain) ganglia to allow preganglionic sympathetic fibers leaving the spinal cord (T1–L2/3) to enter the trunk and leave it again to be distributed with spinal nerves at all levels.
- The spinal nerves divide into *ventral* and *dorsal (primary) rami* (Figs. 13.1 and 13.11); the dorsal rami supply the paravertebral muscles and skin near the midline of the back; the ventral rami of the thoracic spinal nerves form the intercostal and subcostal nerves (T1–T12) (Sect. 13.5) which supply the walls of the thorax and abdomen (including the parietal pleura and peritoneum). The remaining ventral rami (C1–T1 and L1–S3) form the cervical, brachial, lumbar, and sacral plexuses, which supply the muscles, skin, and subcutaneous tissues of the neck, lower trunk, and extremities.

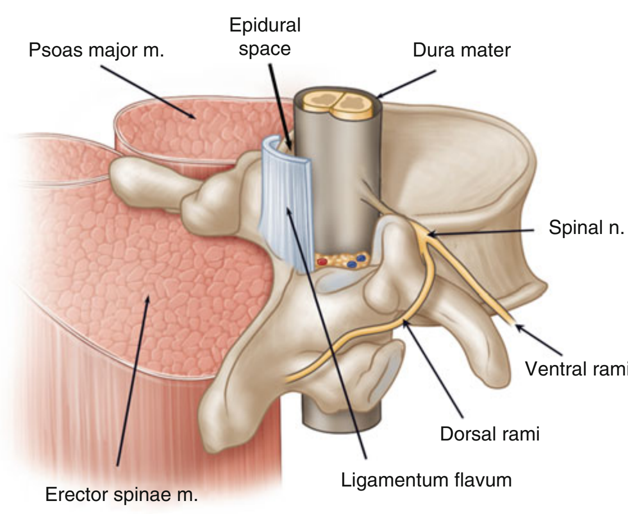

Fig. 13.11 The spinal epidural space

13.6.3 Termination of the Spinal Cord and Dural Sac

- The spinal cord occupies the upper two thirds of the vertebral canal. It begins at the superior border of the atlas vertebra (C1) and, in the average adult, ends at the *conus medullaris*, approximately at the level of the IV disk between the first and second lumbar vertebrae. Its level of termination varies somewhat between individuals and with posture, especially vertebral flexion, during which its position rises slightly. It may end as high as T12 or in some cases as low as the L2–L3 IV disk. There is some correlation between its level of termination and the length of the trunk, especially in females. The spinal cord appears to "decrease" in length significantly throughout prenatal and antenatal development, with the cord reaching as far down as S1 or 2 in the last few intrauterine months and as low as L2 or 3 at birth (Fig. 13.12). This apparent "decrease" is really the result of the greater rate of growth of the vertebral (spinal) column as compared to the cord and elongation of the lumbosacral region.
- The *dural sac* extends beyond this level, to approximately the second sacral vertebral level (S2); within the sac, the nerves forming the *cauda equina* run vertically from the conus medullaris in the lumbar section of the vertebral canal and within the sacral canal (between the posterior surface of the sacrum and the fused pedicles [intervertebral foramina in infants])
- The nerves forming the cauda equina are suspended within the cerebrospinal fluid occupying the subarachnoid lumbar cistern, which is the subarachnoid space below the conus medullaris and between it and the termination of the dural sac at S2. The arachnoid mater, lining the inside of the dura mater, also terminates at around the S2 before extending inferiorly with the *filum terminale*.
- The filum terminale is a filament of connective tissue about 20 cm long in the average adult that extends from the tip of the conus medullaris to the sacrum and coccyx. Its proximal or upper 15 cm or so, termed the *filum terminale internum* (internal filum terminale), is surrounded by extensions of the dura and arachnoid and reaches down to the posterior aspect of the second sacral vertebra (S2). Its distal or final 5 cm or so, termed the *filum terminale externum* (external filum terminale), fuses with the investing dura mater and attaches to the posterior aspect of the first coccygeal vertebral segment. The filum is continuous above with the pia lining the spinal cord. The central canal of the spinal cord continues into the filum terminale for a short distance (3 to 5 cm) although its patency is variable. The subarachnoid space surrounding the filum terminale internum is expanded to form the lumbar cistern, which contains the cauda equina and is the preferred site for obtaining a sample of CSF through a lumbar puncture.
- Despite the above classical description, a recent study suggests that the conus medullaris terminates most commonly at the level of the L1–L2 disk space and, in the absence of tethering, virtually never ends below the midbody of L2.
  - The spinal cord and dural sac were traditionally thought to terminate at a more caudal level in neonates; however, ultrasonography and MRI scans have demonstrated that the location of the caudal displacement of the conus medullaris in tethered cord syndrome is similar in term infants and adults.
  - The dural sac in neonates and infants terminates more caudally at the level of S3 as compared to adults in whom it ends at S2.

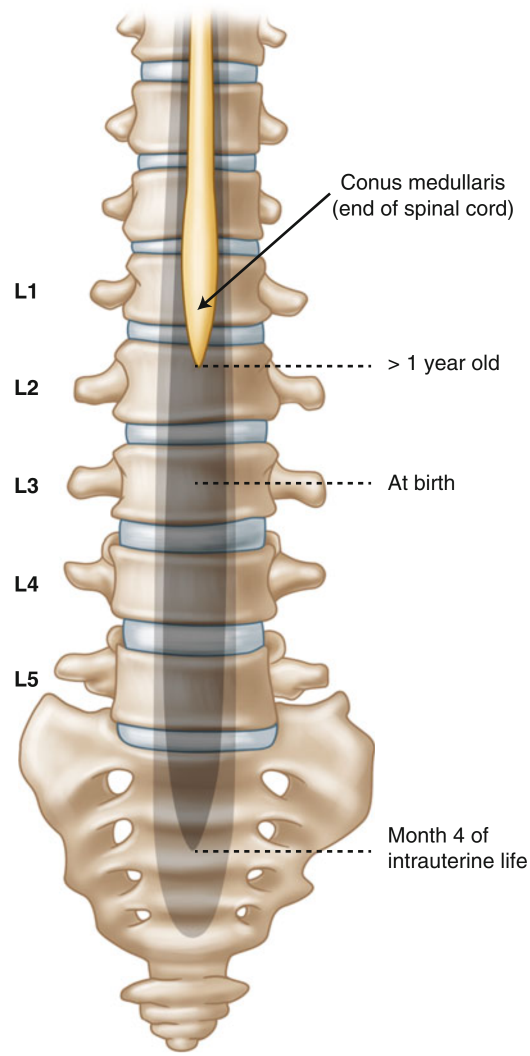

Fig. 13.12 Development of the spinal cord. The spinal cord appears to decrease in length significantly throughout early development due to the relatively faster growth of the vertebral column

13.6.4 CSF Volume

- CSF is produced from arterial blood by the choroid plexuses of the lateral, third, and fourth ventricles through a combined process of diffusion, pinocytosis, and active transfer.
- It is in a state of constant circulation through continuous production and reabsorption into the venous system, primarily through the arachnoid granulations in the superior sagittal sinus.
- While diffusion and the pressure gradient created within the CSF by virtue of its constant production and reabsorption are perhaps the major force causing the CSF to circulate, particularly around the cerebral hemispheres, its flow around the spinal cord is not that active and probably regulated to some extent by changes in body posture.
- Infants and neonates have a larger volume of CSF circulating on an ml/kg basis (neonates = 10 mL/kg; infants under 15 kg = 4 mL/kg; young children = 3 mL/kg) compared to adults (2 mL/kg). This fact may account for the higher dose of local anesthetic required per kilogram of body weight and shorter duration of action of spinal anesthesia in infants owing to the larger CSF volume in children.

Reference

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Suggested Reading

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