Spinal Vascular Anatomy

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KEYWORDS

• Angiography • Vascular anatomy • Spinal arteries • Spinal veins • Spinal cord vascularization

KEY POINTS

- The vascularization of the spinal cord depends on the intersegmental artery and its derivates.
- Thoracic and lumbar ISA keep a primitive configuration between T3 and L4 (those are ISAs, not nerves).
- Intersegmental artery derivates include the vertebral artery (C1-C6), the supreme intercostal artery (C7–T1), and the sacral arteries (S1-S4).
- The spinal cord is supplied by a small number of constant radiculomedullary arteries, including the superior and inferior arteries of the cervical enlargement, the artery of von Haller, and the artery of Adamkiewicz.

THE SPINAL ARTERIAL SYSTEM

The Intersegmental Artery and Its Branches

Developmental anatomy

The primitive intersegmental arteries (ISAs) first emerge from the unfused primitive dorsal aortas at the 6-somite stage 1; 14 to 16 pairs of ISAs of aortic origin persist in adults (T2/T3 to L3/L4). The first 6 cervical ISAs combine with the proatlantal artery (ProA) to form the subclavian artery, the vertebral artery (VA), and the vertebrobasilar junction (**Fig. 1**). At the lumbosacral level, the aorta becomes the median sacral artery (MSA),[1] whereas the first 4 sacral ISAs form the lateral sacral arteries. Despite these variations, a typical intersegmental pattern that includes an aortic stem and 3 branches (spinal, lateral, and dorsal) remains identifiable at any level.

Primitive intersegmental loops run from one dorsal aorta to the ipsilateral posterior cardinal vein; their proximal and distal limbs differentiate into ISAs and veins. Rami sprouting from the arterial limb connect to homologous branches from adjoining ISAs to form a capillary plexus along the neural tube. The dorsal branches of the primitive aortas and their capillary plexuses form the primary elements of the ISA: the aortic stem and its spinal branch. The dorsal and lateral branches are secondary vessels appearing later (**Fig. 2**).[2]

The intersegmental ostia are well-aligned longitudinally but frequently asymmetric transversally. Lumbar and low thoracic ostia are close to the midline, mid and upper thoracic ostia deviate leftward, a trend that increases with age. The proximity of the low lumbar intersegmental ostia explains their tendency to form bilateral trunks.[3]

Paraspinal arterial anastomoses and unilateral intersegmental trunks

ISAs form a complex paraspinal arterial network. This network is an important source of collateral supply and takes part in the formation of unilateral intersegmental trunks, that is, stems branching off 2 or more ipsilateral ISAs, most commonly in the lower lumbar and upper thoracic regions. A complete unilateral trunk includes spinal, lateral, and dorsal branches for each involved ISA. An incomplete trunk often lacks its spinal and dorsal branches, which originate from the aorta as a separate vessel identified as an isolated dorsospinal artery.[4–7]

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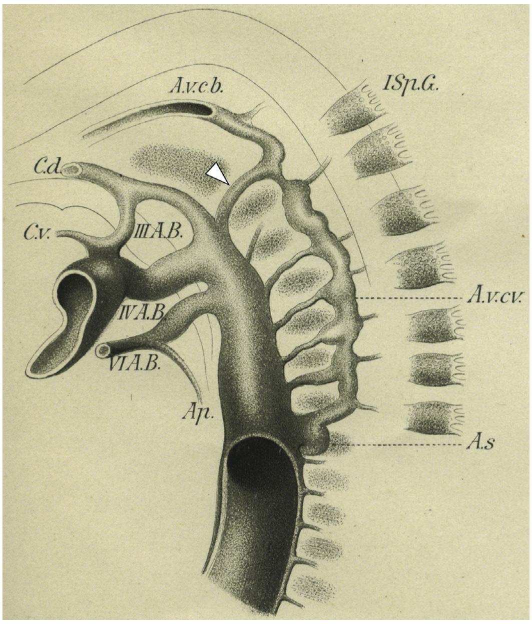

Fig. 1. Development of the VA in rabbits. The ProA (*arrowhead* added to original figure) and the subclavian artery (A.S) are interconnected by a succession of anastomoses linking the first 5 cervical ISAs (A.v.cv.). The ProA accompany the first cervical nerve,[11,82,83] whereas the subclavian artery is derived from the sixth cervical ISA.[84] Other depicted structures include the first cervical ganglion (I.Sp.G.), the internal carotid artery (C.d.), the external carotid artery (C.v.), the third, fourth and sixth aortic arches (III A.B., IV A.B., VI A.B.), the basilar artery (A.v.c.B.), and the pulmonary artery (A.p.). (*From* Hochstetter F. Uber die Entwicklung der A. Vertebralis beim Kaninchen, nebst Bemerkungen über die Entstehung des Ansa Vieussenii. *Morphol Jahrb.* 1890;16:572-586.)

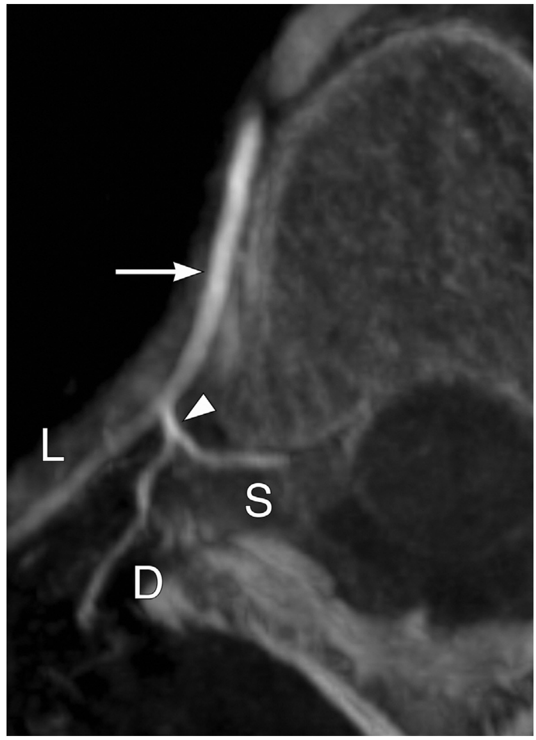

Fig. 2. The ISA. A typical ISA is made of an aortic stem (*arrow*) and 3 branches. The dorsal branch is essentially muscular; the name of the lateral branch varies by region (intercostal, subcostal, lumbar). A small trunk for the dorsal and spinal branches, the dorsospinal trunk (*arrowhead*), is formed when the lateral branch takes off proximally. D, dorsal; L, lateral; S, spinal. (© 2019 Philippe Gailloud.)

Locoregional modifications of the intersegmental pattern

The vertebral artery The ProA provides anterior and posterior radiculomedullary arteries (RMAs) that respectively become the distal VA and the vertebral root of the posterior spinal artery (PSA).[8–10] The distal VA divides into ascending and descending rami. The left and right ascending rami fuse over the midline to form the proximal basilar artery; the left and right descending rami converge medially to form the anterior spinal artery (ASA) (Fig. 3). The cervical VA consists of a succession of longitudinal anastomoses connecting the subclavian artery to the distal VA (Fig. 4).[11]

The site of origin of the VA depends on the primitive ISA forming its proximal segment; it is most often the sixth cervical ISA (ie, the subclavian artery), but any cervical or upper thoracic ISA can be involved. Persistent cervical ISAs are identified by their relation with the transverse canal: a persistent seventh cervical ISA always passes through the C7 transverse foramen but may originate from the supreme intercostal artery or from the aorta, distal to the left subclavian artery (Fig. 5). Persistent second cervical ISAs are extremely rare.[12,13] Persistent third, fourth, and particularly fifth cervical ISAs are more common, either in isolation or as part of a proximal VA duplication.

Thoracic VAs are divided into ascending and descending types.[14] In general, descending thoracic VAs form a trunk with a cervical VA.[15] Ascending thoracic VAs originate from a thoracic ISA and continue cranially as a cervical VA[16] (see Fig. 5). Injury to a thoracic VA supplying the posterior fossa can be catastrophic; an enlarged costotransverse space (T1, T2) may be the only warning sign on preoperative imaging.[14]

The supreme intercostal artery The supreme intercostal artery arises from the subclavian artery as an individual vessel or as a trunk with the deep cervical artery. It most often provides the seventh

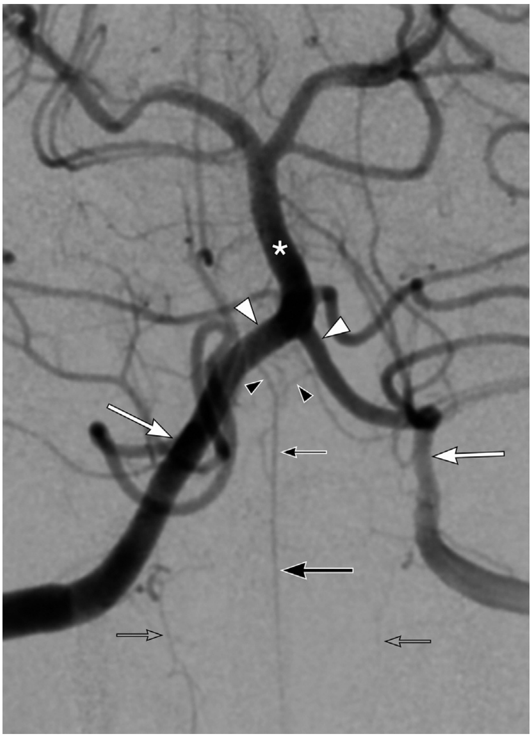

Fig. 3. The distal VA and the basilar artery. The distal VA (*large white arrows*) is formed by the anterior radiculomedullary branch of the ProA; it divides into ascending (*white arrowheads*) and descending (*black arrowheads*) rami. The basilar artery (*asterisk*) and the ASA (*large black arrow*) are formed by the fusion of these ascending and descending rami, respectively. The descending rami of the posterior radiculomedullary branch of the ProA form the posterior vertebrospinal trunks (*gray arrows*). The small black arrow indicates a focal ASA duplication. (© 2019 Philippe Gailloud.)

cervical and first thoracic ISAs[17] but can also branch off, in order of decreasing frequency, the second, third, and fourth thoracic ISAs.

The lumbosacral region The aorta continues below the iliac bifurcation as the MSA.[1] The MSA courses over the anterior aspect of the sacrum and occasionally provides a prominent renal or rectal branch.[18] There are 5 pairs of lumbar ISAs; the fifth pair arises from the MSA, as does the fourth pair when the iliac bifurcation is above L4 (Fig. 6). The diminutive L5 ISA is supplemented by the iliolumbar artery. The 4 sacral ISAs most commonly form 2 trunks, the superior S1 and inferior (S2, S3, S4) lateral sacral arteries.[19]

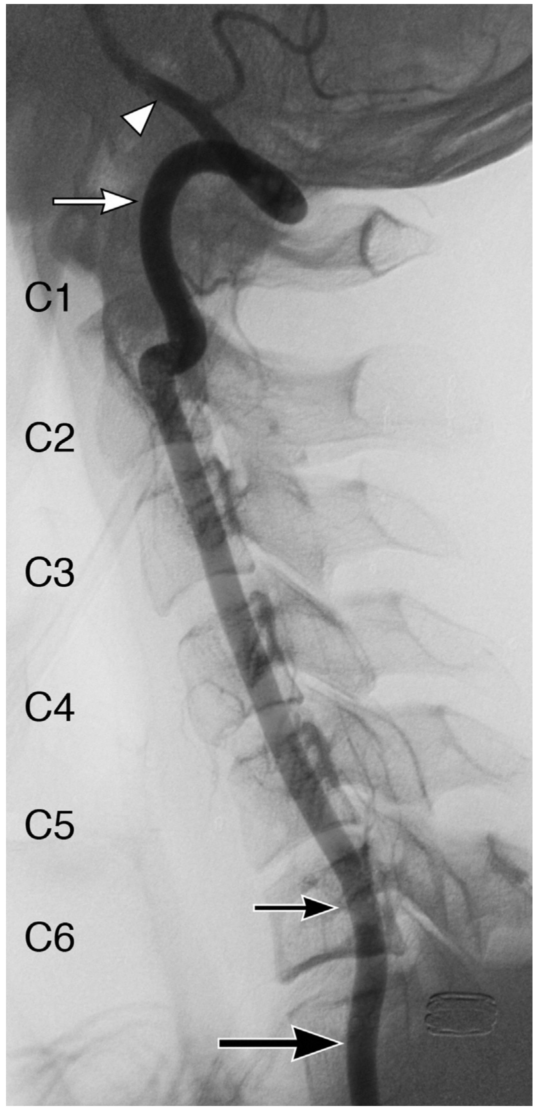

Fig. 4. The VA. The normal adult VA is a composite vessel consisting of 3 portions of different embryonic origin: a proximal segment made of a persistent sixth cervical ISA (*large arrow*), an intermediate segment formed by a chain of anastomoses established between the first 5 cervical ISAs, and a distal segment derived from the ProA. Seamless transitions connect the proximal and intermediate segments below the transverse foramen of C6 (*small black arrow*), and the intermediate and distal segments above the transverse foramen of C1 (*small white arrow*). The anterior radiculomedullary branch of the ProA is particularly prominent; it becomes the distal VA (*arrowhead*). (© 2019 Philippe Gailloud.)

The Spinal Division of the Intersegmental Artery

In its complete form, the spinal division of the ISA provides the retrocorporeal, radicular, and prelaminar arteries. The retrocorporeal artery has ascending and descending branches that pass beneath the posterior longitudinal ligament to connect with opposite and adjacent arteries, and form a diamond-shaped anastomotic network.[20,21] This

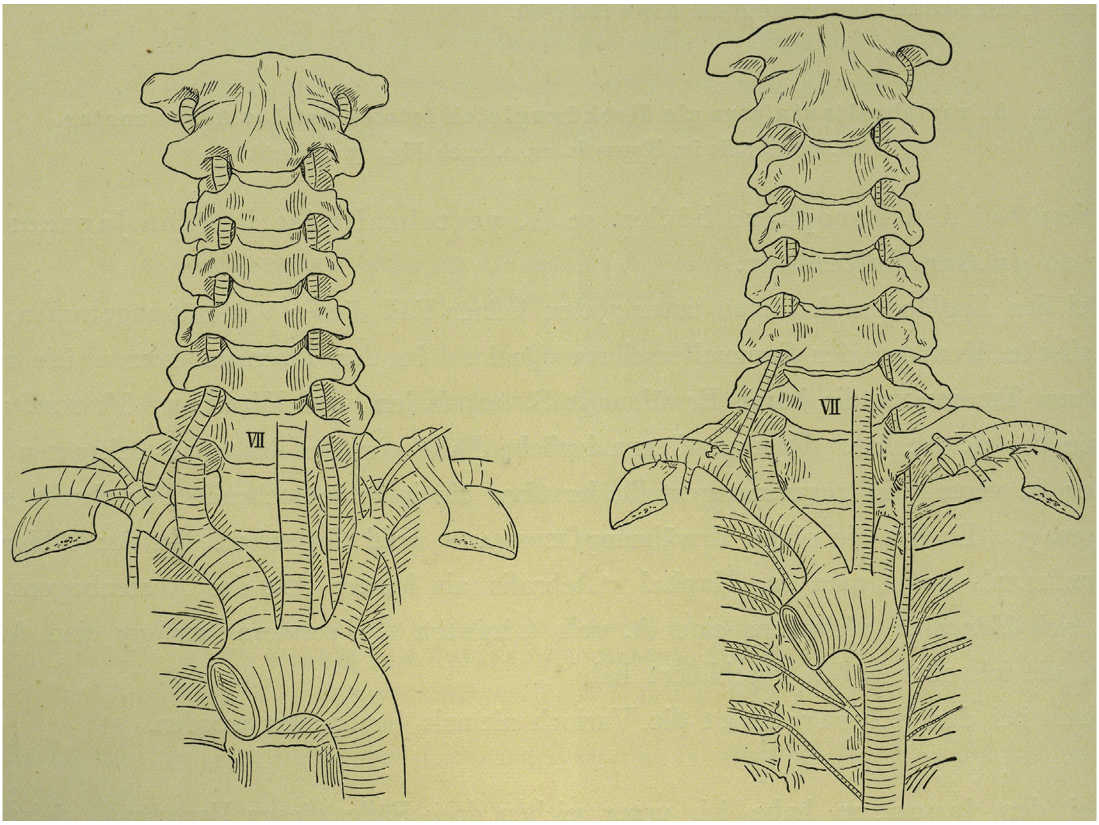

Fig. 5. Persistent cervical and thoracic ISA. (*Left*) A persistent left seventh cervical ISA takes off from the aorta distal to the subclavian artery; it is identified by its passage through the seventh transverse foramen. (*Right*) A persistent first thoracic ISA also takes off from the aorta distal to the subclavian artery; it is identified by its passage through the first costotransverse space. This variant is also known as a thoracic VA (ascending type). (*From* Adachi B. *Das Arteriensystem der Japaner.* Kyoto and Tokyo: Kaiserlich-japanische Universität zu Kyoto, in kommission bei "Maruzen Co."; 1928.)

network represents an important source of collateral supply; it is prominent in children but regresses with age (**Fig. 7**). The prelaminar arteries form a similar network over the anterior aspect of the posterior arch.

The Vertebral Body Vascularization

Anterolateral osseous branches

The anterolateral osseous arteries arise from the ISA stem and penetrate the periphery of the vertebral body. They are more numerous on the right because of the leftward deviation of the aorta.[22] Ascending and descending anterolateral branches connect with similar vessels from adjacent levels to form a periosteal network over the anterior and lateral aspects of the vertebral column.

Posteromedial osseous branches

One or 2 large posteromedial osseous arteries arise from the ascending branch of the retrocorporeal artery; they penetrate the vertebral body through the basivertebral foramen or, less often, through an accessory canal (see **Fig. 7**).[20,23]

The vascularization of the posterior arch

The posterior arch is supplied by the prelaminar artery and by the dorsal branch of the ISA, which sends small rami to the lamina, the posterior vertebral joint, and the spinous process. The dorsal branch also takes part in the formation of a complex arterial network within the paraspinal musculature.[24]

The prelaminar network provides a central artery that penetrates the base the spinous process, and bilateral laminar arteries that pierce the lamina and bifurcate into ascending and descending branches for the apophyseal joints. The posterior elements, less robustly supplied than the vertebral body, are more prone to ischemia during surgical procedures.[24]

The vascularization of C2

The vascularization of the odontoid process comes from the anterior and posterior ascending

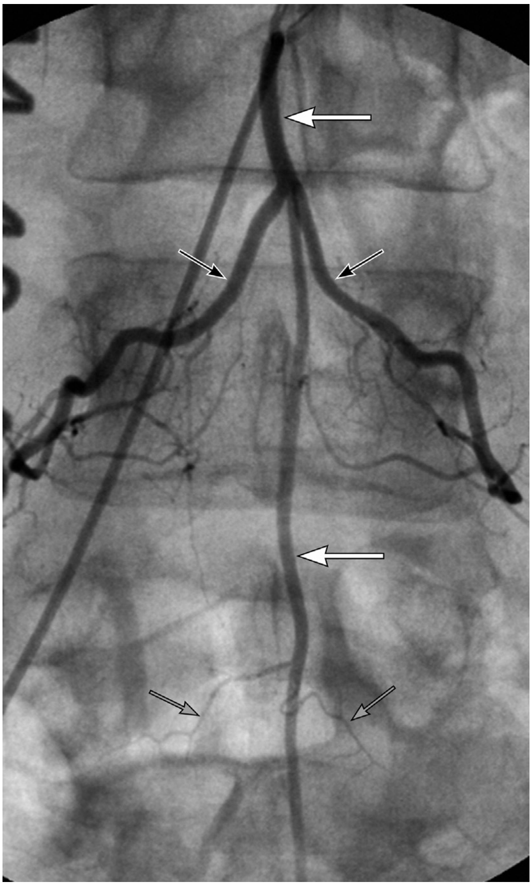

Fig. 6. Selective MSA angiography. The MSA is the continuation of the abdominal aorta: in this case, a prominent MSA (*white arrows*) provides the L4 (*black arrows*) and L5 (*gray arrows*) ISAs. Note the diminutive nature of the L5 ISAs, which share their territories with the iliolumbar arteries and L4 ISAs.[23] (© 2019 Philippe Gailloud.)

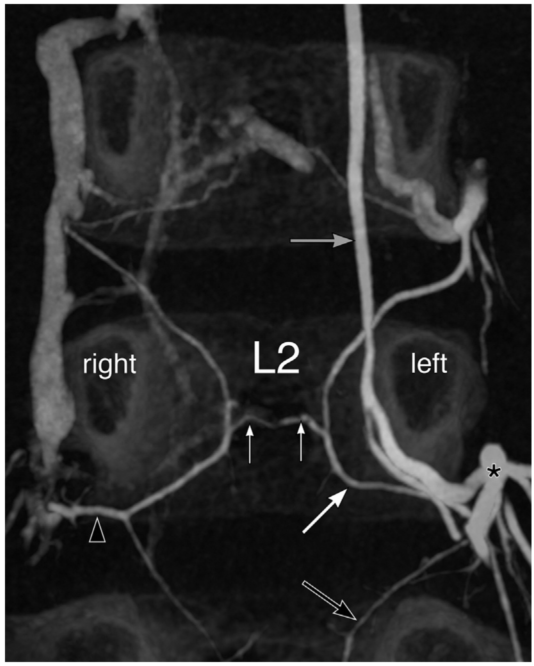

Fig. 7. The retrocorporeal network. Three-dimensional angiography of the left L2 ISA in an 8-year-old boy. The left L2 ISA (*asterisk*) supplies a prominent retrocorporeal network via ascending (*large white arrow*) and descending (*black arrow*) retrocorporeal branches. The retrocorporeal artery of right L2 is well-appreciated (*black arrowhead*). The posteromedian osseous arteries (*small white arrows*) come from the ascending branches and enter the basivertebral foramen. A prominent posterior RMA (*gray arrow*) supplies a spinal vascular malformation sitting above the field of view. (© 2019 Philippe Gailloud.)

branches of the VA[25,26] (**Fig. 8**). The main contributor is the posterior ascending artery (or anterior meningeal artery of the VA[27,28]), a cranial extension of the retrocorporeal artery of C2.[29] The left and right posterior ascending arteries connect above the odontoid process to form the apical arcade.[25] The anterior ascending artery is a tributary of the ISA stem of C2. Branches of the ascending pharyngeal artery also participate, notably those passing through the hypoglossal canal.[30]

The hemivertebral blush

Selective ISA angiography routinely documents a vertebral body blush. Initially central, this blush becomes hemivertebral in adults as the dominant osseous supply shifts from posteromedial to anterolateral osseous branches. A linear contrast uptake follows the upper and lower vertebral endplates in children; it gradually diminishes before disappearing with the closure of the growth plates at age 20 years (**Fig. 9**). The hemivertebral blush fades in later life as fat replaces the bone marrow.

The Radiculomedullary Arteries

All the primitive RMAs take part in the formation of the longitudinal spinal arteries, but only a few remain functionally important in adults[8,31,32]: 8 anteriorly and 16 posteriorly, on average.[8] This regression is an adaptation of the vascular supply to the metabolic demand of the spinal gray matter.[33] Although the marked dominance of the arteries of the cervical and lumbosacral enlargements is well-established, it is important to remember that any ISA can participate in the spinal cord supply.[34]

The relative ascent of the conus medullaris within the spinal canal explains the near vertical course of the lumbosacral RMAs. Thoracic anterior RMAs overwhelmingly originate from the left side, a prevalence apparently linked to geometric

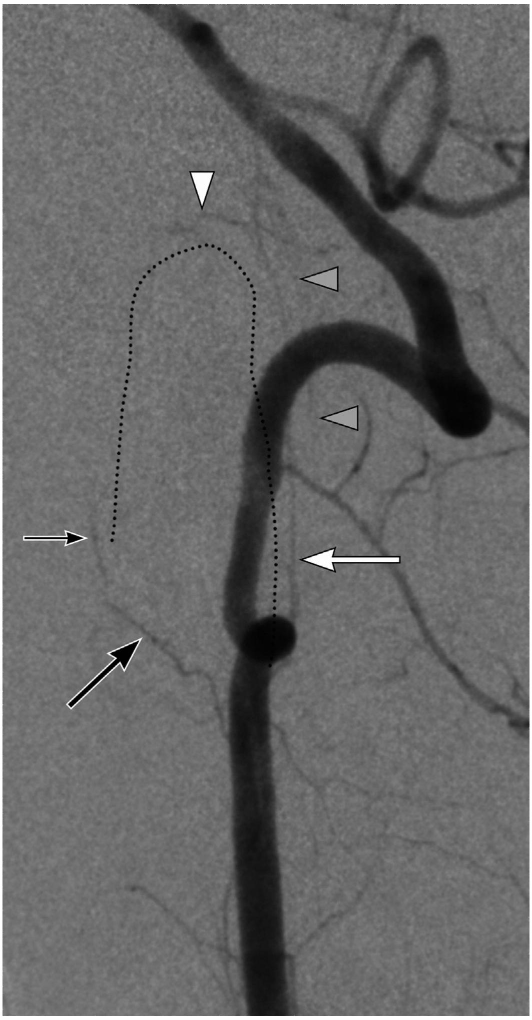

Fig. 8. The vascularization of the odontoid process. The anterior ascending branch (*small black arrow*) comes from the remnant of the C2 aortic stem (*large black arrow*). The posterior ascending branch (*white arrow*) is derived from the C2 retrocorporeal artery; with its contralateral counterpart, it forms the apical arcade (*white arrowhead*) above the odontoid process (*dotted line*). The posterior ascending branch is ventral to the ASA (*gray arrowheads*) on lateral projections. (© 2019 Philippe Gailloud.)

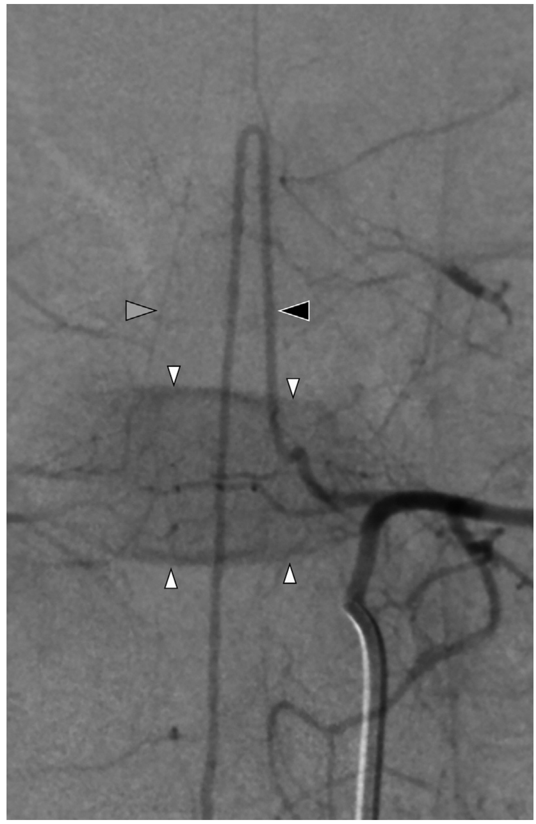

Fig. 9. Vertebral blush in a 5-year-old child. The central blush observed during selective angiography of a left T9 ISA spread to both sides of the midline (indicated by the position of the ASA). Note the linear contrast uptake marking the active vertebral growth plates (*white arrowheads*). The ISA provides a robust anterior RMA (artery of Adamkiewicz, *black arrowhead*); a contralateral posterior RMA (*gray arrowhead*) is opacified via collaterals. (© 2019 Philippe Gailloud.)

factors (ie, selection of the shortest path). Posterior RMAs are evenly distributed in all regions, possibly because of the lack of fusion of the PSAs. Significant anterior and posterior RMAs can originate from a single radicular artery (ie, artery of Lazorthes). Variations in which an RMA territory extends beyond its normal boundaries are common; an anterior vertebrospinal trunk can supply the entire cervical cord. Fig. 10 illustrates the locoregional variations in the designation of anterior RMAs.

Anterior and posterior vertebrospinal trunks

The distal segment of the VA provides anterior and posterior radicular arteries that each end in ascending and descending rami. The anterior descending rami (anterior vertebrospinal trunks) converge medially to form the ASA; their territory does normally not exceed 1 or 2 cord segments. The posterior descending rami (posterior vertebrospinal trunks) remain unfused and continue caudally as the posteromedial spinal arteries (PmedSAs) and posterolateral spinal arteries (PlatSAs) in front and behind the posterior spinal nerve rootlets, respectively.

The superior and inferior arteries of the cervical enlargement

At least 2 RMAs supply the cord between C3 and T2. The superior artery of the cervical enlargement originates from 1 of the VAs between C3

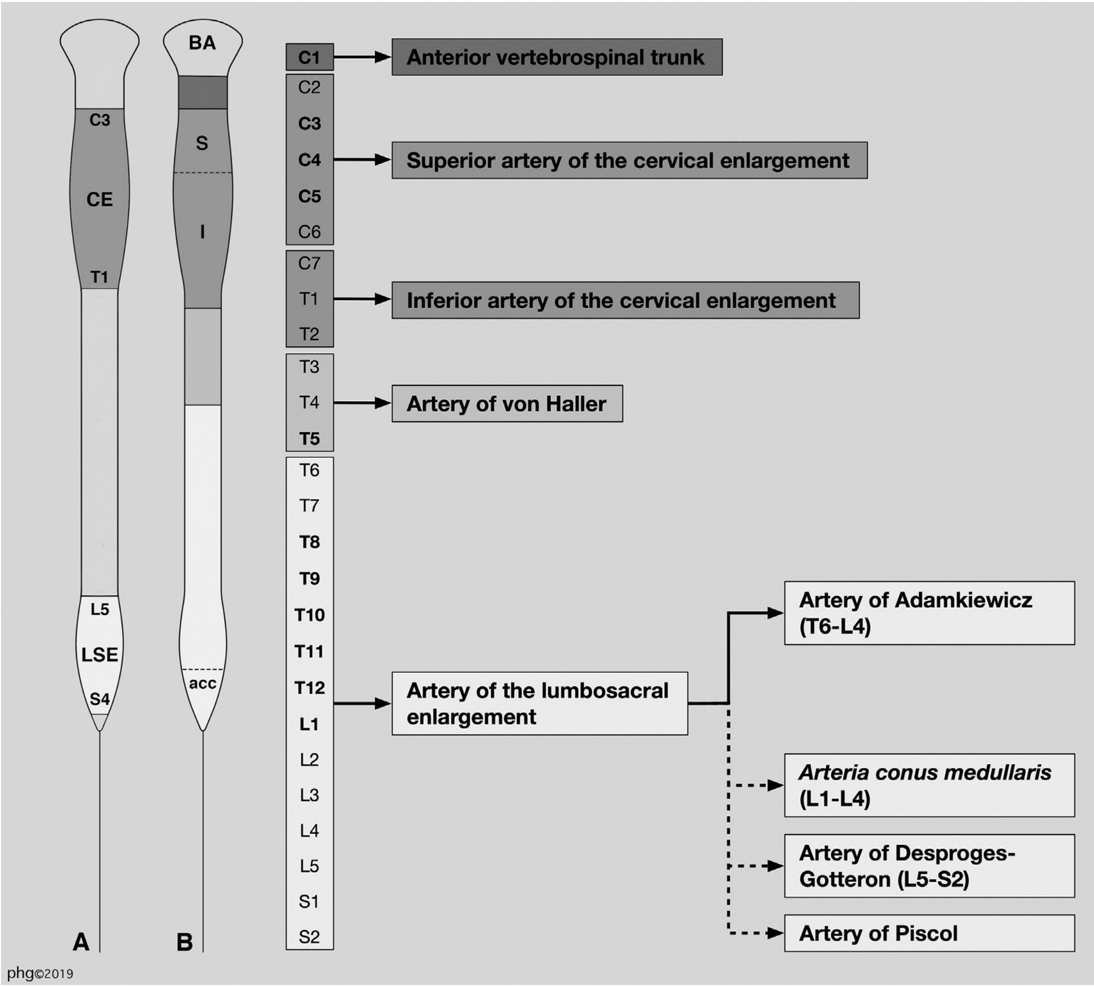

Fig. 10. Origin and labeling of anterior RMAs. The ASA is supplied by 5 constant RMAS. This diagram shows their vertebral levels of origin (numbered column) and approximate territories (spinal cord outline B). The most common levels of origin of each RMA are indicated in bold, with the exception of the inferior artery of the cervical enlargement, for which this information is not currently known. The cervical enlargement (CE) and lumbosacral (LSE) enlargement are illustrated in spinal cord outline A. The spinal cord outline is based on the data published by Ko and colleagues[85]. (1) the anterior vertebrospinal trunk comes from the VA (V4 segment) at C1, (2) the superior artery of the cervical enlargement arises from the VA between C2 and C6, (3) the inferior artery of the cervical enlargement originates from the supreme intercostal artery between C7 and T2, (4) the artery of von Haller arises from the left side of the aorta between T3 and T5, and (5) the artery of the lumbosacral enlargement most often originates between T6 and L4 on the left side (artery of Adamkiewicz). Accessory arteries are indicated by dotted arrows; under normal conditions, their territories rarely extends beyond the tip of the conus medullaris. acc, accessory; BA, basilar artery; I, inferior; S, superior. (*Data from* Ko HY, Park JH, Shin YB, Baek SY. Gross quantitative measurements of spinal cord segments in human. *Spinal Cord.* 2004;42(1):35-4; © 2019 Philippe Gailloud.)

and C5; it supplies a variable but relatively limited portion of the cervical cord. The inferior artery of the cervical enlargement is, in general, dominant. It comes from the supreme intercostal artery (C7-T2) but may also originate from the subclavian artery (C6), from a second thoracic ISA of aortic origin, or from a VA formed by a persistent seventh cervical ISA (**Fig. 11**).

The artery of von Haller

The artery of von Haller is a constant upper thoracic anterior RMA, most often found between T3 and T5 on the left side.[31,35] Its small caliber matches its limited territory, but the artery of von Haller may, as a variant, be the only source of supply for the lower thoracic and lumbosacral cord. It represents an endovascular pitfall, notably during bronchial procedures.[36,37]

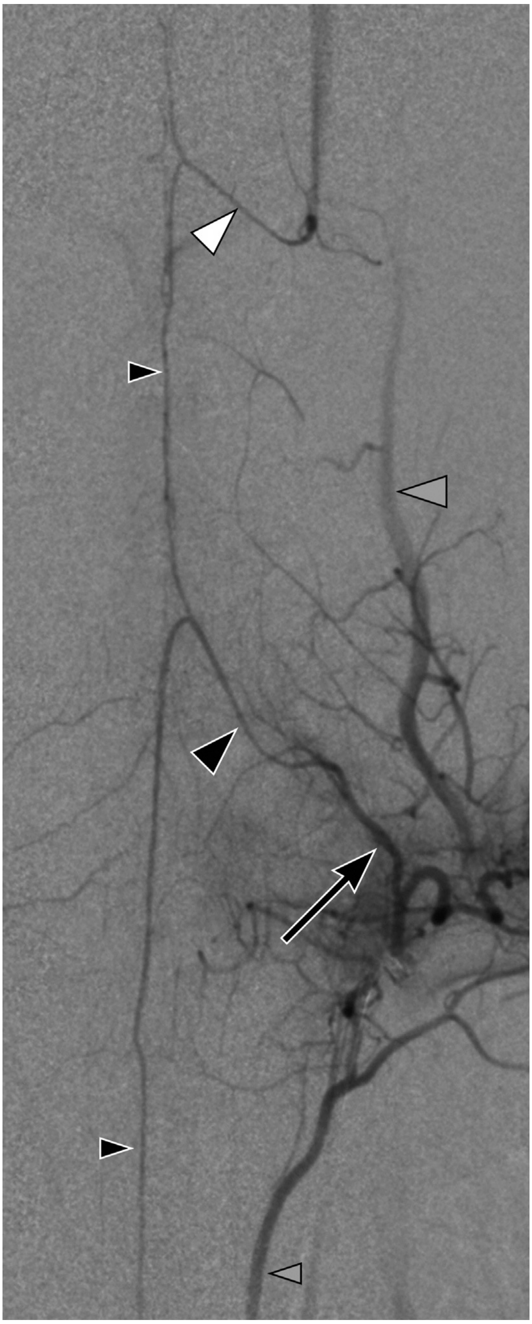

Fig. 11. Superior and inferior arteries of the cervical enlargement. The superior and inferior arteries of the cervical enlargement have been considered as variants of a single vessel but the author's experience suggests that they are independent and constant branches. This selective angiogram of the supreme intercostal artery (*arrow*) in a 27-year-old woman opacifies the inferior artery of the cervical enlargement at C7 (*large black arrowhead*) and, by reflux through the ASA (*small black arrowheads*), a superior artery of the cervical enlargement originating from the VA at C5 (*large white arrowhead*). In this case, the supreme intercostal artery is an isolated branch of the subclavian artery; the deep cervical artery (*large gray arrowhead*) and the T2 ISA (*small gray arrowhead*) are separate vessels opacified through anastomotic connections. Also note the duplication of the cervical ASA at C5. (© 2019 Philippe Gailloud.)

The artery of the lumbosacral enlargement

The artery of the lumbosacral enlargement, or artery of Adamkiewicz, is the main source of spinal cord supply. It most often originates between T6 and L4 on the left side but may, in theory, arise from lower lumbar or sacral ISA[32,38,39] (**Fig. 12**A). Accessory branches include the arteria conus medullaris[40] between L1 and L4, and the artery of Desproges-Gotteron between L5 and S2.[41] An artery of Piscol is a variation in which the descending ramus connects with the ASA, whereas the ascending ramus ends as a sulcal artery.[42] Contrary to an artery of Adamkiewicz of caudal origin (**Fig. 12**B), accessory branches have a territory limited to a portion of the conus medullaris (**Fig. 12**C); they are commonly associated with an artery of Adamkiewicz of cranial origin (T6-T9); conversely, a cranial accessory branch often accompanies an artery of Adamkiewicz of low origin. An accessory RMA can be injured by a lateral lumbar disc herniation,[41] a transforaminal injection,[43] or a spine manipulation.[44]

The Spinal Cord Vascularization

The extrinsic arterial vascularization

Several longitudinal arterial chains can be individualized within the arterial network covering the surface of the spinal cord (ie, the vasocorona)[45,46]: the ASAs, the anterolateral spinal arteries, the lateral spinal arteries, the PlatSAs, and the PmedSAs. The ASAs and PlatSAs are primary chains connected directly to the anterior and posterior RMAs. The anterolateral spinal arteries, lateral spinal arteries, and PmedSAs are secondary chains supplied by transverse branches of the primary chains (**Fig. 13**).

Developmental anatomy Medial branches stemming from the primitive ISAs contribute to the formation of a pair of paramedian anastomotic chains on the anterior surface of the neural tube. The more or less complete coalescence of these chains over the midline forms a single ventromedial channel corresponding to the basilar artery cranially and the ASA caudally.

Similar branches extending over the lateral and posterior surface of the neural tube form paired dorsolateral anastomotic chains. These chains remain separate despite being richly

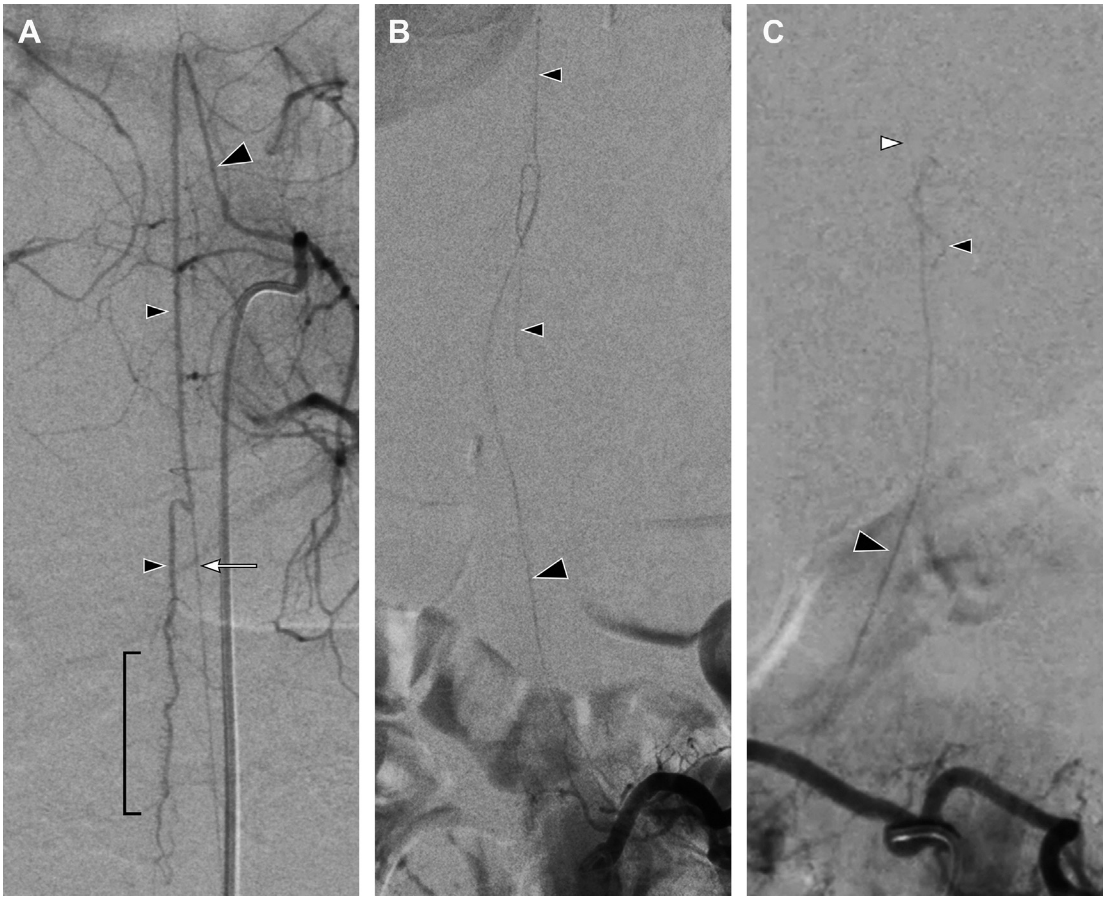

Fig. 12. The artery of the lumbosacral enlargement. (*A*) Left T9 injection in a 10-year-old girl documenting a robust RMA, the artery of Adamkiewicz (*large arrowhead*). A small L1 anterior RMA (*arrow*) is opacified by reflux via the ASA (*small arrowheads*); it may regress completely before adulthood or persist as an accessory vessel (arteria conus medullaris). The sulcal arteries are visible at the level of the conus medullaris (*bracket*). (*B*) Left L4 injection in a 79-year-old man showing an artery of Adamkiewicz of caudal origin (*large arrowhead*) supplying the lower thoracic and lumbosacral territory normally covered by an artery of the lumbosacral enlargement (*small arrowheads*). (*C*) Right L4 injection in a 59-year-old man opacifying an accessory anterior RMA (*large arrowhead*) that only participates in the supply of a portion of the ASA (*small black arrowhead*) limited to the tip of the conus medullaris; the ascending ramus (*white arrowhead*) appears to end as a sulcal branch (artery of Piscol). (© 2019 Philippe Gailloud.)

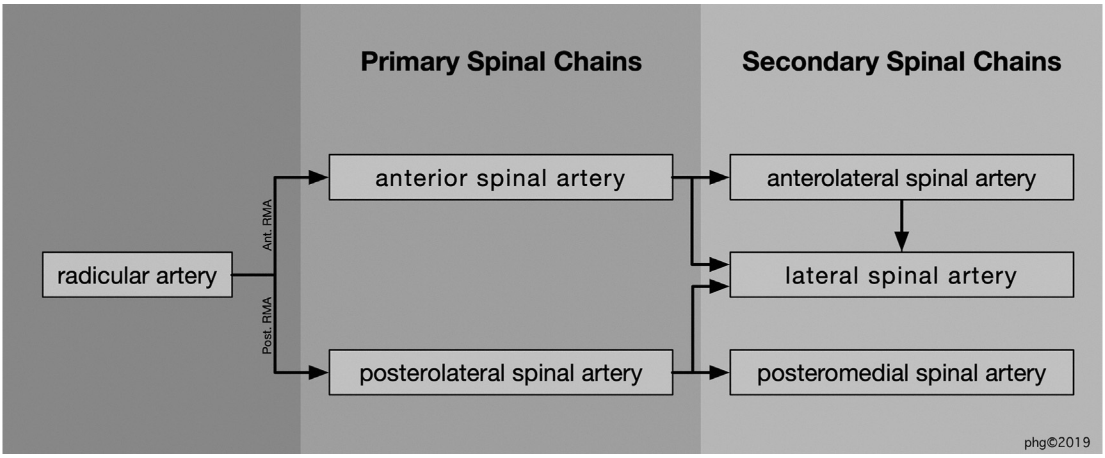

Fig. 13. Diagram of primary and secondary spinal arteries. Anterior (Ant.) and posterior (Post.) RMAs participate in the formation of the primary chains, the ASA, and the PlatSA. The secondary chains are not directly connected to RMAs; they are formed by transverse branches of the primary chains. The left and right PmedSAs are interconnected by a dense posterior plexus (not illustrated). (© 2019 Philippe Gailloud.)

interconnected across the midline; each has a lateral and a medial component lying in front and behind the line of emergence of the dorsal nerve roots, the PlatSAs, and PmedSAs.

The anterior spinal artery The ASA extends from the medulla oblongata to the tip of the conus medullaris, beyond which it continues as the artery of the filum terminale. The ASA forms through the selection of a preferential path within a primitive ventral arterial mesh.[47] Partial persistence of this mesh leads to the formation of focal or extensive duplications, in particular at the cervical level (see **Fig. 11**). Thoracic and lumbosacral duplications are, on the other hand, rare (**Fig. 14**). The ASA caliber varies between 0.2 mm at the thoracic level and 1.2 mm in the lumbosacral region.[48] Some segments may regress with age, notably at the upper cervical and midthoracic levels, where short interruptions are possible.[49,50]

The posteromedial and posterolateral spinal arteries The posterior RMAs supply the PlatSAs, which send small rami to the PmedSAs through the posterior nerve rootlets. The PmedSAs and PlatSAs alternate between plexiform channels and individual branches of variable, often inversely proportional, calibers. Multiple anastomoses connect the left and right PmedSAs across the midline (posterior plexus).[51] The upper cervical PlatSA is prominent, likely because of the large volume of white matter at that level.[52,53]

The periconal arterial anastomotic circle The ASA provides small arcuate arteries (rami cruciate) near the tip of the conus medullaris; these vessels course laterally and posteriorly to connect with the PSAs and form the periconal arterial anastomotic circle[8,54–56] (**Fig. 15**). Through this anastomosis, which is the only functionally significant connection between the anterior and posterior spinal circulations,[57] the distal ASA supplies the terminal segment of the PSAs.[58]

The intrinsic arterial vascularization

The sulcal arteries vascularize the central gray matter (centrifugal system), whereas the PSAs and the vasocorona supply most of the surrounding white matter via small perforating branches (centripetal system).[59] The 2 systems are interconnected by intramedullary anastomoses but remain functionally independent.[40]

Between 200 and 300 sulcal arteries arise from the ASA[8,59]; they travel down the anterior median fissure to penetrate the gray commissure, where they take the name of sulcocommissural arteries.[59] Their density is higher at the lumbosacral than at the cervical or thoracic levels.[60–62] These variations are caused by the pronounced elongation of the thoracic and cervical cord segments during development.[63] The thoracic sulcal arteries are smaller, and their ascending and descending terminal rami cover

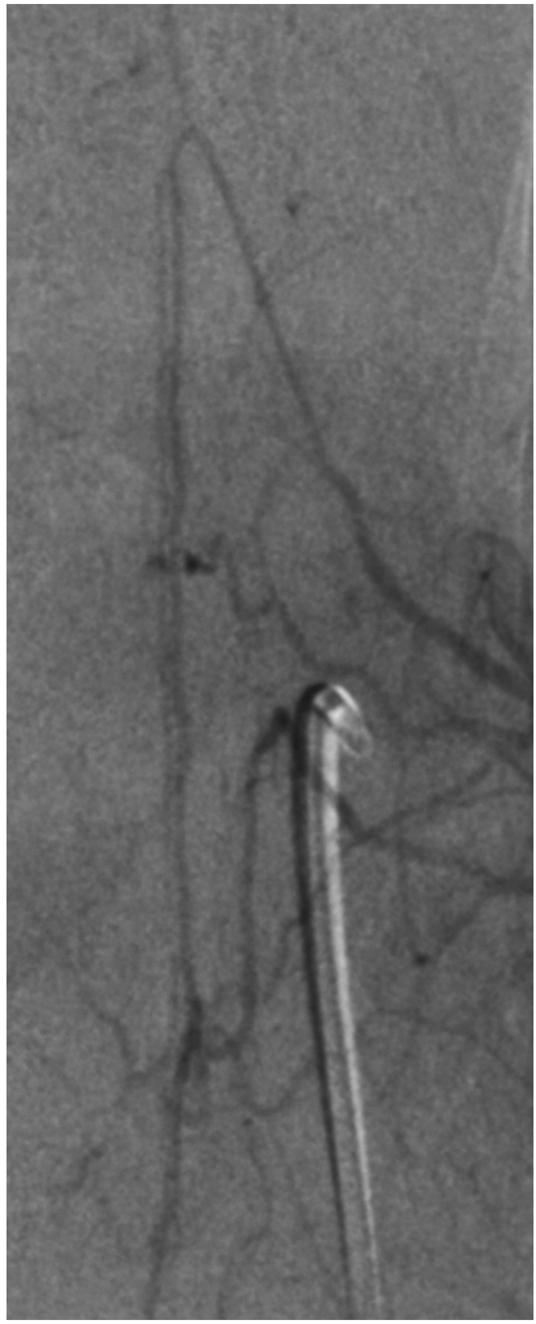

Fig. 14. Duplication of the thoracic ASA. This left T10 angiogram documents a duplication of the thoracic ASA in an 18-year-old woman, resulting from the focal persistence of paired primitive paramedian spinal chains. (© 2019 Philippe Gailloud.)

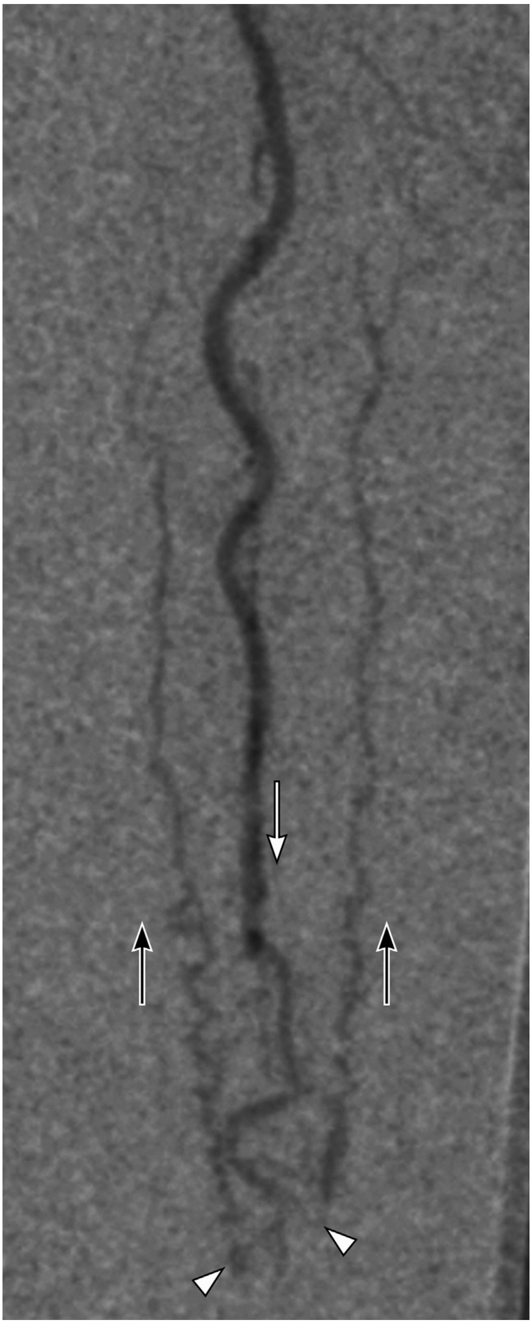

Fig. 15. The periconal arterial anastomotic circle. This magnified view of a left T9 angiogram in a 7-year-old boy documents anastomoses between the ASAs and PSAs via small arcuate branches (*arrowheads*). The flow is craniocaudal in the ASA (*white arrow*) and caudocranial in the PSAs (*black arrows*). (© 2019 Philippe Gailloud.)

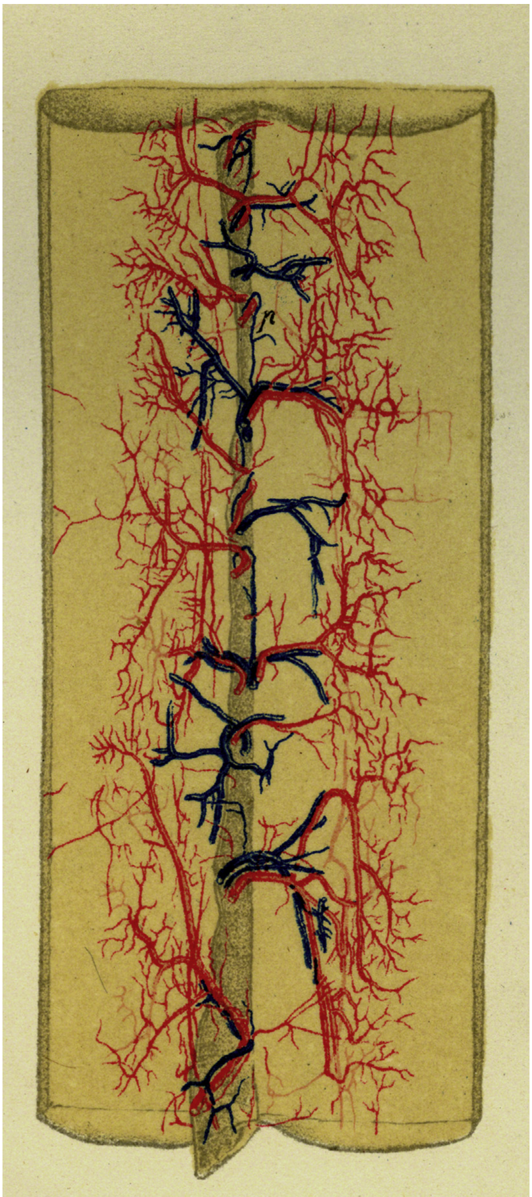

Fig. 16. Branching pattern and distribution of sulcal arteries and veins. Sulcal arteries generally have a unilateral distribution, irregularly alternating between the left and right sides. On the other hand, most sulcal veins have bilateral drainage territories. (*From* Kadyi H. *Über die Blutgefässe des Menschlichen Rückenmarkes.* Lemberg: Gubrynowicz & Schmidt; 1889.)

longer distances within the anterior median fissure, particularly in tall individuals. These features may represent an anatomic substrate for the increased sensitivity of the thoracic cord to ischemia.[62,64,65]

Most sulcal arteries have a unilateral territory but bilateral trunks also exist.[50,61,62] Trunks with multiple ipsilateral branches are less frequent.[61] The predominantly unilateral distribution of sulcal branches is consistent with the paired origin of the ASA. Left and right branches do not strictly alternate: 2 or 3 successive arteries may aim for the same hemicord, particularly at the thoracic level[66] (**Fig. 16**). Damage to a single sulcal artery can thus result in a limited unilateral infarct or be more extensive, longitudinally and/or transversally. Each limb of an ASA duplication provides sulcal branches for the ipsilateral hemicord.[66,67] The cervical predominance of the sulcal syndrome suggests that the occlusion of 1 limb of a duplicated ASA is a more likely mechanism than the loss of a single sulcal artery.[68]

Spinal collateral pathways

The development of collateral spinal cord supply relies on the enlargement of osseous and muscular anastomoses (**Fig. 17**), on the recruitment of alternate RMAs, and on the periconal arterial anastomotic circle. Collateral pathways influence the extent and severity of ischemic injuries, but their availability depends on the patient's age and the site, type, and timing of the arterial injury. The principles once established by Lazorthes remain valid[40]:

1. "The nearer the arterial obstruction is to the aortal origin and the farther it is removed from

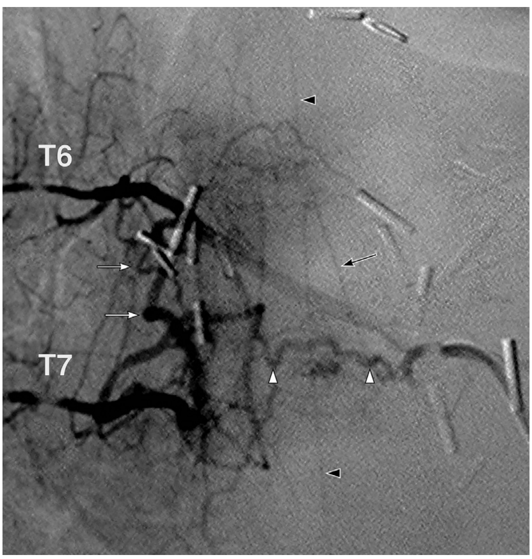

Fig. 17. Muscular and osseous collateral pathways. Right T6 ISA angiography in a young woman with prior spine tumor surgery. The only documented contribution to the thoracolumbar ASA (*black arrowheads*) was provided by a left T7 RMA (artery of Adamkiewicz, *black arrow*). Both T7 ISAs had been surgically ligated at their aortic origin; the artery of Adamkiewicz was supplied instead by the right T6 ISA via a combination of muscular (right T6 to right T7, *white arrows*) and retrocorporeal (right T7 to left T7, *small arrowheads*) anastomoses. These anastomotic pathways are most potent in children and young adults. (© 2019 Philippe Gailloud.)

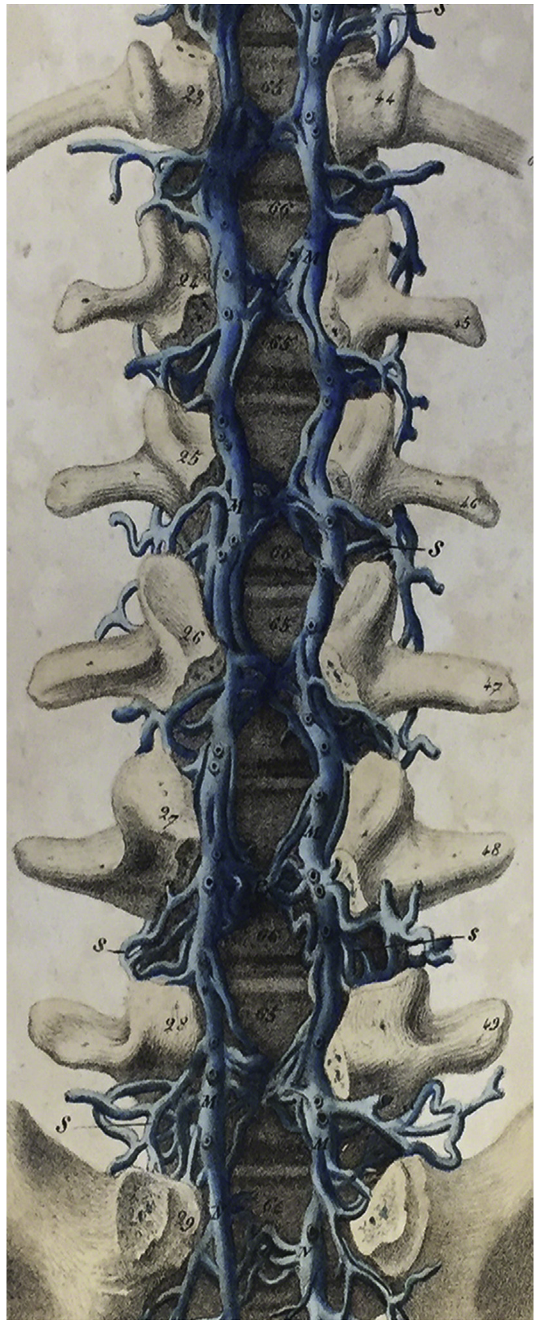

Fig. 18. Depiction of the anterior epidural plexus. The left and right anterior longitudinal veins are linked across the midline at the level of the basivertebral foramina; they connect laterally, through each neural foramen, with the EVVP. (*From* Breschet G. Recherches Anatomiques Physiologiques et Pathologiques sur le Système Veineux. Première Livraison. Paris: Rouen Frères, Libraires-Éditeurs; 1829.)

the spinal cord, the greater the possibilities of anastomotic substitution."

2. "The slower the obstruction is in establishing itself, the greater the chances of effective intervention by the substitution pathways, whereas a sudden obstruction takes the substitution pathways by surprise."

Spinal watershed zones

Axial watershed zone The axial watershed zone lies at the interface between the centripetal and centrifugal intrinsic circulations. The zone at risk is theoretically circular[40]; when combined with the increased gray matter vulnerability to ischemia, it produces the snake-eye pattern typical of minimal or early ischemic injuries.[69] More severe lesions can damage the entire gray matter yet still spare the white matter.[70]

Longitudinal watershed zones Longitudinal watershed zones sit at the junction between adjacent radiculomedullary territories. They predominantly involve the anterior circulation as the plexiform nature of the posterior circulation offers a better protection against ischemia. Their topography depends on the number, size, and location of the contributing anterior RMAs, and the mechanism of injury (eg, single-branch occlusion vs hypotensive episode).

Posterior lumbosacral watershed zone The ASA supplies the most caudal portion of the PSAs via the periconal arterial anastomotic circle. This

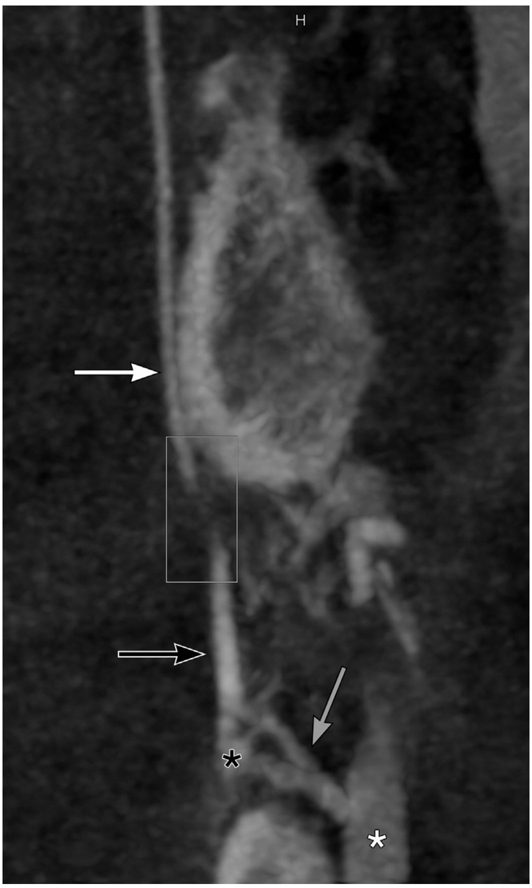

Fig. 19. The RMV and the antireflux mechanism. Coronal reconstruction of a 3-dimensional angiogram obtained in a 36-year-old woman, depicting the distal segment of a left L1 RMV. The intradural (*white arrow*) and extradural (*black arrow*) portions of the vein are delimited by its passage through the thecal sac. The short segment of RMV traveling within the 2 layers of the dura (*square*) corresponds to the antireflux mechanism; its narrowed lumen is below angiographic resolution. The RMV ends in the epidural plexus (*black asterisk*); the venous blood is drained toward the EVVP (*white asterisk*) by the transverse veins of the intervertebral venous plexus (*gray arrow*). (© 2019 Philippe Gailloud.)

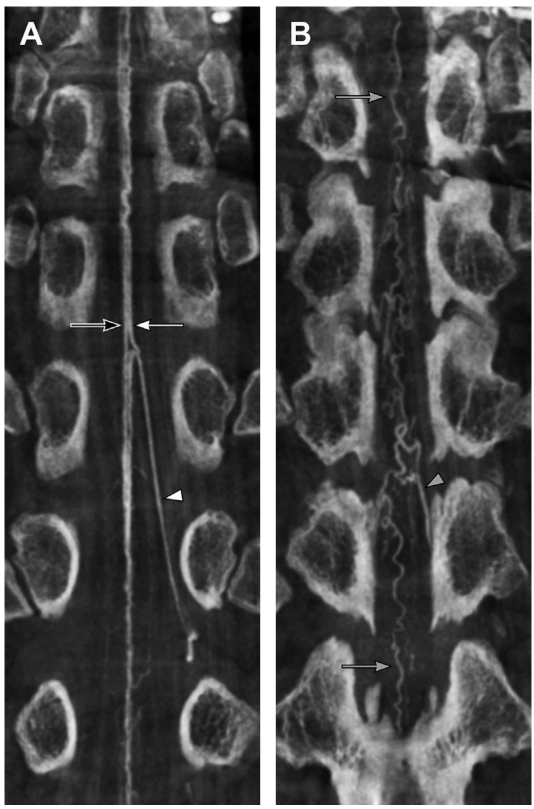

Fig. 20. The perimedullary venous system. Coronal reconstructions of a 3-dimensional angiogram (flat panel catheter angiotomography) obtained in a 25-year-old woman. The anterior perimedullary venous system (*A*) is more continuous and less sinuous that the posterior system (*B*). The AMSV (*white arrow*) courses along or deep to the ASA (*black arrow*); it drains into a left L1 RMV (*white arrowheads*). The PMSV (*gray arrows*) is partly well-delineated and partly plexiform. A posterior L1 RMV is seen (*gray arrowhead*). (© 2019 Philippe Gailloud.)

configuration establishes a longitudinal watershed zone along the dorsal aspect of the conus medullaris, the posterior lumbosacral watershed zone.[56]

THE SPINAL VENOUS SYSTEM

The spinal venous system is divided into 4 compartments:

1. The intrinsic spinal venous system
2. The extrinsic spinal venous system
3. The internal vertebral venous plexus (IVVP)
4. The external vertebral venous plexus (EVVP).

The antireflux mechanism is a valve-like structure formed by the passage of the radiculomedullary veins (RMVs) through the thecal sac; it demarcates the intradural and extradural compartments. The EVVP is not discussed further in this article.

The Internal Vertebral Venous Plexus

The IVVP comprises anterior and posterior longitudinal veins with numerous lateral and transverse anastomotic connections. The anterior longitudinal veins are attached to the vertebral bodies by the basivertebral veins and pressed against the vertebral wall by the posterior longitudinal ligament (**Fig. 18**). Their location is sensu stricto, not epidural.

The size and configuration of the posterior longitudinal veins are more variable. Breschet[71] distinguished between posterior longitudinal veins, present at the dorsal level only, and posterior epidural plexus, extending over the whole spine. Walther[72] simplified this notion by suggesting that the posterior longitudinal veins alternate plexiform and individualized configurations. The posterior longitudinal veins and plexus are not attached to the lamina but to the dorsal aspect of the thecal sac, with which they can move.

The neural foramen contains the intervertebral plexus, a venous ring made by the anterior and posterior longitudinal veins interconnected cranially and caudally by transverse anastomoses. The intervertebral plexus is a valve-free connection between the IVVP and EVVP.

The Radicular and Radiculomedullary Veins

RMVs are more numerous than RMAs: studies have found 11 to 40 anterior RMVs and 12 to 42 posterior RMVs.[73] These variations are likely explained by an age-related reduction in the number of RMVs, and by the use of different

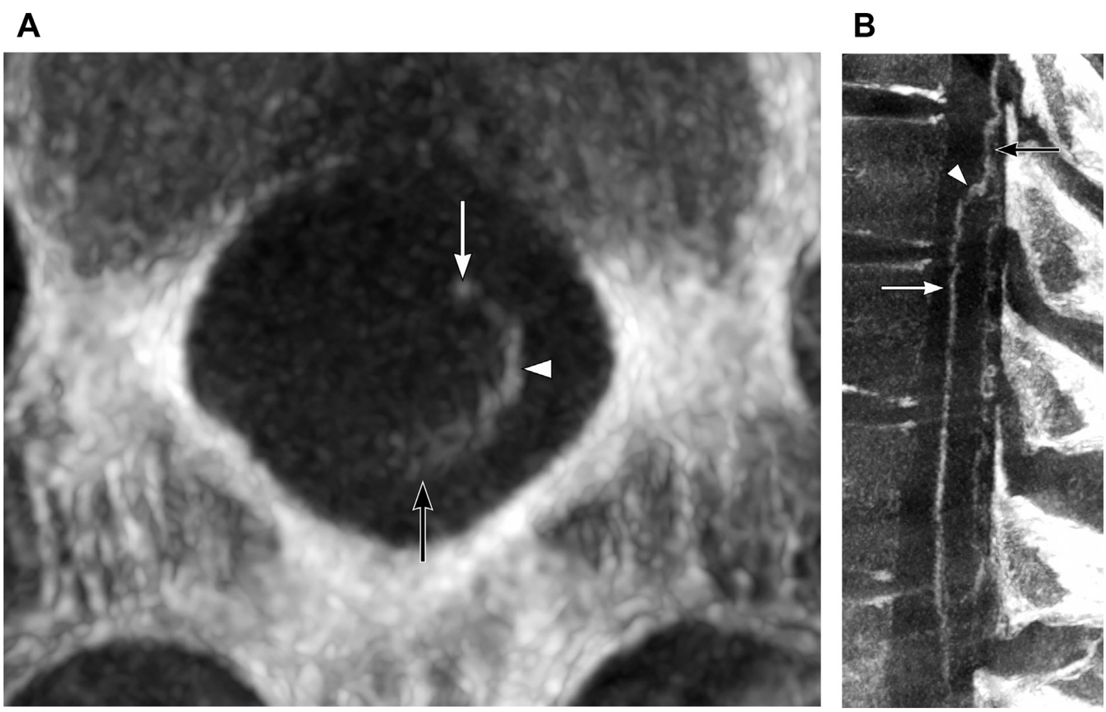

Fig. 21. Perimedullary venous anastomoses. Axial (*A*) and coronal (*B*) reconstructions of a 3-dimensional angiogram (flat panel catheter angiotomography) obtained in a 54-year-old woman. The anterior perimedullary venous system (*white arrow*) drains, in this case, toward the posterior perimedullary venous system (*black arrow*) via a left pial anastomosis (*arrowhead*). (© 2019 Philippe Gailloud.)

investigation techniques and anatomic definitions (RMVs vs radicular veins).

Dominant RMVs are most often found at the lumbosacral level[49]; they are more constant and prominent posteriorly.[74] Tadié and colleagues[74] identified 1 or 2 posterior RMVs and 1 anterior RMV at the thoracolumbar level, and 2 or 3 posterior RMVs in the midthoracic region, including a fairly constant 1 at about T6-T7.[74]

The antireflux mechanism

After observing that substances injected into the IVVP did not penetrate the intradural circulation, early anatomists postulated the existence of valves at or near the point of termination of RMVs in the epidural plexus.[64] Valves have now been ruled out, but modern investigators have discovered various mechanisms with a valve-like function.[75] The antireflux mechanism is principally a focal narrowing of the RMV as it crosses the thecal sac.[74,76–79] The caliber of this transdural segment roughly decreases from 950 to 130 μm, a relative stenosis of about 85% (**Fig. 19**). Additional factors may include an intraluminal dural fold and a focal increase in muscular fibers.[79]

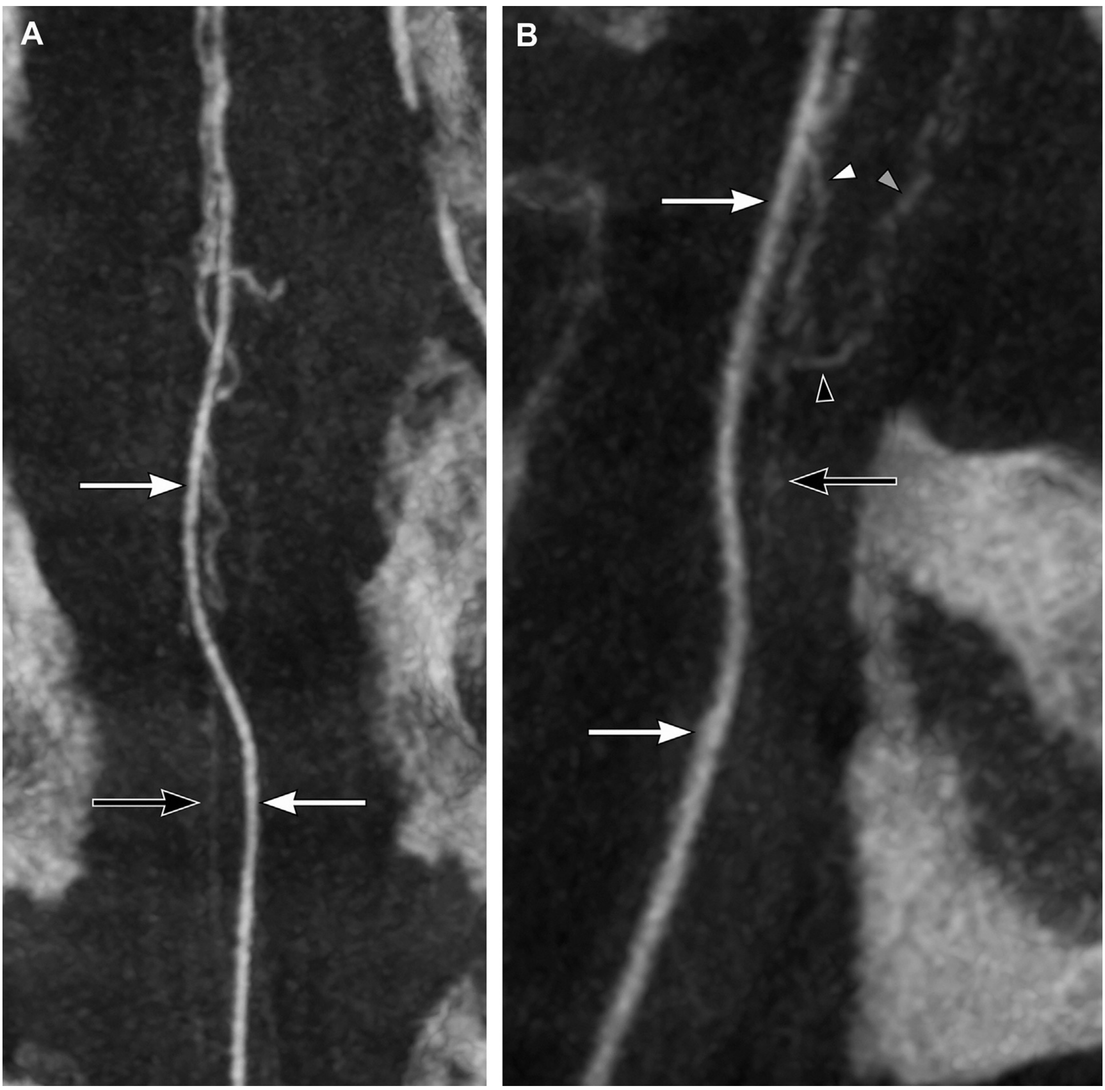

Fig. 22. The periconal venous anastomotic circle and the vein of the filum terminale. Coronal (*A*) and sagittal (*B*) reconstructions of a 3-dimensional angiogram obtained in a 74-year-old man. The vein of the filum terminale (*black arrow*) is a small midline vessel coursing along the filum terminale. The white arrows point to a lower lumbar or sacral RMV. The anterior (*white arrowhead*) and posterior (*gray arrowhead*) perimedullary venous systems are interconnected around the tip of the conus medullaris by the periconal venous anastomotic circle (*black arrowhead*). (© 2019 Philippe Gailloud.)

The antireflux mechanism controls the direction of the blood flow within the RMV. It protects the perimedullary network from pressure surges reaching the IVVP (eg, sneezing, pregnancy). The antireflux mechanism, combined with the near vertical course of lower thoracic and lumbosacral RMVs in the standing and sitting positions, appears to represent a risk factor for stagnation and thrombosis, which likely play a role in the development of spinal dural arteriovenous fistulas.[80]

The radicular veins

Numerous small veins course along the nerve roots from the venous plexuses of the spinal ganglia to the longitudinal spinal veins. Up to 3 true radicular veins accompany each nerve root. They flow toward the perimedullary venous system, are generally not connected with the IVVP, and do not contribute to the spinal cord drainage.[74,75]

The Perimedullary Venous System

The perimedullary venous network includes several longitudinal anastomotic chains, which lie alongside or deep to their arterial counterpart.[75] The anteromedian spinal vein (AMSV) and the posteromedian spinal vein (PMSV) are dominant; they are flanked by smaller anterolateral and posterolateral spinal veins. The AMSV is a relatively constant and straight channel extending from the skull base to the filum terminale (**Fig. 20**).[74] It receives tributaries from the anterior spinal nerve rootlets and connects cranially with the venous network of the brainstem. It can also drain into the posterior perimedullary system via a perimedullary thoracolumbar anastomosis.[74]

The lower thoracic and lumbar PMSV is a constant, sinuous, and usually dominant perimedullary venous channel.[74] It collects tributaries from dorsal and lumbar nerve rootlets, from the cauda equina, and from the anterior and posterior aspects of the spinal cord. Between T2 and T10, the posterior venous system has a plexiform appearance; its tortuosity increases with age.[74] Small or absent in the midthoracic region,[49] the PMSV is again clearly discernible at the cervical level, often as a duplicated channel.[74] The upper thoracic and cervical PMSV collects tributaries from dorsal nerve rootlets.

The perimedullary venous (coronary) network interconnects the longitudinal spinal trunks. However, large anastomoses are infrequent and their function unclear; they may represent an alternate drainage pathway protecting the spinal cord during transient, posture-related flow impairment. They occasionally drain one perimedullary venous system into the other (**Fig. 21**). The venous network surrounding the tip of the conus medullaris is similar to the periconal arterial anastomotic circle (**Fig. 22**).

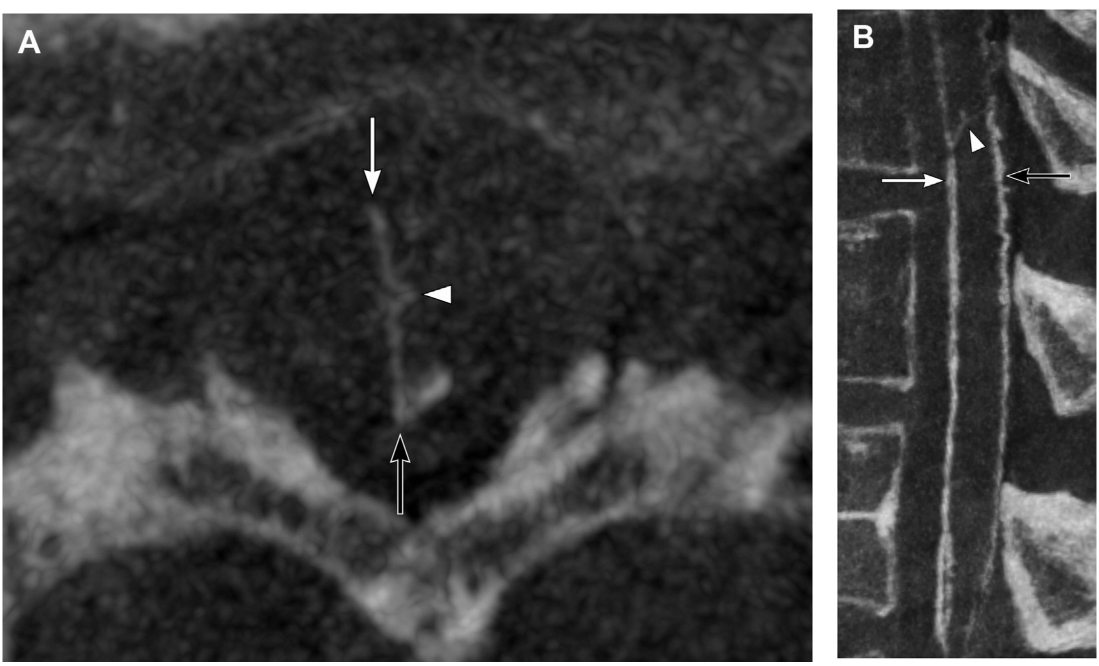

Fig. 23. Transmedullary venous anastomoses. Axial (*A*) and coronal (*B*) reconstructions of a 3-dimensional angiogram (same patient as **Fig. 22**). The anteromedian (*white arrow*) and posteromedian (*black arrow*) spinal veins are connected by a transmedullary anastomosis (median anteroposterior type) (*arrowhead*). (© 2019 Philippe Gailloud.)

The Intrinsic Venous System

The intramedullary venous network has a central and a peripheral compartment. The sulcal veins drain the median and anterior portion of the spinal cord into the AMSV[81]; they typically have bilateral territories. Sulcal veins establish longitudinal anastomoses, both at the level of the central gray matter and within the anteromedian fissure.[81]

The short peripheral veins follow a radial course ending in the coronary plexus; those within the anterior and posterior radicular fasciculi are, in general, more robust.[49] The larger, more constant septal veins drain into the PMSV.

Two main types of transmedullary venous anastomoses are recognized: a centrodorsolateral type[65] and a more common median anteroposterior type[50,76] (**Fig. 23**). Both can become conspicuous when associated with a vascular malformation.

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