Spine

2

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The functions of the spine are apparently divergent: axial stabilisation of the upright position and mobility, indispensable for the movement of the segments. The spine plays a crucial role, together with the skull, in the protection of the neuraxis and enables the connection with other organs through the foramina crossed by the nervous roots. We can therefore logically distinguish between the containing part and the content of the spine, the first one consisting of the bones, muscles, and ligaments of the vertebral column and the second one consisting of the spinal cord and cauda equina, nervous roots, meninges, epidural vessels, and adipose tissue.

2.1 Normal Macroscopic Anatomy

2.1.1 Vertebrae

There are 33 vertebrae, normally 7 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 4 coccygeal vertebrae; this subdivision applies to the 20 % of the population only. Normally the sacral and the coccygeal vertebrae are merged together. The vertebra number may vary between 32 and 35, the cervical portion is generally more regular, while the coccygeal part is more variable.

We should consider the vertebral column as a unique, axial element, with both static and dynamic characteristics. In adults, the column curves towards the opposite directions: two concave backward curvatures (cervical and lumbar lordosis) and two towards the front (dorsal and sacral kyphosis) (Fig. 2.1). The lumbar region is subject to a high degree of individual variability; beyond these variations, the curves may be considered pathological for the excessive straightening or accentuation.

In the foetus, we can observe a single concave curvature of the rachis, towards the front. After 4 months only, cervical lordosis appears, and the child learns to hold his or her head up; lumbar lordosis and sacrum tilt take place when the child starts trying to achieve the upright and walking position, that is, between 10 months and 2 years of age. The mechanic adjustment of the curvature derives from the need of increasing the resistance to higher loads, determined by the human bipedal position and movement. Bioengineering researches show that the physiological curves increase by ten times the column resistance to the vertical compression.

The first two cervical vertebrae, the atlas (C1) and the epistropheus (C2) are morphologically different for their head-support function and for their capacity of allowing the movements of rotation and bending. The atlas has a ring shape and its vertebral body is not completely formed.

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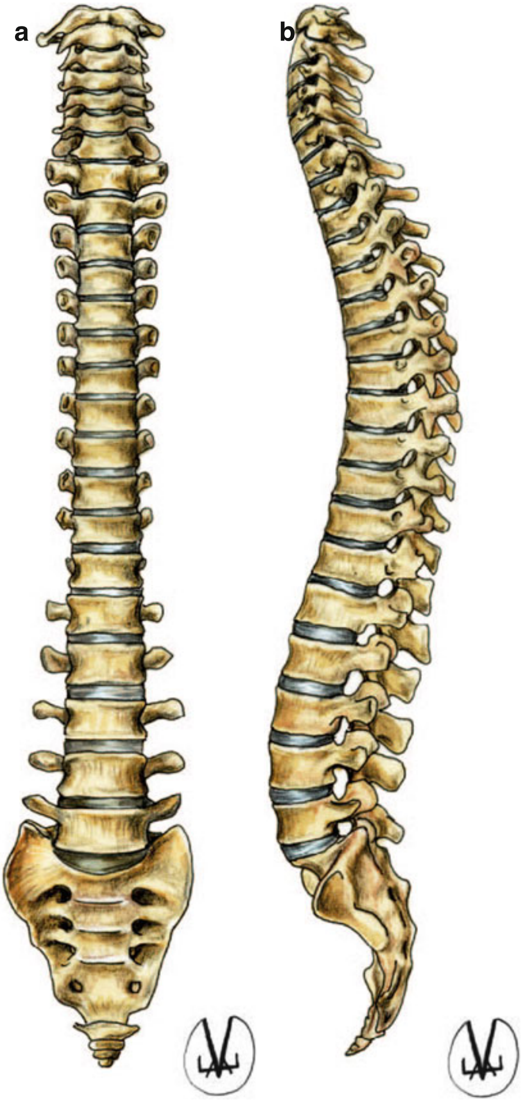

Fig. 2.1 The vertebral column, AP (**a**) and LL projections (**b**). (**b**) Cervical and lumbar lordosis and dorsal and sacral kyphosis

It consists of an anterior and a posterior arch, connected through a lateral mass. The superior articular facets are connected to the corresponding condyles of the occipital bone, at the cranial base, while the inferior facets articulate with the superior facets of the epistropheus. From the superior part of the epistropheus, the odontoid process develops, also referred to as the dens epistropheus. It forms a synovial joint with the posterior profile of the anterior arch of C1, it is supported by a resistant ligament structure, and it is the fulcrum of rotation for the atlas and the cranium. The occipito-cervical junction is a cardan system, with two perpendicular and fixed axes of rotation and an instantaneous axis obtained by the variable combination of the first two ones. In particular, in order to satisfy the needs of coordination of the ocular-cervical movements, we can distinguish a superior cardan system, in correspondence of the occipito-cervical junction, that enables limited but precise movements of the head and an articular cervical system that enables more ample, but less precise, movements for the flexion-extension and the rotation towards the sides. Such dynamics are connected to the visual function and justify the presence of the system of muscles involved in the movement of the cranio-vertebral junction, overlapping the system of muscles that enable the stabilisation of the cervical part of the rachis. The regular mechanical stress of the cervical spine justifies the frequent arthrosis involvement of this area.

Except for the first two cervical vertebrae, all the other vertebrae consist of a body, positioned in the anterior part, and of a posterior arch, characterised by the right and left pedicle connected to the pars interarticularis. Bone protuberances are located above and below each pars interarticularis, forming the superior and inferior articular processes, connected through a synovial joint to the relevant articular processes of the adjacent vertebral bodies. The intervertebral joints are subject to regular mechanical stress that causes the frequent morphological and structural alteration of the posterior arch, which may be deformed or even interrupted (isthmus), with the consequent possible ventral slip of the vertebral body (spondylolisthesis). The posterior arch consists of two posterior laminae merging in the spinous process that completes the ring, forming the spinal canal. Laterally, the posterior arches originate from the transverse processes that, along with the spinous processes, allow the insertion of several scheletric muscles (Fig. 2.2). In the cervical region, we do not find the synovial joints only but also another joint: the uncus or uncinate process, a lateral bone protuberance developing from the superior surface of the body of each cervical vertebra and

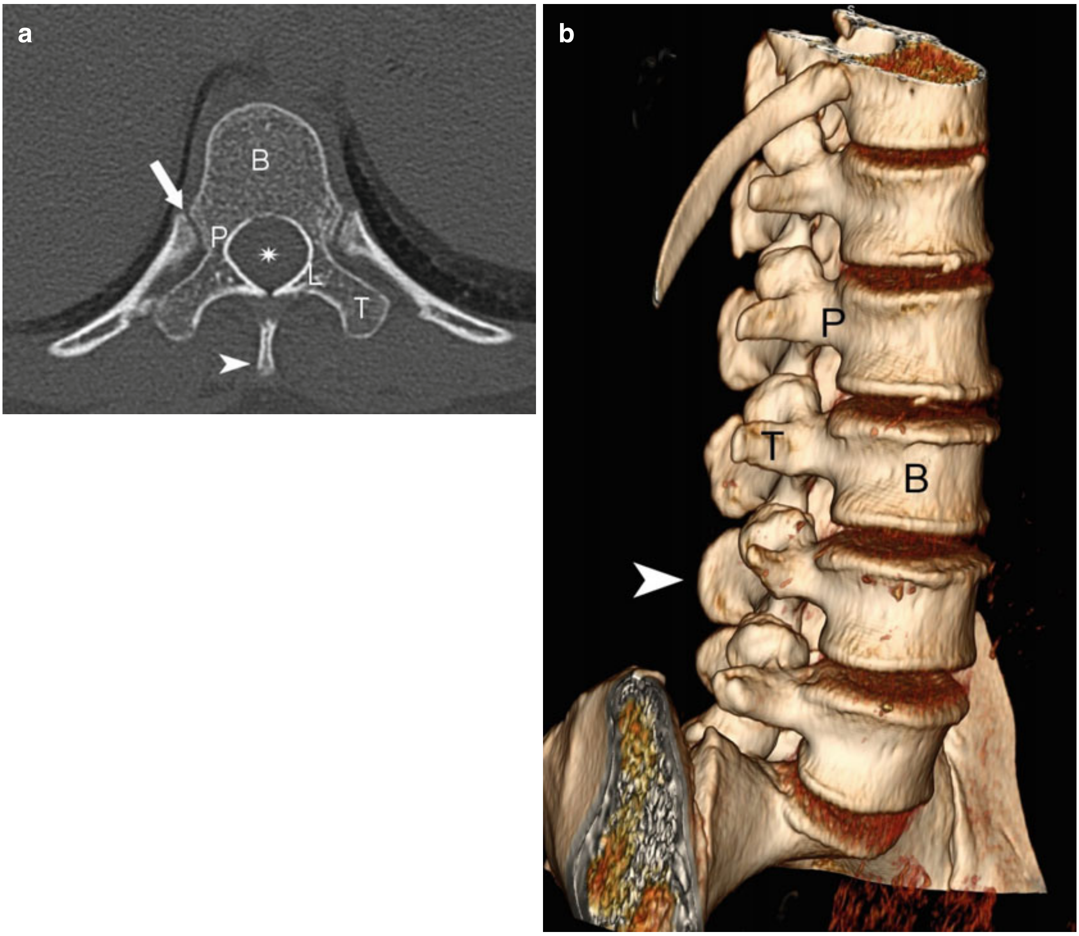

Fig. 2.2 (**a**) CT axial section of a dorsal vertebra. (**b**) Tridimensional CT, oblique projection of the lumbar rachis. Vertebral body (*B*), pedicles (*P*), laminae (*L*), transverse apophysis (*T*), spinous process (*arrowhead*), and costotransverse joint (*arrow*). The *star* shows the spinal canal

articulating with a depression on the inferior profile of the superior vertebral body, forming the Luschka joint, considered the lateral extension of the intervertebral disc.

The vertebral bodies, going from the cranium to the pelvis, need to support heavier and heavier loads, and their diameters increase accordingly. Not only the diameters but also the shape of the vertebrae changes: the body of the cervical vertebrae is quadrangular, the thoracic vertebrae have an almost triangular body, while the lumbar vertebrae are bean-shaped. The axial CT and MRI scanning perfectly demonstrates the progressive cranio-caudal increase of the transversal section of each vertebral body, due to the need to support the increasing load and therefore the need to increase the resistance of the lumbar spine.

The space between the two vertebral bodies is occupied by the intervertebral disc, whose shape corresponds to the adjoining vertebral bodies.

Also the spinal canal changes its shape: it is triangular in the cervical and lumbar regions and round in the thoracic vertebrae. In the thoracic tract, the spinal canal has a smaller diameter, because the spinal cord is thinner in this region, while the diameter is bigger in the inferior cervical region and in the lumbar one, in correspondence of the so-called cervical and lumbar protuberances. Therefore, the transverse sections of the spinal cord and the spinal canal match. The spinal nerves exit through the neural foramina in each vertebral body. In the cervical spine, such foramina may be morphologically stretched and form a channel surrounded by the pedicles of the adjacent superior and inferior vertebrae: the anterior margin consists of the posterior part of the vertebral body and the uncinate process; the apophyseal masses and the interapophyseal joints form the posterior margin. The ventral and dorsal roots are located in the inferior part of the foramen, on the level of the disc, or underneath. Also in the lumbar region, the superior and inferior margins of the neural foramen are formed by the pedicles; at this level, the posterior profile of the above vertebral body and the posterior margin of the below disc form the anterior margin; the interapophyseal joint and a small part of the yellow ligament form the posterior margin. The lumbar nerve roots are localised in the superior part of the foramen, above the disc.

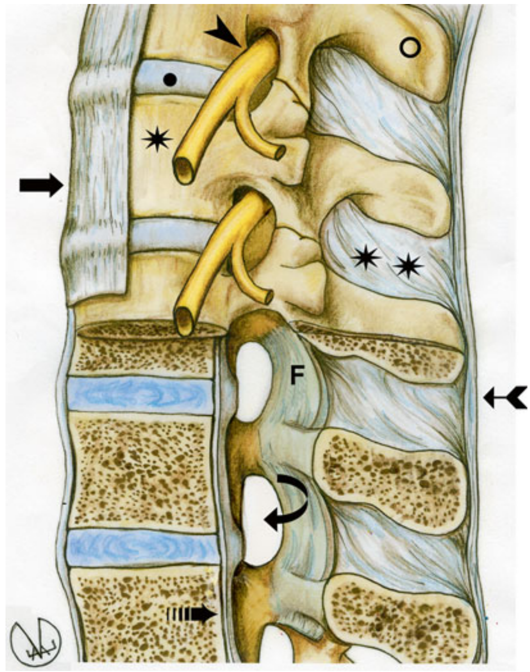

Fig. 2.3 Anatomy of the vertebral column, lateral view. Spinous apophysis (*ring*), intervertebral disc (*circle*), intervertebral foramen (*curved arrow*), interspinous ligament (*double star*), longitudinal anterior (*arrow*) and posterior (*broken arrow*) ligaments, supraspinous ligament (*arched arrow*), ligamentum flavum (*F*), nervous roots (*arrowhead*), and vertebral body (*star*)

2.1.2 Intervertebral Discs

For the length and the peculiar shape of the spinal column, the intervertebral discs are essential elements, representing approximately 1/4 of the total length of this part of the skeleton. The height of the lumbar and thoracic discs diminishes from the bottom to the top. The discs are also involved in the formation of the normal curves of the spinal column: in the cervical and lumbar column, they are higher in the front than in the back; in the thoracic tract, they are instead shorter in the front than in the back, but not as much as the vertebral bodies. The intervertebral disc is composed of two parts, structurally well distinguished but strictly connected: the nucleus pulposus, a central gelatinous core composed of water, proteoglycans, and scattered collagen fibres, and an outer annulus fibrosus with collagen content (Fig. 2.3).

The nucleus pulposus reacts to the load as a water cushion and distributes the pressure in a uniform way, in the transverse surface of the vertebral body, putting the fibrous ring under tension. In rest position, the nucleus is in the centre of the annulus or slightly oriented towards the dorsal region, such as in the thoracic and lumbar regions. When moving, it goes towards the side of the extension.

The discs, up to the second year of age, become avascular and their metabolism is exclusively governed by the phenomena of diffusion; in adult subjects, blood vessels appear in pathological conditions only. The superior and inferior disc facets perforate, without interruptions, the hyaline cartilage of the vertebral body end plates, where the collagen fibres of the annulus fibrosus are anchored. The relevant jointure formed between the vertebral bodies is termed a synchondrosis. The collagen fibres of the fibrous rings run in multiple directions, forming spirals due to the multiple forces. In particular, the vertical ones can minimise the compression and traction stresses; on the contrary, the oblique ones, towards the sides (from 30° to 45°) form a helicoidal system that minimises the stresses of rotation and pullout stresses. The mechanical resistance of the fibrous peripheral area of the disc is, in general, capable of resisting traumatic lesions, and therefore, in the event of a trauma, the vertebral body may fracture without dislocating or breaking the disc.

The intervertebral discs control the amplitude of the movements between vertebral bodies, while the articular processes affect the movement directions, limiting them, like rails. Protrusions of the cartilage of the intervertebral disc through the vertebral plate, and into the adjacent vertebra, may occur, forming discal hernias, because the plates may get weaker with advancing age, the so-called Schmorl's nodes in Scheuermann's disease (Fig. 2.4).

During the day, in upright position, the intervertebral discs reduce their volume, and a minimal amount of fluid is in fact squeezed out by the pressure of the body; also the articular cartilages may flatten after prolonged pressure. In the evening, therefore, the overall stature of the body may be around 3 cm shorter than in the morning. As we get older, the stature variation during the day become less visible; in older people, the vertebral discs are less flexible due to their physiological progressive dehydration, and the stature reduction gets permanent. The alterations of the annulus fibrosus appear relatively earlier, between the 20th and the 40th year of age. When the nucleus pulposus is under pressure, it tends to move and put pressure on the fibrous ring, which is already weak; a protrusion, or hernia, may occur and push the content, generally the nerve roots, inside the spinal canal or the junction foramina. The intervertebral disc is innerved, especially on the anterior side, and this justifies the discal origin of specific back pain.

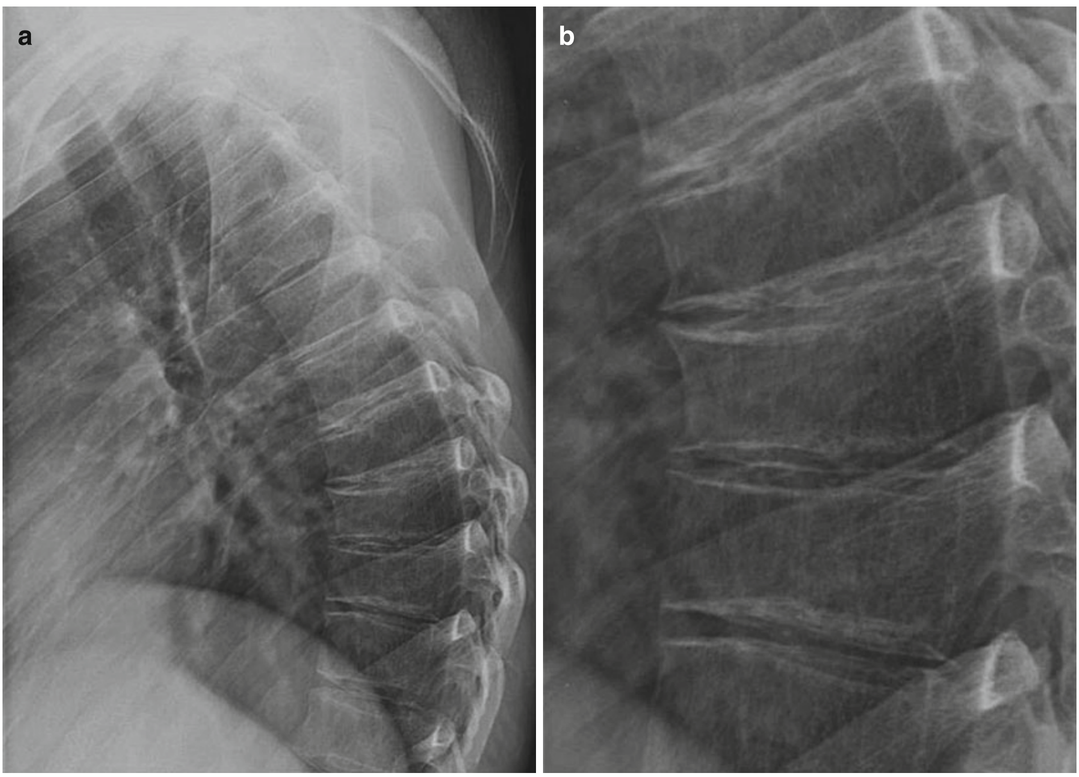

Fig. 2.4 X-ray, latero-lateral projection (**a**) and detailed view of the middle-inferior dorsal tract (**b**): anterior wedge-shaped deformation of the vertebral bodies and irregularity of the vertebral plates, more visible on the targeted projection, typical of Scheuermann's diseases. (**c**) Sagittal T2-weighted image of the same patient, supporting the radiographic evidence and showing some Schmorl's little nodules in the vertebral plates

Fig. 2.4 (continued)

2.1.3 Ligaments

The vertebrate bodies and the intervertebral discs are connected to several ligament structures. The anterior longitudinal ligament goes from the base of the cranium to the sacrum and adheres to the anterior margin of the vertebral bodies and discs; the posterior longitudinal ligament goes from C2 to the sacrum, well adhering to the vertebral plates and to the posterior margin of the disc but separated from the middle posterior portion of the vertebral body by the interior-anterior epidural venous plexus and the basal vertebral veins. The superior extension of the posterior longitudinal ligament is the tectorial membrane that goes from C2 to the inferior part of the clivus.

In the elastic system of the vertebral disc bodies, tension is maintained through the ligaments, and such system is contrasted by the tension on the vertebral arches, maintained by the yellow ligaments.

The yellow ligaments (ligamenta flava) are flat; they connect the lamina of the vertebral hemiarch in cranio-caudal direction; the name is due to the yellowish colour of the prevailing elastic fibres that may extend considerably, without laceration, and that release the energy accumulated during the traction; such a capacity is reduced with advancing age. The ligamenta flava, which are longer and more robust in the lumbar region and thinner in the cervical region, work under strong tension and tend to stretch the spinal column; they oppose, along with the long dorsal muscles, to the anterior masses of the trunk that would otherwise bend the body forwards. The yellow ligaments have a static function also for their support to the posterior border of the neural foramina: in fact, their anterolateral border reaches the intervertebral joint and adheres to the anterior side of the capsule; in such a way, the vessels and nerves crossing the foramen lean on the smooth surface of the yellow ligament, rather than on the rough surface of the articular capsule.

The spinous processes are connected through the supraspinous and interspinous ligaments (Fig. 2.3).

In the cranio-vertebral junction, we find other ligaments whose function is to stabilise the atlantoaxial articulation and the cranio-cervical joint. The anterior atlantooccipital membrane connects the anterior margin of foramen magnum to the anterior arch of C1; the corresponding posterior atlantooccipital membrane runs from the posterior margin of the foramen magnum to the posterior arch of C1. Another important ligament is the cruciate ligament of atlas, consisting of the transverse ligament, strong horizontal component between lateral masses of C1, passing behind the dens and keeping it together with the anterior arch of C1, and the cranio-caudal component, fibrous band running from the transverse ligament and inserted superiorly (along with the tectorial membrane) in the caudal portion of the clivus. The apical ligament connects the apex of the dens to the anterior margin of the foramen magnum while the alar ligaments run laterally, from the dens to each occipital condyle (Fig. 2.5).

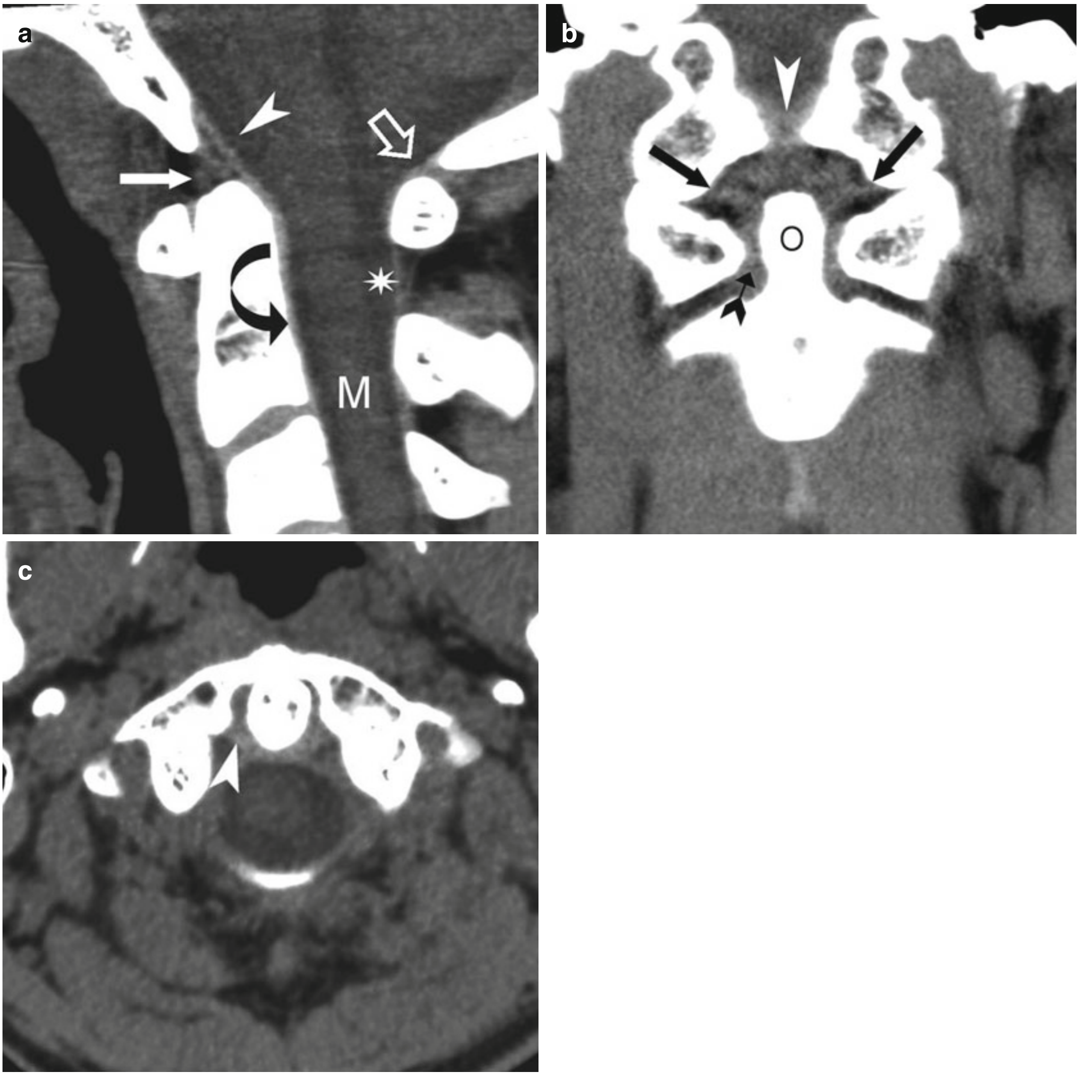

Fig. 2.5 CT sagittal (**a**), coronal (**b**), and axial (**c**) reconstruction, with algorithm for soft parts, showing the main ligaments of occipito-cervical junction. (**a**) The tectorial membrane (*arrowhead*), cranial part of the posterior longitudinal ligament (*curved arrow*), apical ligament (*arrow*), and atlantooccipital membrane (*empty arrow*). Cervical cord (*M*) contained in the hypointense cerebrospinal fluid of the subarachnoid space (*star*). (**b**) The alar ligament (*arrows*), transverse ligament (*arched arrow*), tectorial membrane (*arrowhead*), and odontoid process (*O*). (**c**) The transverse ligament (*arrowhead*), horizontal part of the cruciate ligament, inserting into the internal tubercles

2.1.4 Vertebral Canal

The cylindrical space, going from the occipital foramen to the sacrum, is the vertebral canal, and it is, therefore, the first "content" structure of the vertebral column; it has the form of a tube, structurally irregular for the alternation of rigid (vertebrae) and elastic (intervertebral discs) elements and for the presence of the lateral foramina (neural foramina) (Fig. 2.3). The vertebral canal, during the spine movements, is under mechanical stress; this is the reason why its anatomy is so complex; it is structured for the protection of the nerve structures contained therein.

The structure of the vertebral canal changes according to the kinematics of the rachis; in particular, the variations in flexion-extension determine sensible variations in the behaviour of the osteoligamentous walls: for example, during extension, the vertebral canal reduces from 5 to 9 cm, according to the different mobility, which is not equal in all the rachis tracts and that increases in the cervical and lumbar regions.

The transversal section dimensions of each vertebral canal tract vary on an individual basis and have been subject to several researches because of their clinical relevance. If the channel is too narrow, the adaptability of the spinal cord to the canal bone walls is limited. In vertebral canals smaller than the normal, any pathological issue, especially of degenerative-arthrosic nature, may determine a direct compression of the nerves (in particular, in the cervical-lumbar region) or involve the vascular systems and therefore indirectly affect the nerves.

The measurement of the diameters of the vertebral canal, previously based on the direct radiography or tomography, is currently carried out with computed tomography (CT) or magnetic resonance imaging (MRI). For such a purpose, it is important to remind that the pathological variations of the canal diameters can be almost exclusively performed with sagittal section and, in adults, diameters inferior to 11.5 mm should be considered abnormal. The transverse diameter is always wider than the sagittal one, in all regions of the spine; the maximum diameters are located in the cervical and lumbar regions.

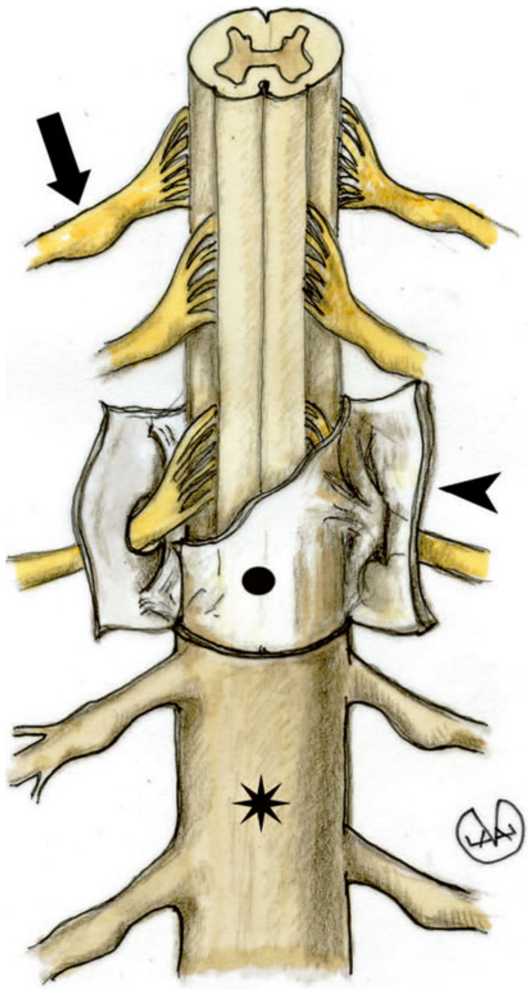

Fig. 2.6 Anatomy of the spinal cord. Dura mater (*star*), adherent to the arachnoid (*circle*). The *arrow* shows a spinal ganglion and the *arrowhead* shows the dura mater in section

2.1.5 Meninges

The spinal cord and its roots are enveloped by the meninges arriving from the cranial cavity. The adjacent dura and arachnoid mater (only virtually separated) surround the subarachnoid space, whose internal border is determined by the pia mater, strictly adherent to the spinal cord and the nerve roots (Fig. 2.6). In the fibrous dural sac, very resistant and closely adherent the anterior wall of the vertebral canal, the dura mater separates the cerebrospinal fluid—which freely circulates into the subarachnoid space (the space between the arachnoid and pia mater) and the ventricular system around and inside the brain and spinal cord—from the epidural space, where two components play an essential role: the adipose tissue, plugging the spaces between the dural sac and the vertebral bones' borders, and the venous plexuses, draining the blood coming from the tissues of the vertebral spongiosa, functioning as an hydraulic cushion for the external stresses received by the nerve structures.

2.1.6 Spinal Cord

The spinal cord, a prolongation of the brain and the brainstem, contained in the vertebral canal is a component of the central nervous system (CNS), more similar, in comparison with other components, to the primitive neuraxis; also when completely developed, it mostly preserves, in fact, the shape of the embryonic neural tube.

Its distal extension may vary according to age.

From the functional point of view, the spinal cord can be considered as a tidy series of overlapping cylindrical segments (myelomeres) responsible for the nervous regulation of an equal amount of corresponding corporal segments. The intersegmental connections are responsible for the coordination between the various segments, while the neural pathways, ascending (sensory pathways) or descending (motor pathways) the marrow, are responsible for the overall integration of the organism. The spinal cord guarantees the connection of the CNS periphery with the superior levels and, at the same time, through the individual medullary centres, the execution of essential and complex functions.

The spinal cord represents the 2.5 % of the CNS only, but it governs the motor, sensory, and vegetative functions of the whole organism.

A very important element, from the clinical point of view, is the relation between vertebral segments and myelomeres. During the intrauterine development up to the third month, the vertebral column and the spinal cord have the same length because both of them originate from the metameric segmentation of the axial mesoblast. At this point, spinal roots emerge horizontally from the corresponding neural foramina. At a later stage, for the different growth (allometry) of the spinal cord and the column, the apex of the medullary cone “goes up” towards the front of the first lumbar vertebral body (L1), in adults, with a possible variation from the twelfth thoracic intervertebral space to the second lumbar one. The cone continues into the terminal filum, a delicate pial strand (its diameter is less than 2 mm), anchoring the terminal cone to the first coccygeal segment.

For the different length of the spinal column and spinal cord, the disparity in the levels of the vertebral and medullary segments increases in craniocaudal direction. As a consequence, the nerve roots’ pathways become progressively more vertical along the thoracic region and below the apex of the cone, where the lumbar nerve and sacral roots become more elongated, parallel, and vertical (cauda equina). On the contrary, the cranial roots and in particular the cervical ones run horizontally, because the medullary segment of origin remains at the same level of the correspondent intervertebral foramina. We also need to remind that the spinal roots have to go through the intervertebral foramen of the metamer which is embryologically correspondent to their myelomere of origin; therefore, when they are completely developed, the ganglia of the nervous roots of the lumbar myelomeres, situated in their primitive intervertebral foramina, actually have their corresponding insertion point in the spinal canal at the level of the dorsolumbar passage. The precise knowledge of the existing relations is essential in the neurological assessment of traumatic lesions of the rachis; in fact, it is not otherwise possible to establish the exact place of the damaged myelomere (Fig. 2.7).

The spinal cord is a long, tubular cordon, whose diameter is not uniform because of the aforementioned cervical and lumbar enlargements from where the nerve roots of the limbs originate. The length of the spinal cord depends from the size of the person; in adults, it is generally around 45 cm; the maximal transverse diameter, in the cervical region, measures 14 mm.

The relation between the spinal cord and the vertebral canal is not regular throughout the cranio-caudal extension: dorsally, the diameter of the spinal cord diminishes in comparison with the canal; in this region, in fact, the compression tolerance is lower than in the cervical and lumbar regions, where the hard vertebral case is more spacious. The spinal canal size has a high degree of interindividual variability.

The structural conformation of the spinal cord is identical from the cranial to the caudal region, with a central axis of grey matter (containing nerve and amyelinic fibre elements) and a circular envelope of white matter (containing myelinic fibres). The medullary grey matter has a “butterfly” or “H” shape: the motor roots originate from the anterior extremities (horns), while the posterior ones receive the sensory roots. In the white medullary matter, we find the anterior, lateral, and posterior fibrous bundles, ascending or descending, with different origin, development, and destination (Fig. 2.8). Thin nerve roots also emerge from the anterior and posterior lateral sulci of the spinal cord, forming the ventral and dorsal nerve roots. The ventral-motor and dorsal-sensory roots merge into the spinal nerves. There are eight pairs of cervical nerve roots and seven cervical vertebral bodies only. The first seven cervical nerves emerge above the pedicles of the corresponding vertebral

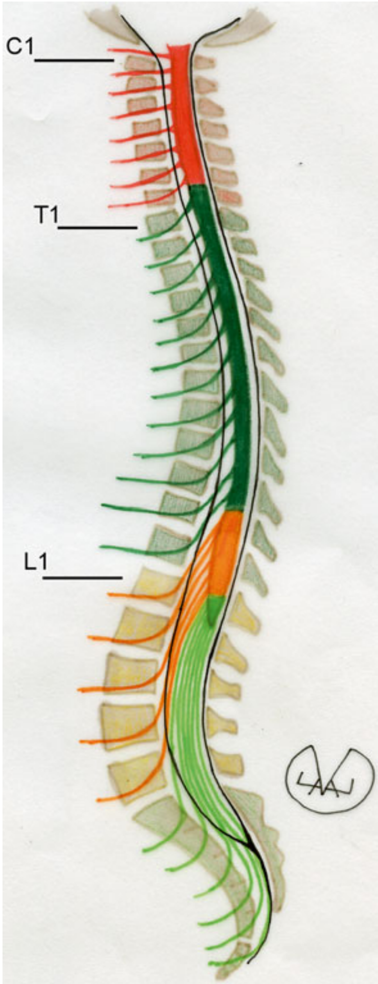

Fig. 2.7 Lateral view of the spinal column section. It shows the difference between the vertebral column and the spinal column length, with the medullary cone in normal position, at the level of the L1 body; the nerve roots are more and more oblique, oriented downwards, from the dorsal tract, and get almost vertical at the level of the cauda equina. Cervical nerves (*red*) and dorsal (*green*), lumbar (*orange*), sacral, and coccygeal (*light green*) nerves

body. Given the different length of the spinal cord and rachis, the more caudal sacrococcygeal roots need to vertically cross (as previously explained) the vertebral channel, in order to reach the corresponding pair of intervertebral foramina. On the way, the roots are freely floating into the cerebrospinal fluid of the dural sac and wrapped around the terminal filum (Fig. 2.9).

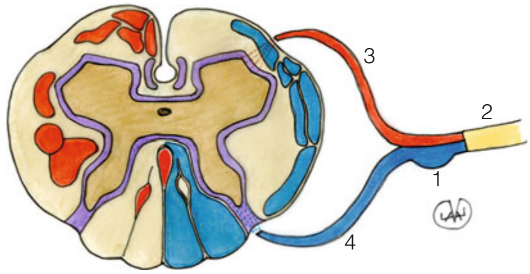

Fig. 2.8 Axial section of the spinal cord with grey and white matter. Spinal ganglion (*1*), spinal nerve (*2*), and anterior (*3*) and posterior roots (*4*). Ascending (*light blue*) and descending pathways (*orange*)

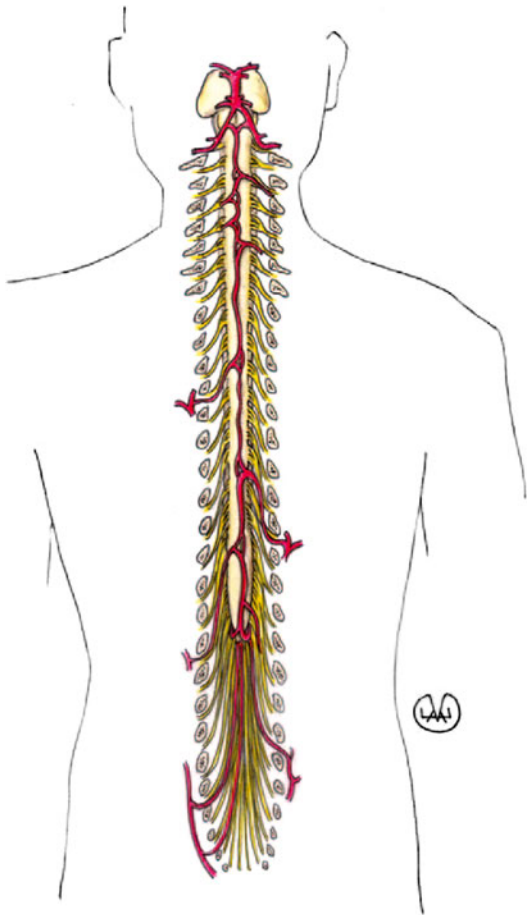

Fig. 2.9 Coronal section of the spinal column, with the spinal nerves exiting from the neural foramina. It clearly shows the vertical course of the cauda equina. The arteries supplying the spinal cord are also clearly identifiable

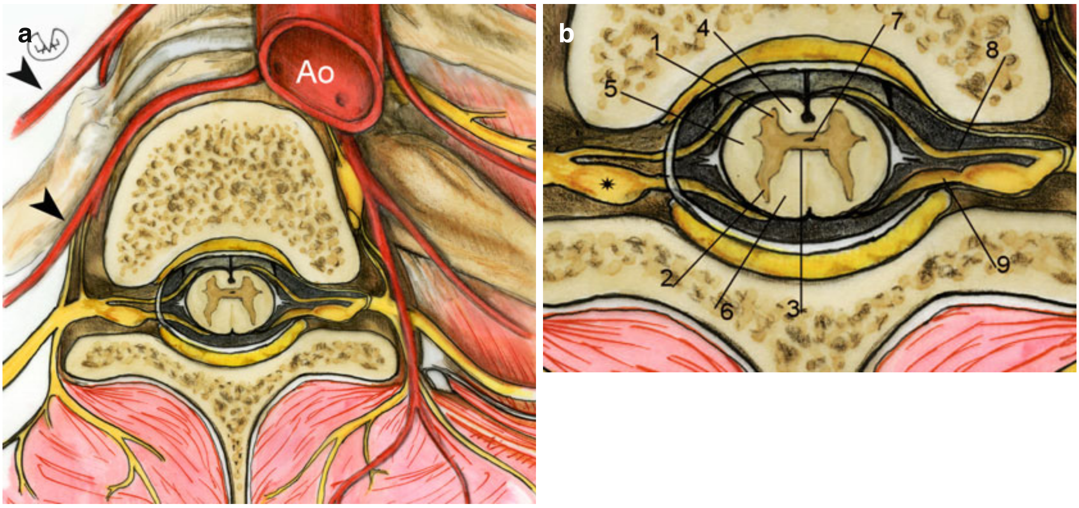

Fig. 2.10 (**a**) Axial section of the dorsal part of the vertebral column. The *arrowheads* highlight the posterior intercostal arteries. *Ao* aorta. (**b**) Detailed anatomy of the spinal cord: the anterior horn (*1*), posterior horn (*2*), anterior commissure (*3*), anterior cordon (*4*), lateral (*5*) and posterior cordon (*6*), central ependymal canal (*7*), anterior root (*8*), posterior root (*9*), and spinal ganglion (*star*)

2.1.7 Roots and Spinal Nerves

In the spinal cord, the efferent anterior motor roots differ from the afferent posterior sensory ones; the diameter of these last ones is three times wider than the anterior ones. The root insertion takes place on the vertical part of the spinal cord's lateral walls; the anterior roots are unique and the posterior ones multiple, formed by axial thin wires, from 4 to 8, vertically positioned.

Spinal ganglia are usually located in correspondence of the intervertebral foramen; such a topographical relation enables to identify them through CT and MR imaging. Each spinal ganglion has its corresponding anterior root in the front, before the anterior root merges its fibres into the sensory ones, forming the mixed spinal nerve (Fig. 2.10). This nerve, originated from the merger of the anterior and the posterior spinal roots, when exiting the foramen, splits into the anterior and posterior ramifications. In the sacral region, the spinal ganglia are contained in the radicular canals. In the neural foramen, along with the roots and the spinal ganglion, there are adipose tissues and epidural veins. The relative freedom of roots and nerves at the level of the intervertebral foramina allows the myelin-radicular complex adaptation to the dynamics of the spine.

2.1.8 Vascularisation

The blood supply to the spinal cord is carried out by a wide anterior spinal artery, vascularising 1/3–4/5 of the anterior spinal cord, and by two small posterior spinal arteries, supplying the remaining part. The posterior and anterior spinal arteries are asymmetrically and irregularly supplied, with few connections among them, by the medullary ramifications of the radicular-medullary arteries, originating from the vertebral, intercostal, and lumbar artery. At the cranial base, the medullary ramifications of the vertebral intracranial arteries merge into the anterior spinal artery. An additional artery supply is observed in correspondence of other two or three cervical levels. The superior thoracic spinal cord, until the fourth thoracic vertebra (T4), is vascularised. The artery supply, prevailing in the lombothoracic region, consists of the arteria radicularis magna, or the artery of Adamkiewicz, originating from the intercostal arteries and ramifications of the thoracic aorta, usually between T9 and L2, on the left (in 88 % of cases), but it is variable (Fig. 2.11). It determines a typical curve when forming the anterior ascending, or descending, spinal artery.

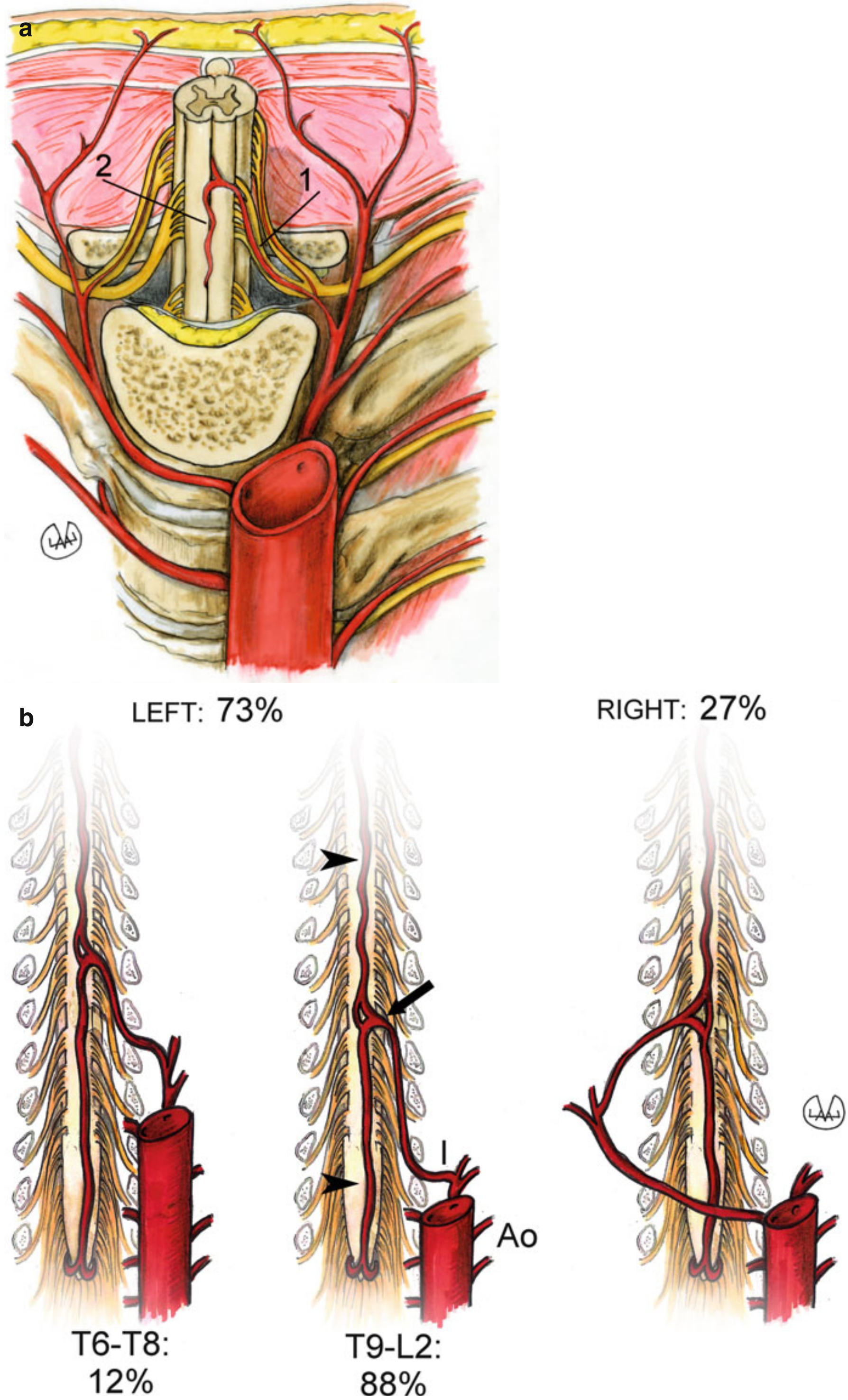

Fig. 2.11 (**a**) Anatomy of the arterial vascularisation of the spinal cord. Radicular artery (*1*) and anterior spinal artery (*2*). (**b**) Representation of the possible origins of the artery of Adamkiewicz (arteria radicularis magna): generally from the intercostal arteries (*I*), ramification of the thoracic aorta (*Ao*), on the left side, between T9 and L2 (88 %). Typical "curve" (*arrow*) of the artery of Adamkiewicz forming the anterior spinal artery (*arrowheads*)

The venous system roughly reflects the arterious system, with multiple medullary veins, draining into the pial veins and communicating with the major posterior spinal vein and the smaller anterior spinal ones. The radicular veins, along the nervous roots at different levels, drain the pial veins in the vertebral internal venous plexus, located in the epidural space and surrounded by adipose tissue. The internal vertebral venous plexus goes into the external one through the basilovertebral vein or the epidural longitudinal anterior veins, draining through the foramen. The venous external vertebral plexus empties into the azygos system.

2.2 Imaging Normal Anatomy

The spinal imaging is difficult to perform. Contrary to the cranium, characterised by a fairly regular volume and composition of the tissues, the column presents a higher degree of interindividual variability. Different diagnostic techniques are available, and they complete each other in the clinical practice.

2.2.1 Conventional Radiology

The conventional radiology (CR) is still considered the first choice for the examination of the spine. The lateral, frontal, and oblique projections allows the precise examination of the bone structures, the articular surface morphology, and the posterior alignment of the vertebral wall in kyphosis and lordosis. The CR accurately shows the bones' normal anatomy and allows to perform dynamic studies but does not allow the examination of the spinal cord, the intervertebral disc and the cartilage, or the capsular ligamentous complex.

2.2.1.1 General Features

Vertebral Body

The size increases from the bottom to the top; in the quadrilateral shape, we can clearly distinguish the superior and inferior vertebral plates, flat and slightly concave, from the anterior and posterior margins. The borders are composed of cortical bone, delimiting the trabecular or spongy part, less evident in the anterior part of the body, which is more delicate and subject to traumatic events. Between the vertebral plates, we find the intervertebral disc, not visible through CR.

Posterior Arch

Pedicle: the posterior body arch connection; the superior margin is slightly indented, while the inferior one is clearly concave; the pedicles of adjacent vertebrae surround the neural foramina.

Pars interarticularis and superior or inferior articular processes: bilateral in each vertebra; the superior process articulates through a facet, with the inferior facet of the above vertebra and vice versa; facets have a different morphology in the various tracts of the rachis.

Isthmus: the part between the superior and inferior articular processes.

Transverse process: with different variables in the different tracts of the spine, laterally projected from the pars interarticularis, almost horizontally.

Lamina: the portion of the arch after the transverse process that joins the contralateral lamina towards the median line.

Spinous process: median and uneven, of different amplitude and orientation in the various tracts of the rachis, it closes the vertebral arch on the back.

Between the posterior arch and the vertebral body, there is the vertebral foramen; the series of vertebral foramina, in articulating vertebrae, forms the spinal canal, which is not directly detectable through conventional radiography.

2.2.1.2 Special Features

The vertebral radiographic morphology, as generally described herein above, sensibly changes in the various spine tracts.

Cervical Rachis

The first, second, and last of the seven cervical vertebrae have peculiar characteristics.

The first cervical vertebra, or the atlas, connected to the cranial base, is wider than the other ones; it is devoid of the vertebral body, replaced

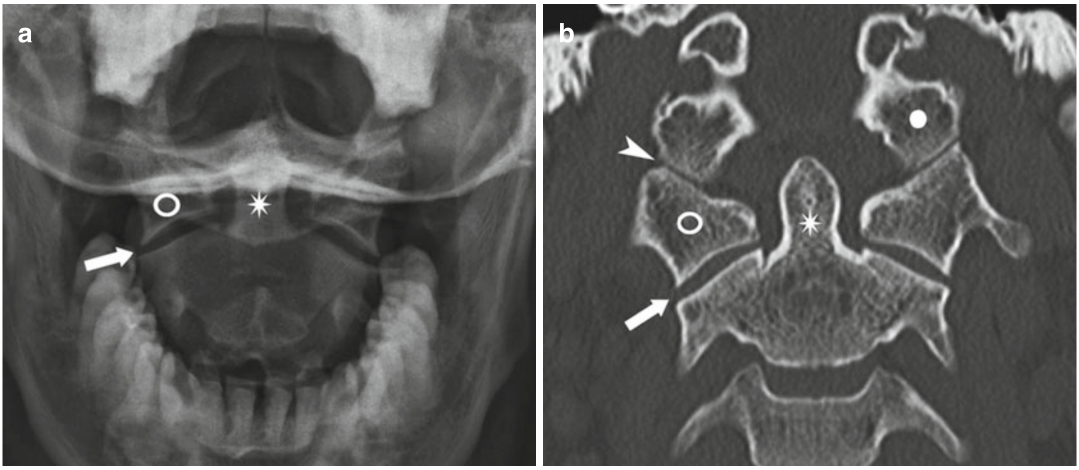

Fig. 2.12 Cranio-vertebral junction (**a**) AP radiography for the examination of the dens of the epistropheus. (**b**) CT coronal reconstruction with bone algorithm, high resolution: atlantooccipital joint (*arrowhead*), atlas-epistropheus joint (*arrow*). Atlas (*ring*), occipital condyle (*circle*), and odontoid process of the epistropheus (*star*)

by the anterior arch, and of the spinous process, replaced by a tubercle (spinous tubercle). Instead, C1 features two lateral masses united by an anterior and a posterior vertebral arch.

The second cervical vertebra, or epistropheus, differs from the other cervical vertebrae for the presence, in the superior side of the body, of a conoid process going upwards, the epistropheus dens or odontoid process that reaches the posterior face of the atlas anterior arch to form the medial atlantoaxial joint (Fig. 2.12).

The last cervical vertebra is similar to the thoracic vertebra; this is the reason why the following radiographic description refers to the central cervical vertebrae.

The vertebral body is small; at the level of the superior plate, there are uncinate processes articulating with the above vertebra. The spinous process is poorly developed, slightly tilted (the grade increases in the last vertebrae); it ends in the two separate tubercles. The superior articular processes are oriented upwards and backwards; the inferior ones, downwards and towards the front (Fig. 2.13).

In addition to the above-mentioned radiographic aspects, the cervical vertebrae differ from the other ones for the following characteristics, documented in CT and MRI: the transverse processes terminate in two tubercles, the anterior and posterior ones, and originate from a wide root with the central transverse foramen, in which we find the vertebral artery and vein.

The vertebral foramen has a triangle shape.

Thoracic Spine

We the exception of the transitional vertebrae (the first and the last three ones), the other eight thoracic vertebrae can be discriminated for their more voluminous body, in comparison with the cervical vertebrae, devoid of uncinate process and characterised by an articular facet for the costal head. The transverse processes are well developed and robust, with a facet for the articulation of the rib tubercles. The articular processes have vertical facets, the superior ones orientated towards the back and the inferior ones towards the front. The laminae are higher, connected through a spinous process, well developed and progressively more oblique up to the ninth vertebra and getting horizontal again in the last vertebrae (Fig. 2.14).

Lumbar Spine

The vertebral body is more voluminous and the transverse diameter is clearly wider. The major distinctive character is the presence of a rib-like process, originating from the pars interarticularis, with oblique orientation outwards, and corresponding to the merger of the outline of the transverse process with rib rudiment. The articular processes are vertically located, with the superior articular concave facet looking towards the medial and posterior direction, while the inferior one, convex, towards the front and the side. The spinous process is thick, short, and horizontal (Fig. 2.15).

Sacrum-Coccyx

The lateral projection clearly shows the convex posterior facet and the concave anterior one. The anterior-posterior projection shows the four pairs of the sacral foramina, leading into the sacral canal, homologous to the spinal canal. Besides the first two sacral foramina, the pars interarticularis develops into the so-called sacral wings. The coccyx, typically formed by the fusion of four or five rudimentary vertebrae, is more visible in latero-lateral projection (Fig. 2.16).

2.2.2 Computed Tomography

With regard to CT imaging, the need to reduce the patient radiation exposure suggests to perform specific studies on single spine segments. However, the modern multidetector CT, thanks to specific improvements such as the "care dose", allows to regulate the radiation exposure (mAs

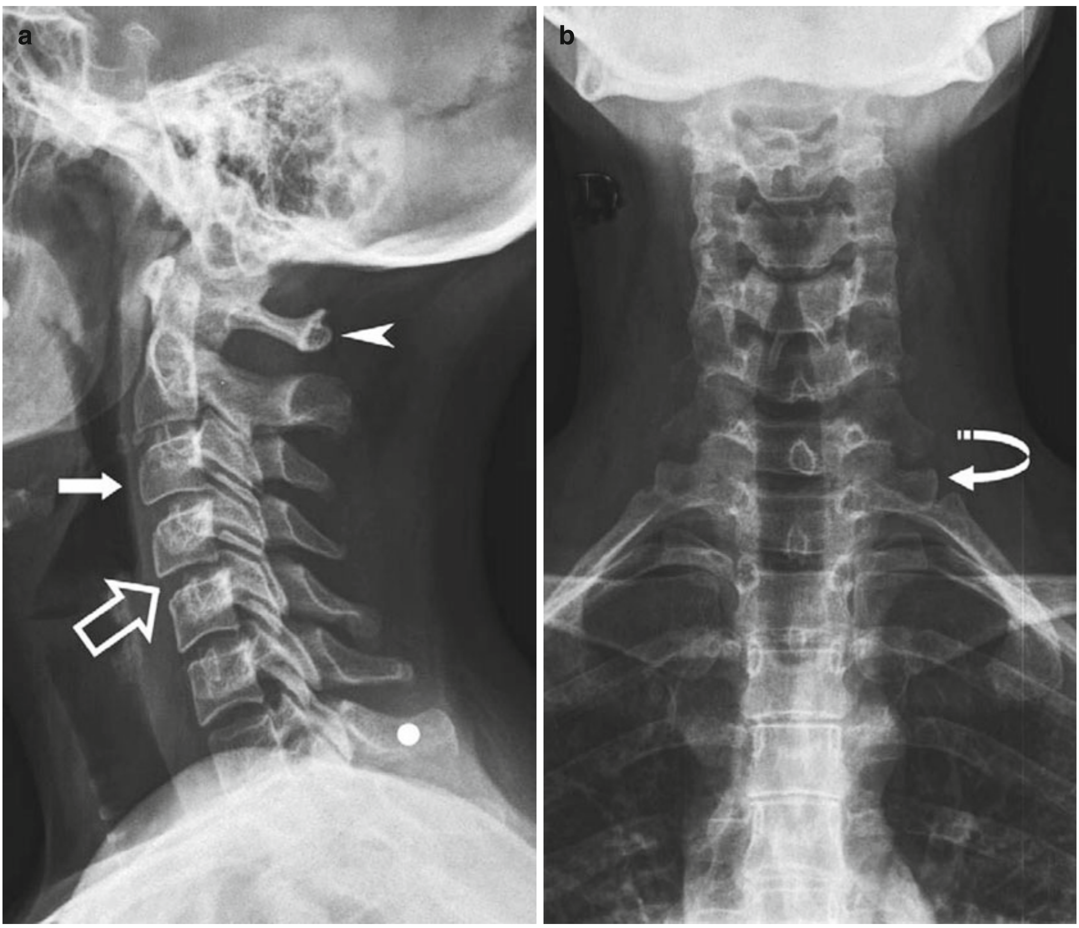

Fig. 2.13 Cervical spine X-ray in AP (**a**), LL (**b**), OAD (**c**), and OAS (**d**) projections. C7 spinous apophysis (*circle*), posterior atlas arch (*arrowhead*), left costotransverse articulation of T1 (*curved arrow*), C3 vertebral body (*arrow*), intervertebral foramina (*stars*), and C4–C5 intervertebral space (*empty arrow*)

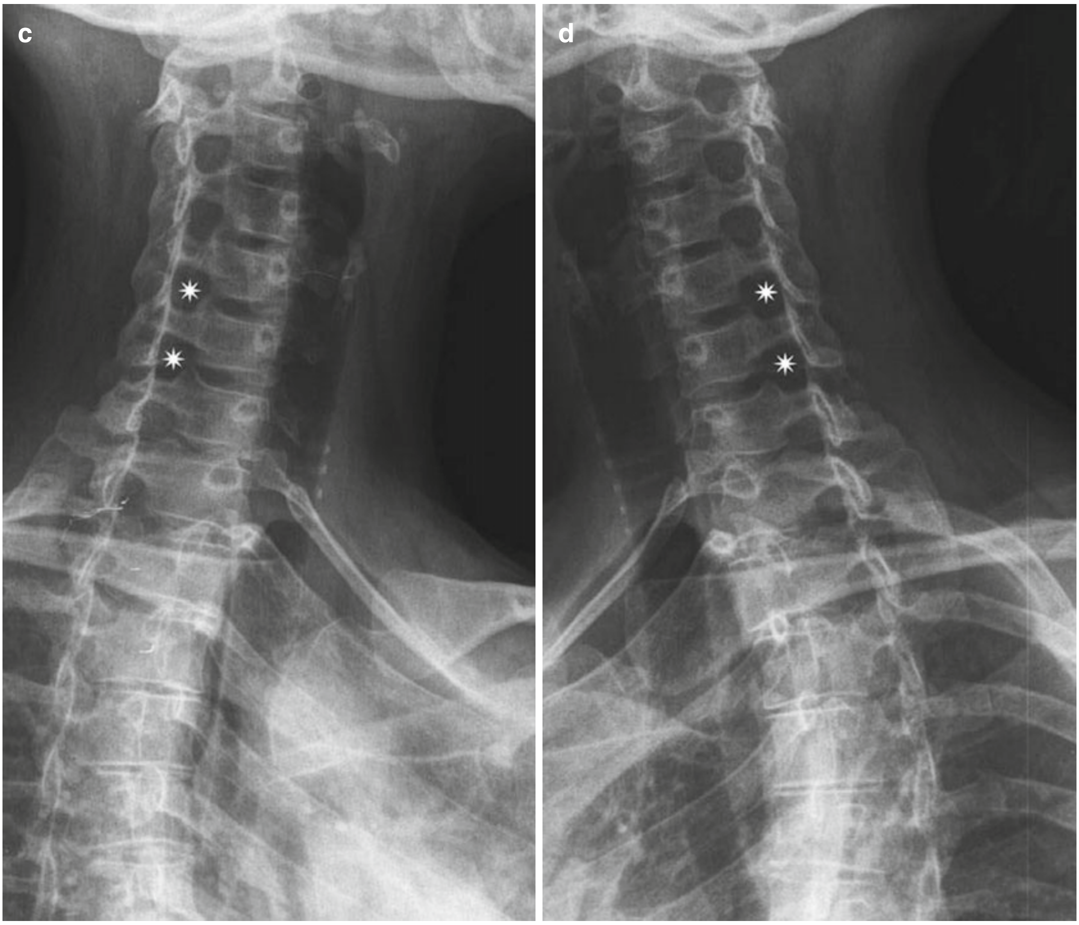

Fig. 2.13 (continued)

and kVp), according to the density of the target tissues and to the patient size, enabling, in a short period of time (a few second will suffice), panoramic examinations and multiple plane reconstructions, decreasing the exposure without penalising the quality of the diagnosis.

CT shows that the vertebral bodies contain thin bone trabeculae in the medullary space, surrounded by the well-visible cortical bone. In the pedicles and the transverse processes, the cortical part is more evident, and the sponge content is less voluminous. The laminae and the spinous processes of the cervical and thoracic spine contain spongy bone, while in the lumbar region, we can usually observe single bone plaques. The articular surfaces of the dense and smooth facets are generally biconvex in the cervical rachis, and they are instead flat in the thoracic and lumbar regions (Fig. 2.17). The intervertebral discs, such as the other soft tissues, are homogeneous (50–100 UH), and the annulus fibrosus cannot be distinguished from the nucleus pulposus. The yellow ligament, with density similar to the soft tissues, connects the interlaminar spaces (Figs. 2.18 and 2.19). In the lumbar rachis, the yellow ligament is normally 3.5 mm large, and it is considered thickened if larger than 5.5 mm. The posterior longitudinal ligament is contained in the anterior epidural space together with fat and vessels. The adipose tissue is contained in the lateral recess which, in the lumbar region, is delimited by the vertebral bodies; in the front and laterally, the pedicles; and behind, the articular superior facets; they are normally 3–5 mm in size; if shorter than 3 mm, they are considered stenotic.

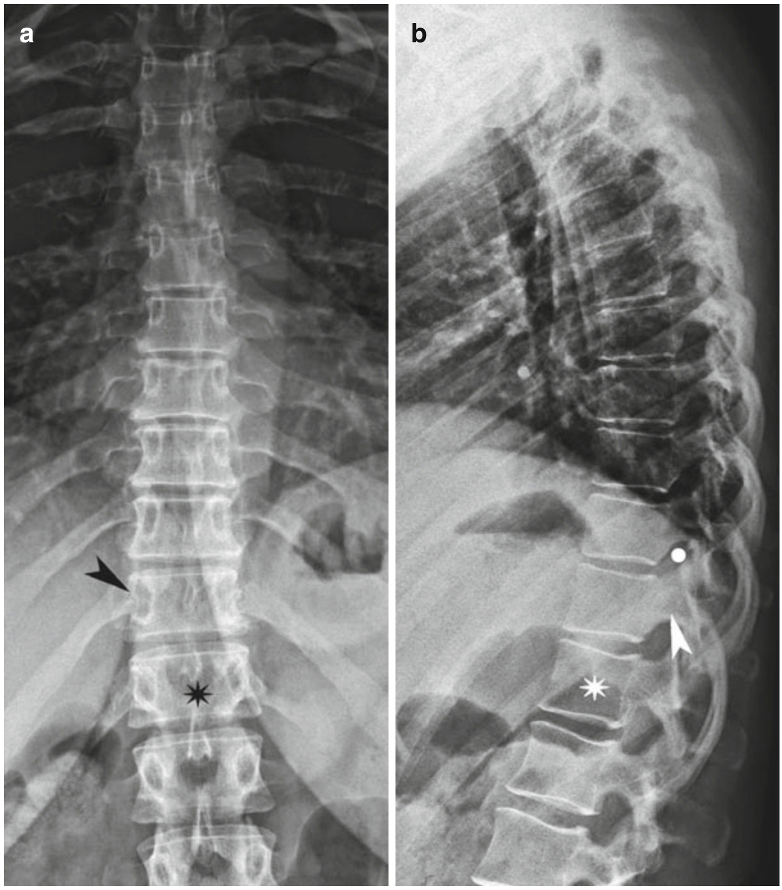

Fig. 2.14 Thoracic spine X-ray in AP (**a**) and LL projections (**b**). Vertebral T12 body (*star*) with rib hypoplasia; T10–T11 intervertebral foramina (*circle*); T11 right peduncle (*arrowhead*)

2.2.3 Magnetic Resonance Imaging

Only with MRI, we can directly display the spinal cord, with a fairly good image resolution. For the length of the spinal column, its posterior position, and the small size of the content of the spinal canal, we need to use specific superficial coils that increase the signal-noise ratio, while for the spatial resolution, we need to use smaller fields of view (from 16 to 24 cm); for the spinal cord approximately 1 cm diameter and nerve roots 1 mm or less, we need to use an excellent spatial and contrast resolution.

For the complete examination of the spinal column, we need to use a multicoil technology that combines the signals coming from different superficial coils located on the axes of the column. The newer reconstruction software have further enhanced the capacity of fast examination of the whole vertebral axes, combining separated series of high-resolution data into a single image (Fig. 2.20).

MRI shows the vertebral end plates as a thin hypointense stripe, both in T1 and T2 sequences, weighted according to their structure: cortical bone, with a low level of proton density, covered with cartilage (Fig. 2.21). The intensity of the signal of the spongy tissue of the vertebral bodies depends on the quantity and type of bone marrow contained. Normally, the relation between the red and the yellow marrow is good, but with advancing age, the yellow marrow increases, producing a high-intensity signal on T1 spin-echo (SE) sequences and T2 fast spin-echo (FSE) sequences. However, in the bone marrow, we can observe, at any age, spot images showing the lack of “red” marrow; such a finding shall not be considered pathological (Fig. 2.22).

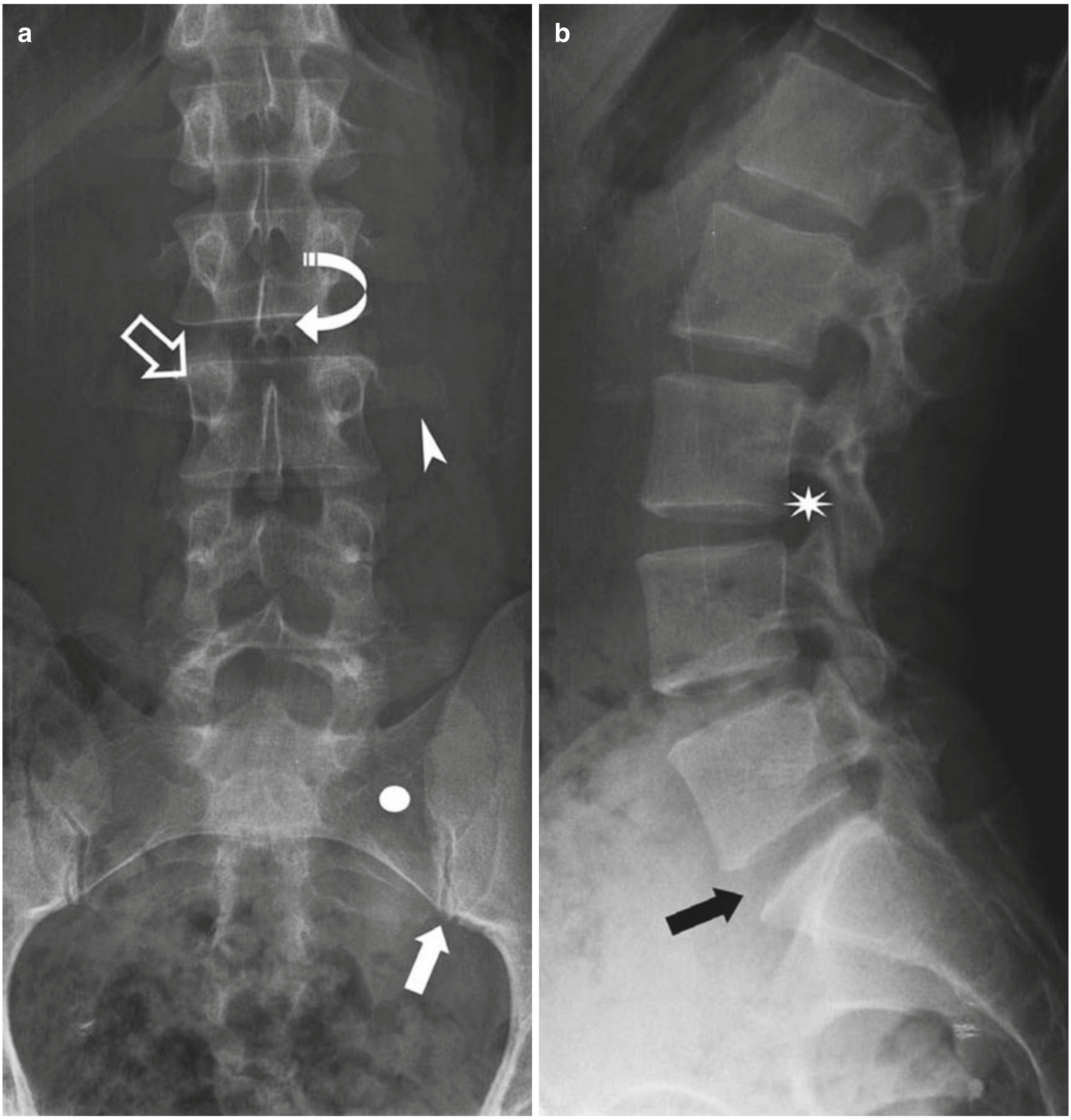

Fig. 2.15 Lumbar spine X-ray in AP (**a**) and LL (**b**) projections. (**a**) left sacral ala (*circle*), L2 spinous apophysis (*curved arrow*), L3 left transverse process (*arrowhead*), L3 pedicle (*empty arrow*), and sacroiliac synchondrosis (*arrow*). (**b**) Neural foramina of L4–L4(*star*) and intervertebral space of L5–S1 (*black arrow*)

In spin-echo (SE) imaging, or gradient-echo (GE) T2-weighted sequences, the vertebral bodies show low signal intensity; however, the signal intensity is intermediate or high on fast spin-echo (FSE) sequences which are used more frequently for their superior imaging quality, associated with reduced examination time. After radiotherapy, the vertebral bodies become hyperintense in T1 sequences because the adipose tissue substitutes the elements of the bone marrow. The normal bone marrow shows homogeneous enhancement after gadolinium intravenous administration. The articular cartilage enveloping the interapophyseal joints usually presents a low signal in T1- and T2-weighted sequences, and it is difficult to distinguish from the cortical bone; however, it shows an increase in signal in GE sequences.

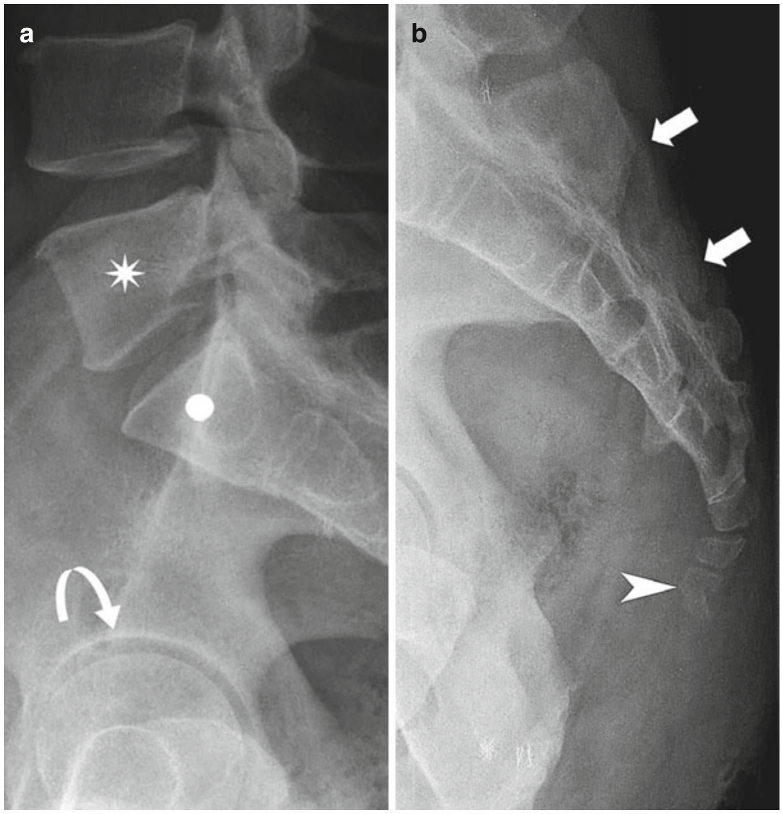

Fig. 2.16 Sacral (**a**) promontory and coccyx (**b**) X-ray in LL projection. Coccyx (*arrowhead*), sacral crest (*arrows*), L5 body (*star*), and S1 body (*circle*). The *curve arrow* shows the acetabular roof and the coxofemoral joint

MRI of the intervertebral discs reflects the water contained therein; normally, the signal intensity is lower in T1-weighted sequences and higher in T2-weighted sequences (Fig. 2.23). The annulus fibrosus appears as a peripheral stripe and thin and with low signal intensity in all sequences; the nucleus pulposus shows a higher signal intensity, horizontally crossed by a dark line which probably represents the normal intranuclear cleft that can be observed in more than 94 % of the patients older than 30. With advancing age, the fluid content of the annulus fibrosus and of the nucleus pulposus progressively decreases, and therefore, the signal intensity of disc on T2 sequences also reduces, for dehydration and degeneration process.

The ligaments, except for the yellow one, have low signal intensity, similar to the bone, in all sequences because the content has high collagen levels; they imperceptibly merge into the cortical bone, with the more external fibres of the annulus fibrosus and the dura mater. The yellow ligament has intermediate signal intensity in T1- and T2-weighted sequences and higher in GE sequences, especially for its biochemical composition represented by 20 % of collagen and 80 % of elastin.

The spinal cord has intermediate intensity signal on T1-weighted sequences and low intensity signal on T2-weighted and GE sequences (Fig. 2.24); in high-resolution examinations, performed with high-field, GE, and T2-weighted sequences, we can identify the internal architecture. This is especially significant in axial images, where you find an H-shaped region, corresponding to the central grey matter, with a slightly higher signal than the white matter cordons. The difference between the white and grey matter is due to three factors: different fluid content, the presence/lack of myelin, and, therefore, different relaxation times. Such elements are not visible in SE T2-weighted sequences, where the spinal cord has an even, intermediate signal.

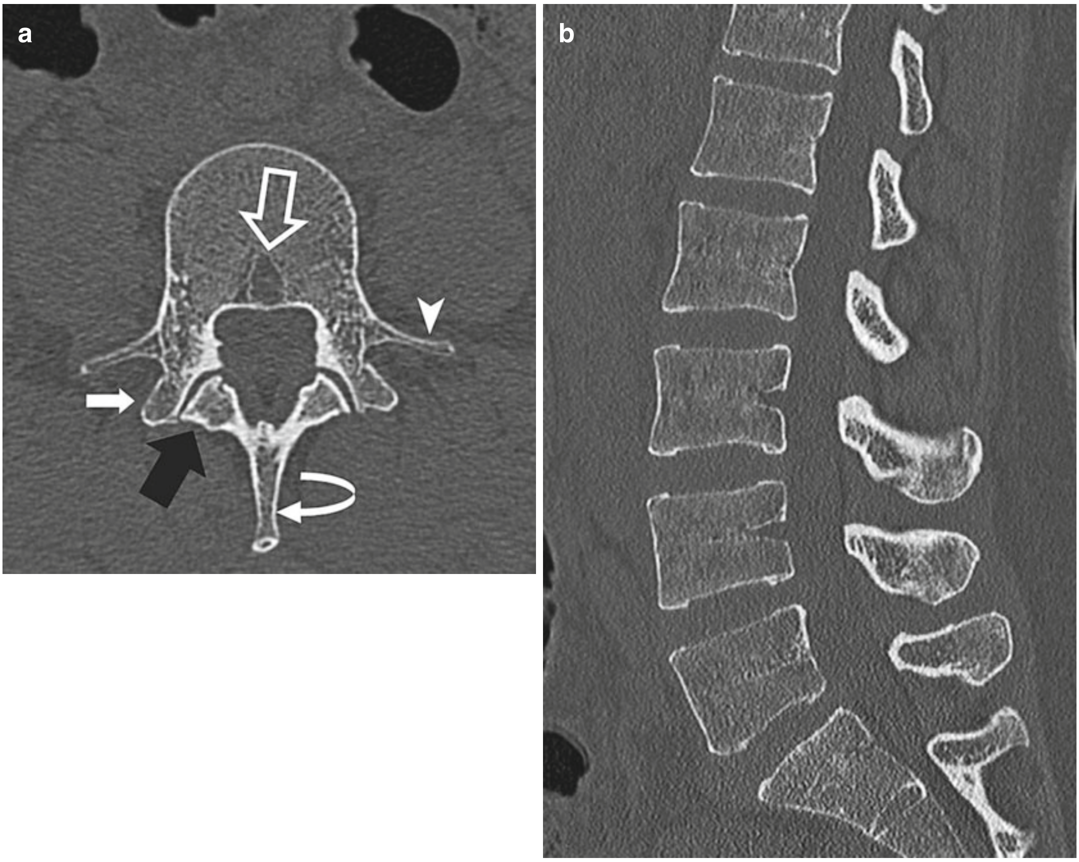

Fig. 2.17 Lumbar spine, CT with bone algorithm. (**a**) Axial section. (**b**) MPR sagittal reconstruction. L3 spinous apophysis (*curved arrow*), vascular foramen (*empty arrow*), spinous apophysis (*arched arrow*), L3 inferior articular process (*arrow*) and the superior one di L4 (*black arrow*) with the relevant joint, rib-like process (*arrowhead*)

Also the single roots and nerve radicles can be seen through high-resolution imaging with high-field MRI system.

With all heavy T2-weighted sequences, acquired with longer repetition times, we can have similar myelographic patterns that highlight the hyperintense cerebrospinal fluid (Fig. 2.25). With FSE sequences, the fluid may be confused with the adjacent structures, containing fat, and it is therefore important to suppress the adipose tissue using specific techniques.

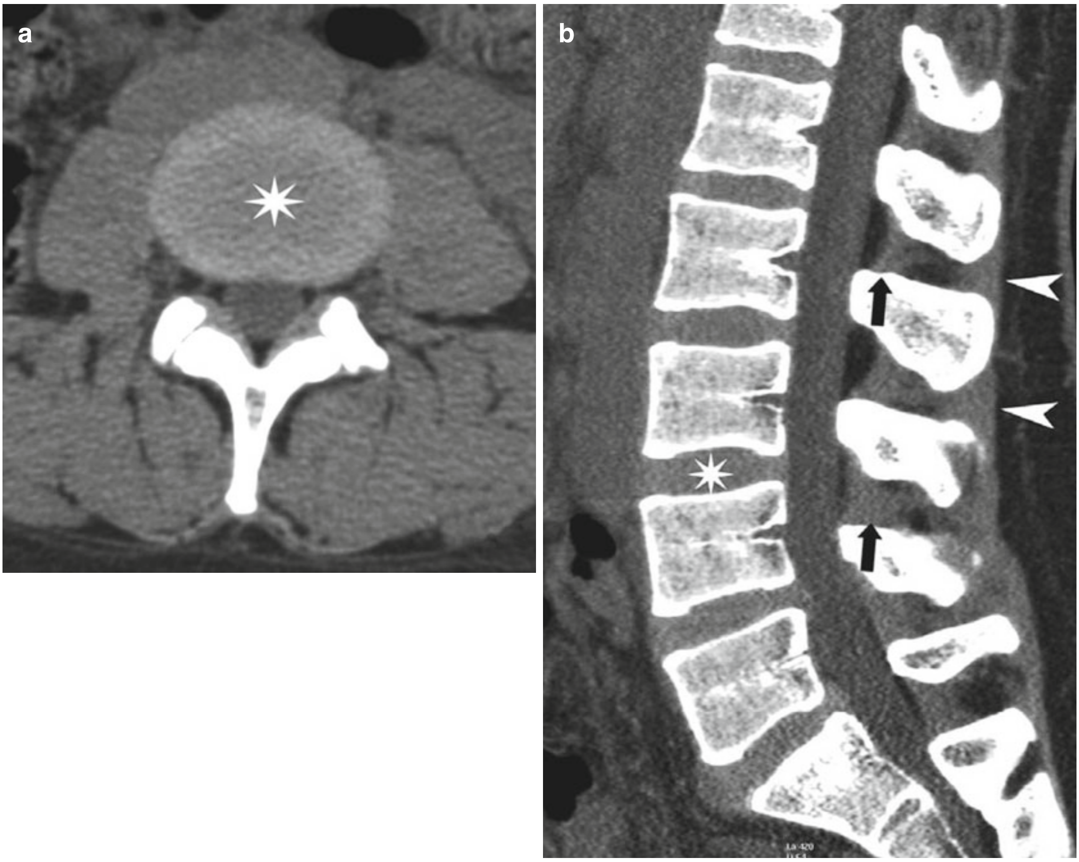

Fig. 2.18 Lumbar spine, CT examination with soft tissue window. (**a**) Axial section. (**b**) MPR sagittal reconstruction. The *star* shows L3–L4 intervertebral disc. The interspinous ligaments are clearly visible (*arrow*) and so are the supraspinous ones (*arrowhead*)

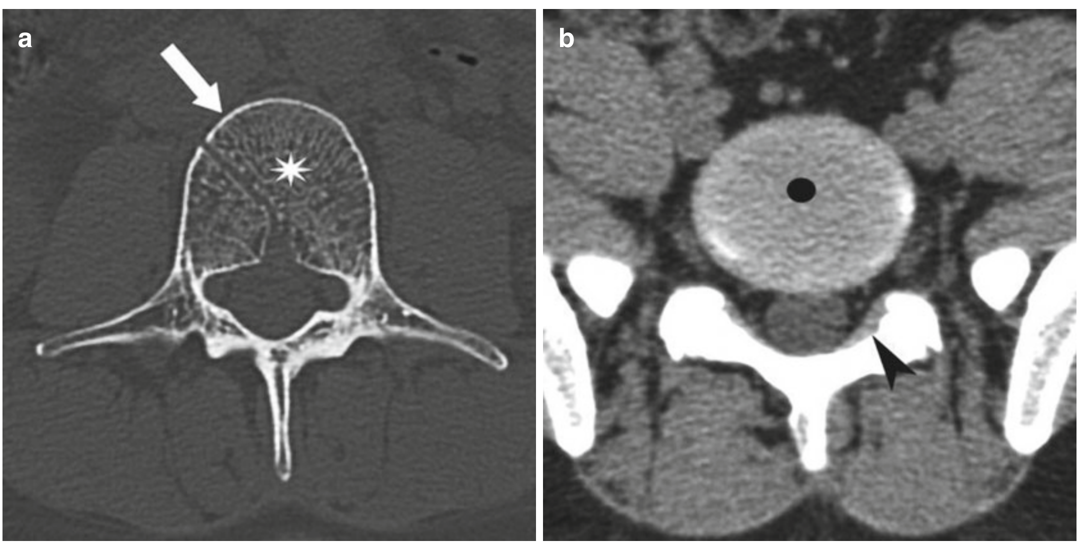

Fig. 2.19 Lumbar rachis CT, with bone algorithm (**a**) and soft tissue window (**b**). The cortical bone (*arrow*), thin, dense, and regular, containing the less dense spongy part (*star*). The intervertebral disc (*circle*) and the yellow ligaments (*arrowhead*) are homogeneous, and their density is similar to the soft tissues

Fig. 2.20 Sagittal MRI TSE T2-weighted (**a**) and T1-weighted (**b**) images "combined" for an overall view of the rachis

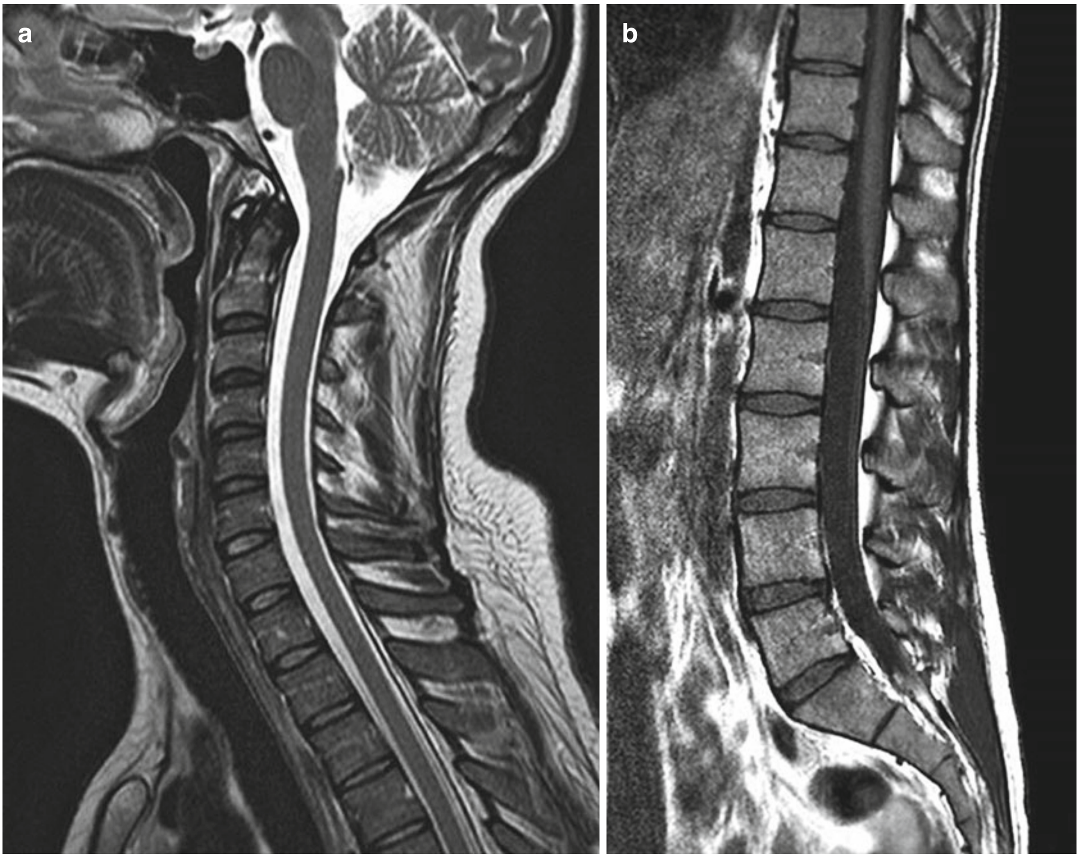

Fig. 2.21 MRI, sagittal TSE T2-weighted (**a**) and T1-weighted images (**b**), respectively, of the cervical rachis and lumbar rachis. The vertebral cortical bone is hypointense in both the sequences. Thanks to high resolution, we are able to clearly display the spinal cord (slightly hyperintense in T2, intermediate in T1)

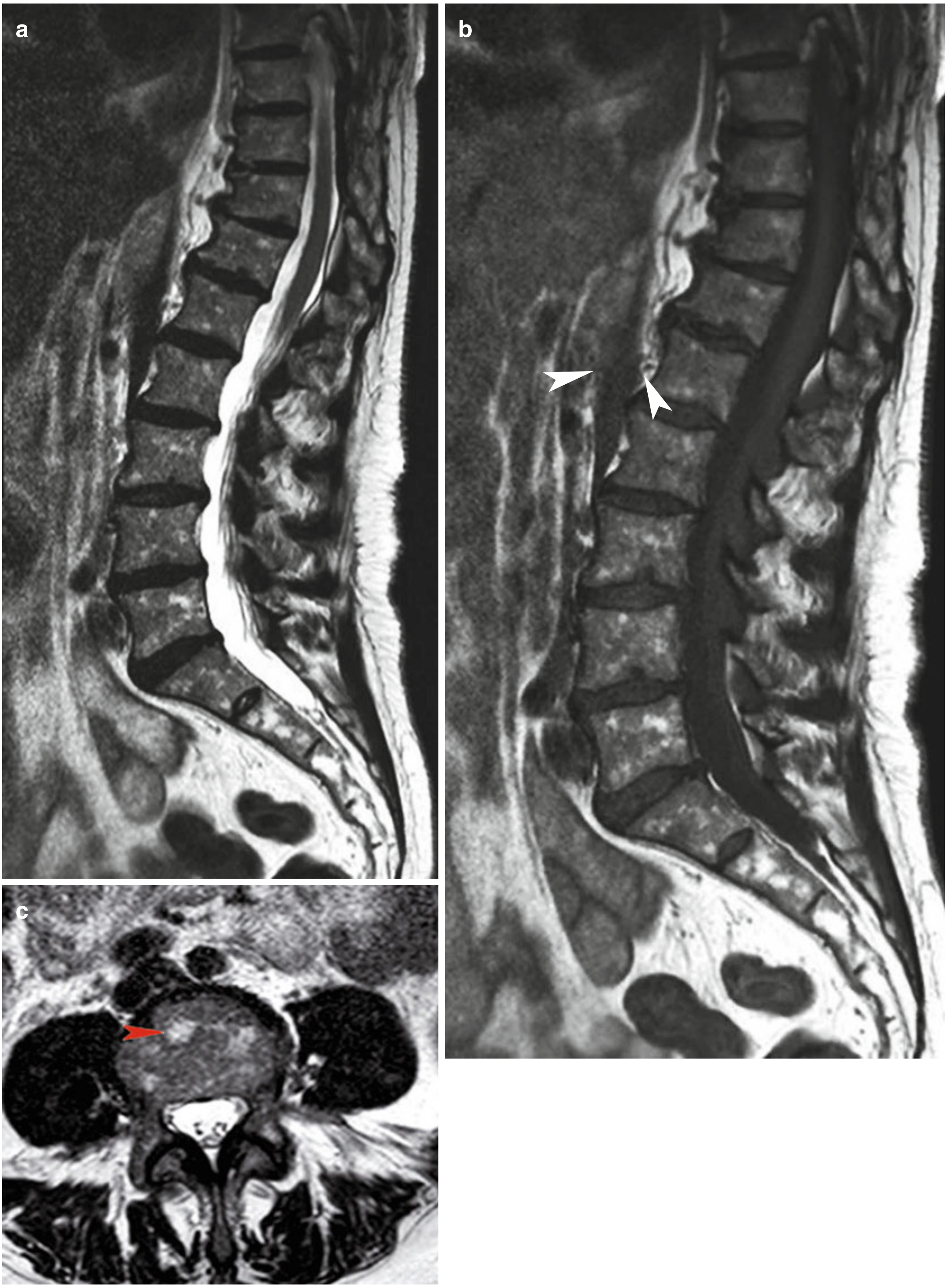

Fig. 2.22 Lumbar sagittal MRI, sagittal TSE T2-weighted (**a**) and T1-weighted (**b**), and axial T2-weighted images (**c**). Adipose degeneration of the haematopoietic bone marrow with multiple fatty nodules (*arrowhead*), hyperintense in all the sequences; it is a paraphysiological finding (*red marrow reconversion*)

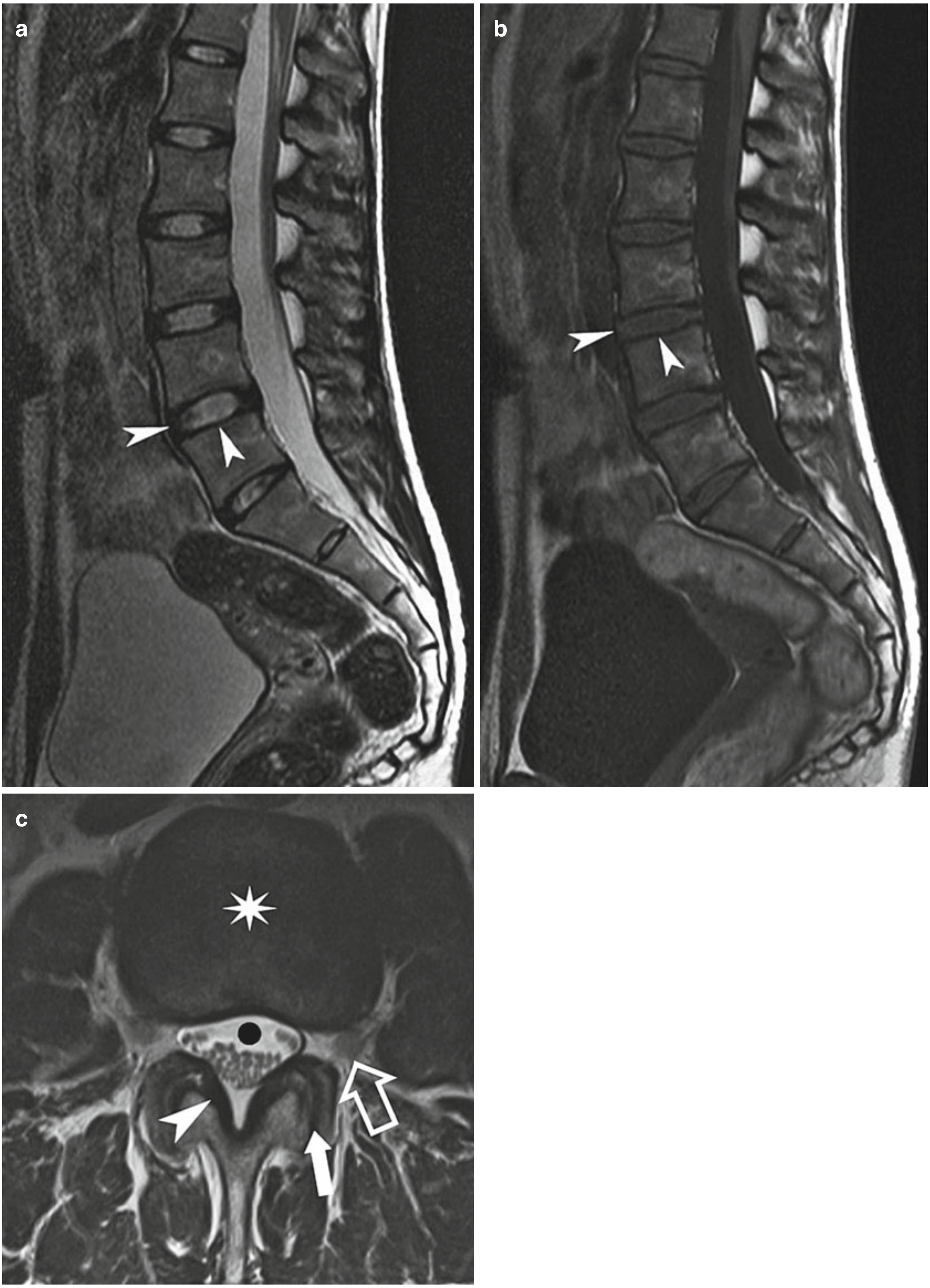

Fig. 2.23 Lumbar spine, MRI sagittal imaging, TSE T2-weighted (**a**) and T1-weighted (**b**) and axial T2-weighted images (**c**). On T2WI, the intervertebral discs are hyperintense and hypointense on T1WI in connection with their fluid content. The annulus fibrosus is hypointense in comparison with the nucleus pulposus (*arrowhead*). (**c**) Intervertebral disc (*star*), yellow ligament (*arrowhead*), interapophyseal joint (*arrow*), spinal ganglion (*empty arrow*), dural sac (*circle*), and cauda equina roots

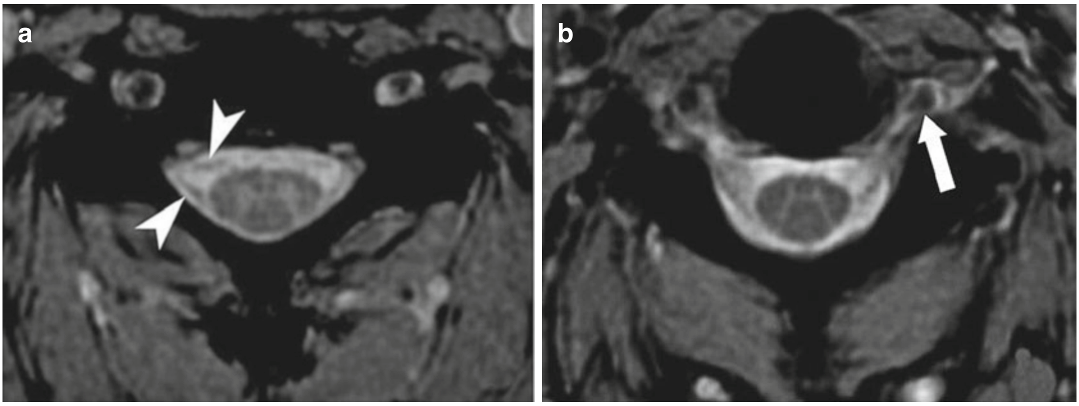

Fig. 2.24 Spinal cord axial MRI GE T2-weighted sequences. This is a good representation of the medullary anatomical structures: note the butterfly shape (**a**) or "H" shape (**b**) of the medullary grey matter. Anterior and posterior roots (*arrowheads*) and spinal ganglion (*arrow*)

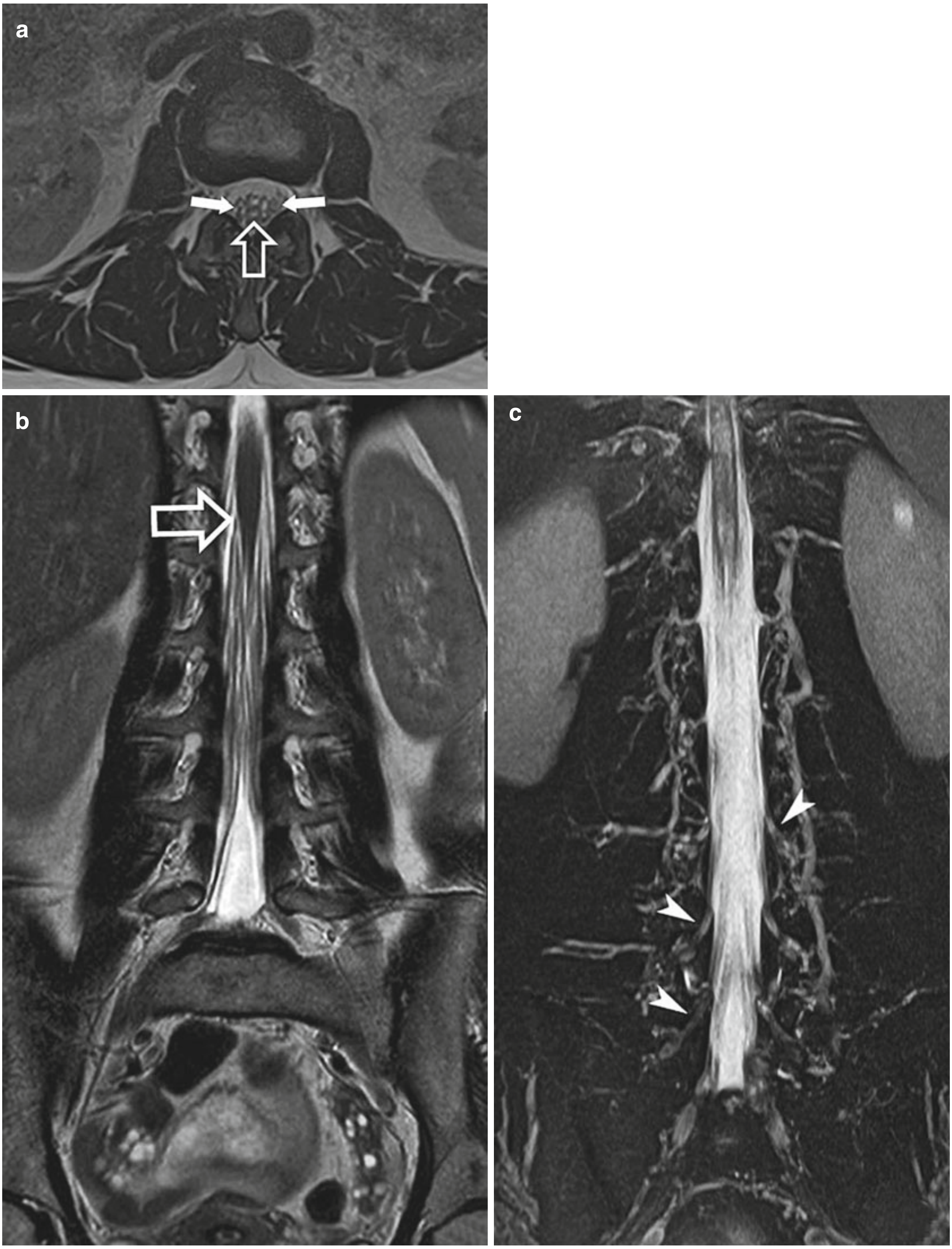

Fig. 2.25 Lumbar spine MRI, TSE T2-weighted, axial (**a**) and coronal (**b**), and coronal STIR images (**c**). The conus medullaris (*empty arrow*) is surrounded by the roots of the cauda equina (*arrows*) in the cerebrospinal fluid (hyperintense) inside the dural sac. (**c**) The spinal nerves (*arrowheads*) are depicted

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