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FUNCTIONAL NEUROVASCULAR ANATOMY OF THE SPINAL CORD

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ABSTRACT

The neurovascular anatomy of the spinal cord composed of segmental structure at each spinal level which also known as metamere. Due to its natural long shape, the anterior and posterior spinal arteries are supported by other arteries branched of several sources i.e. the cervical ascendens artery, deep cervical artery, costocervical trunk, aorta, lumbar arteries and lateral sacral artery. Variations in the vessels amongst individuals are reported to be relatively vast, where the autoregulation or collateral mechanisms to compensate when pathology occurs in one side must be well realised by physicians. The preoperative, intraoperative and postoperative comparative angiography could be applied to elucidate any variations of these vessels thus minimizing the risk of spinal cord ischaemia due to surgery and/ or diseases.

Keywords: Medulla Spinalis; Anatomy; Neurovascular; Health and Disease.

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INTRODUCTION

Spinal cord (*medulla spinalis)* is the caudal, elongated and cylindrical part of the central nervous system (CNS), which is resided at the vertebral canal; this structure extends from the medulla oblongata cranially to the conus medullaris caudally. Until the 3rd month of fetus occupies entire vertebral canal, thereafter the vertebral column grows faster, thus the caudal end of the cord is ± reaching the LIII at birth, and at LI-LII in adult, thus cervical cord segments are located ± 1 spine higher than the corresponding vertebrae, thoracic ± 2 spines higher, lumbar ± 3-4 spines higher. A segmental structure (metameric) is formed from rostral to caudal (C1-C8, T1-T12, L1-L5, S1-S5 and Co-metameres). The spinal cord approximately has a cylindrical shape, with 2 enlargements/ intumescentia; C5-T1 (maximum at C6 ± 38 mm) and L1-S3 (maximum at S1 ±35 mm wide); from conus medullaris at the caudal tip is the filum terminale attached to the dorsal surface of coccyx, the lumbo-sacral radix form a cluster of cauda equina that resides at the caudal part of the spinal canal.[1-3]

The spinal cord is covered by a pachymeninx (serous layer of duramater, with subdural space at the deeper side and epidural space at the superficial layer contains fat and plexus venosus) and 2 leptomeninx (arachnoidmater and piamater, with subarahnoid space filled with CSF in between and ended at S2). The denticulate ligaments at the departure point of adjacent posterior and anterior radices resided at the lateral side serve to lay the spinal cord in the middle of the subarachnoid space.[4-6]

DISCUSSION

General Anatomy of The Spinal Cord

The *medulla spinalis* is the structure where sensory, motor and autonomic innervation for the trunk and limbs are controlled and coordinated; it has a central core of *substantia griseus*, predominatly composed of nerve cell bodies, and a superficial layer of *substantia alba* mainly contins the nerve fibres e.g. Cornu dorsalis of the substantia griseus mostly contains sensory neurons whereas the cornu ventralis mainly contains motor neurons; and the cornu lateralis contains the preganglionic sympathetic neurons of the autonomic nervous system. The cornu dorsalis is the primary location of primary afferent fibres terminal. This includes the substantia gelatinosa (Rexed's laminae I–III), which is vital in the transmission of nociceptive impulses to the encephalon. The neurones of the cornu lateralis contain preganglionic sympathetic cells, as the cornu ventralis contains alpha and gamma motor neurons as parts of the lower motor neurones (LMN) of the peripheral nervous system. In the columna of the spinal cord runs the ascending and descending tracts, which connect the spinal cord with the encephalon. The main sensory-ascendens tracts are the dorsal columns, the spinothalamic tracts and the spinocerebellar tracts; whilst the corticospinal tract is a pyramidal motor-descendens tract.[5,7-9]

The tip of the cornu dorsalis is where the Rexed's laminae I–III located and are also named substantia gelatinosa that receives myelinated (group Aδ) and unmyelinated (group C) afferents linked to the nociceptive sensory predominantly using the glutamatergic neurotransmitter and substance-P. A complex inter-connection between different diameter of afferents fibres of the spinothalamic and spinoreticular tracts with the inetrneurones and the fibres of the descending tracts may overlap the impulses from one another thus rubbing a sore spot may relieve the nociceptive pain. High levels of endogenous opioid peptide i.e. enkephalin which may decreases release of Substance P is also secreted in these areas (Gate Control Theory of pain) (figure 1). The lamina VII of C8–L3 mainly contains the cells of Clarke's column (thoracic nucleus, nucleus dorsalis), which are the origin of the dorsal spinocerebellar tract), the inputs come from e.g. Muscle spindles, Golgi tendon organs, tactile and pressure receptors. This layer also contains the preganglionic sympathetic neurones that form the cornu lateralis (T1-L2), and at S2–S4 contains the preganglionic parasympathetic neurones.[5,7-9]

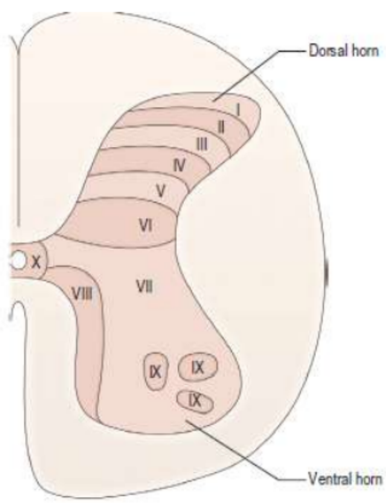


Figure 1. Lamination of the spinal cord horn (Rexed's laminae).[5]

The afferent fibres enter cornu dorsalis via the dorsal roots and divide into ascending and descending branches, mostly ended near the entry point (i.e. cutaneous afferents) but may travel in the dorsolateral fasciculus known as the

Lissauer's tract, at the superficial tip; and to the deeper layers. At the cornu ventralis, lamina IX corresponds to groups of motor neurones that innervate skeletal muscle. Two types of motor neurones are the **α** which innervate extrafusal muscle fibres, and **γ-motor** neurones, which innervate intrafusal muscle fibres in the muscle spindle. In the cervical and lumbar enlargements that innervate the arms and legs, respectively, these are well developed. Neurones innervating axial musculatures are typically located in the medial and for the appendicular muscles are more lateral. In C3-C5 the nucleus phrenic where motor neurones innervate the diaphragm via N. Phrenicus is resided and vital for respiratory function. This area also receives certain input of dorsal root afferents i.e. from muscle spindles of stretch reflex and from descending pathways for motor control.[5,7-9]

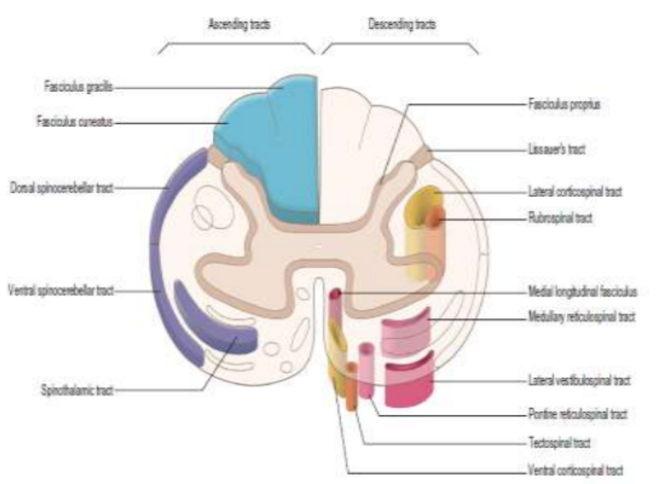


Figure 2. The coronal section of the spinal cord showing the ascendens and the descendens tracts of the columna medulla spinalis.[5]

Nervi Spinales

The 31 pairs of spinal nerves originate from the spinal cord as the ventral and dorsal roots carrying motor and sensory fibres, respectively. The soma of the efferent neurones are in the substantia griseus and the sensory resides in the dorsal root ganglia, the fibres compose the peripheral nervous system run via the foramen intervertebrale. Several traumatic injury of the cord and the nerve roots e.g. lumbar prolapsed intervertebral disc (sciatica, bladder incontinence), spinal dislocation, cervical spondylosis (radiating pain, paraesthesia, weakness and wasting muscles, loss of tendon reflexes, accordingly).[5,10-13]

Spinal Reflex

The spinal reflex mediates via the mono- and poly-synaptic pathyways. The monosynaptic stretch reflex produces deep tendon reflexes subserved by specific cord segments i.e. Biceps reflex: C5-C6, brachioradial reflex (supinator jerk): C5-C6, triceps reflex: C6-C7, quadriceps reflex (knee jerk): L3-L4, Achilles tendon reflex (ankle jerk): S1-S2. Also known as the myotatic reflex, this pathway is regulated by gamma motor neurones of the stretched muscle spindle produces muscle contraction to maintain the muscle tone (figure 3). Whilst the polisynaptic flexor and cross extensor reflex mediates limb withdrawal from noxious stimuli.

Structure of The Funiculus of Medulla Spinalis

In the column of the spinal cord, the ascendens and descendens tracts of sensory and motor nerve fibres run. The ascending tracts carry afferent information to conscious and subconscious levels. The dorsal funiculi composed of fasciculus gracilis and cuneatus serve the proprioceptive and fine touch, where first-order neurones are at the ipsilateral gracilis and cuneatus nuclei, and the second-order neurones decussate and go to the ventroposterolateral and ventroposteromedial nucleus of thalamus before the third-order neurones synapse at Brodmann area 3,1,2 in the somatosensory cortex of the parietal lobe. Tabes dorsalis, vitamin B12 deficiency and other lesions may lead to ataxia and loss of discriminative touch. The spinothalamic tract is another ascending fibre bundle carries pain, temperature, touch and pressure, with second-order neurones in the cornu dorsalis.[5,14-16]

This tract would decussates and pass to the sensory nuclei of thalamus and fibres project at similar ways to the dorsal column tract. Syringomyelia may lead to dissosiative sensory impairment of the spinothalamic tract. **Spinocerebellar tracts,** on the other hand, have a muscle, joint and tactile information involved in extrapyramidal motor control which lesions lead to ataxia (e.g. Friedreich's ataxia) (figure 2).[5,15-16] The descending tracts carry efferent motor outputs; the **corticospinal tract,** for example, controls distinct, trained movements, particularly of the inferior extremities. This tract originates from the pre-central gyrus of the frontal lobe, and the fibres descend via the capsula interna, crus cerebrimof the mesencephalon, tegmentum pontis to the pyramis of the medulla oblongata.[5,9,16]

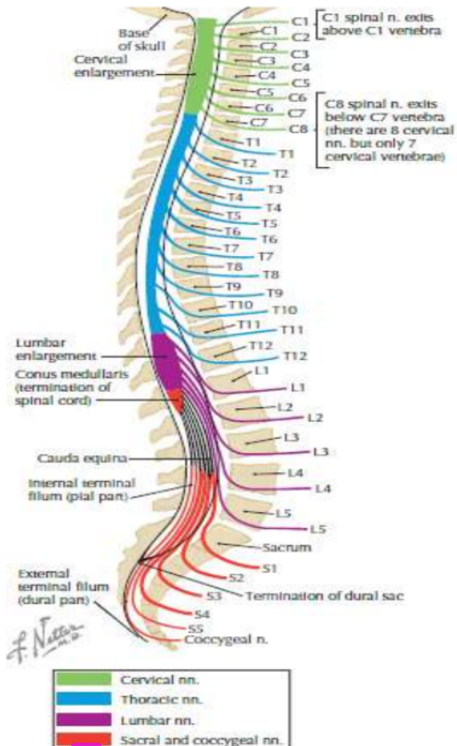


Figure 3. The segmental levels of the spinal cord and their relations to the vertebrae.[9]

Approximately 75-90% of these fibres will decussate at the decussatio pyramidalis located at the border between the spinal cord and the lower edn of the medulla oblongata; the rest of these fibres will cross at more caudal levels before exiting the spinal cord as the spinal nerves (the lateral *vs*. the ventral corticospinal tracts). The **rubrospinal tract** controls the flexor muscle groups of the inferior extremities, the fibres comes from the nucleus ruber of the tegmentum mesencephali whilst decussate at the ventral tegmentum and receives affernes from the motor cortex and neo-cerebellum structures as part of extra-pyramidal pathway. The te**ctospinal tract** plays role in the visual pathway, fibres will decussate at the dorsal tegmental decussation and receives inputs from the contralateral of the colliculus superior at tectum mesencephali. The v**estibulospinal tract** descends from the vestibular nuclei at the brainstem, the lateral tract originates from the ipsilateral lateral vestibular nucleus and mediates excitation of inferior extensor muscles. The r**eticulospinal tracts** descend from the pons and medulla; involve in the control of reflexes, muscle tone (together with the emboliforme and globose nuclei of the cerebellum), and vital functions (in coordination to the reticular formation nuclei of the brainstem).[5,15-16]

Structure of The Spinal Cord Blood Supply

Embryology

Vertebral Artery

A marked variation between individuals is shown due to differences in embryonic development (table 1-3). The vertebral arteries start to develop at day 32 to 40 of gestational period which will fuse and shaping longitudinal anastomoses connect the cervical intersegmental arteries (ISA) of the primitive paired dorsal aorta. Later, the 7th ISA remains to form the proximal subclavian artery which branches off vertebral artery. As the juncture of primitive dorsal aorta receded, the vertebral artery shaped as beaded and contortuous anastomoses, and the basilar artery would then be formed by left and right primitive vertebral arteries fusion.[1,3,11]

Spinal Arteries

Spinal arteries develop from an anterior and posterior segemental artery network of the cord. Two primitive longitudinal systems grow and will fuse as a longitudinal ventral median of anterior spinal artery (ASA), prior to a various regression of segmental alimentary vessels (predominantly in the thoracic and lumbar levels), which is completed by the 4th month of fetal life. Segmental arteries sprouts from the intercostal and lumbar arteries, the radicular arteries represent vital sources reinforce the anterior and posterior spinal arteries. From specific period of neurulation, each cord metamere is supported bilaterally by radicular vessels. These vessels will run in the intervertebral canals as the spinal arteries and penetrate the spinal meninges to follow the nerve roots. They derive from e.g.vertebral, thyrocervical, costocervical, (ascending cervical, deep cervical, ascending pharyngeal), occipital, posterior intercostal, lumbar and lateral sacral vessels. Most of these radicular arteries will regress; the remains form anastomoses with ASA dan PSAs. The branches from various arteries formed the radicular arteries, these tributary vessels support the longitudinal artery system of the cord especially for the segments lower than cervical metemeres.[2,3,11]

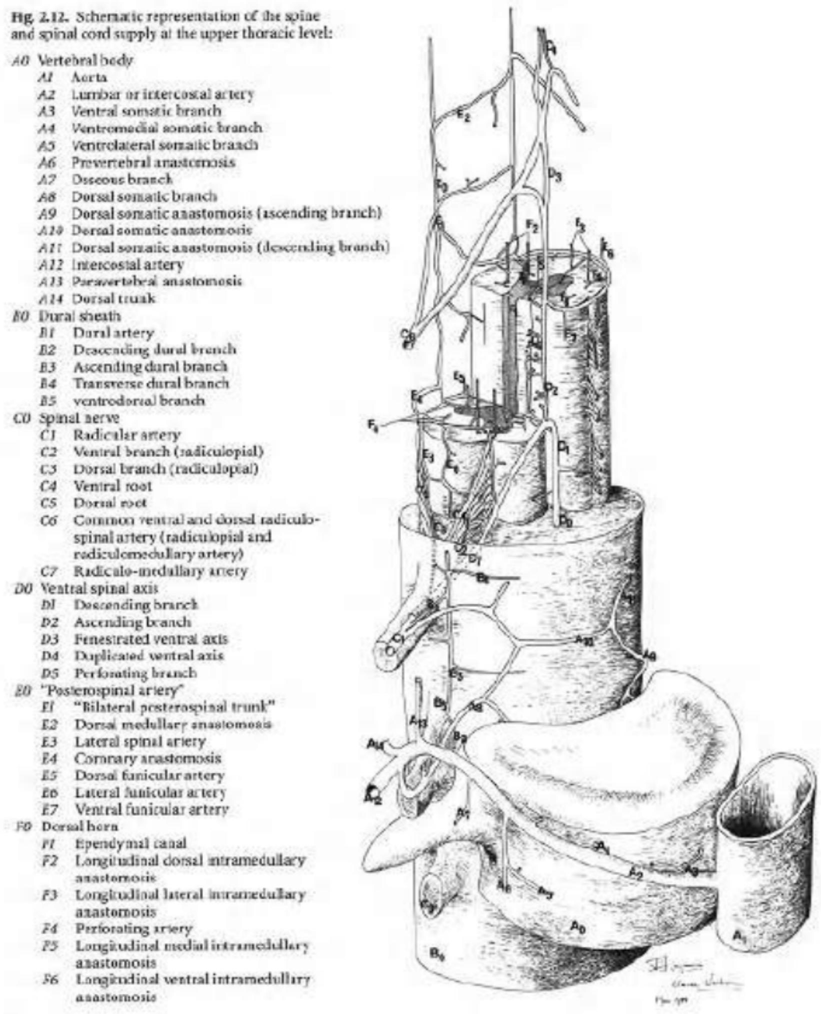
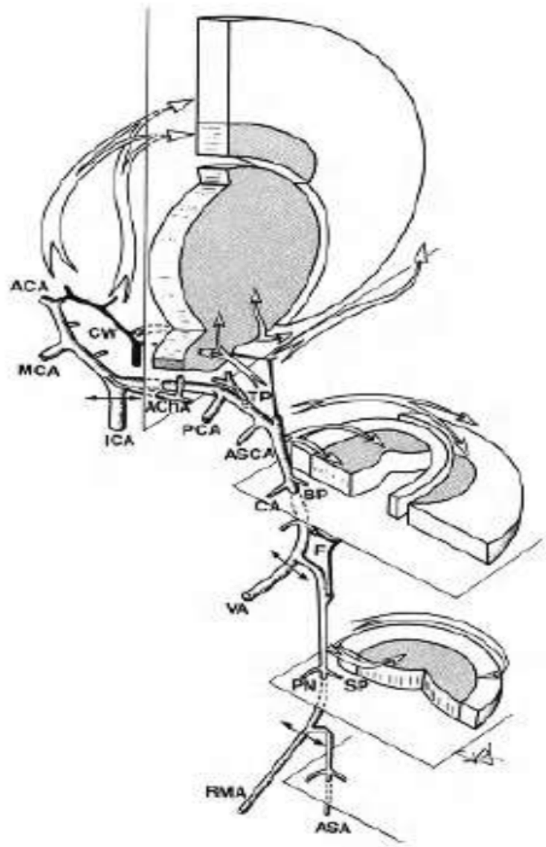


Figure 4. A schematic picture of the vertebral body, dural sheath, spinal nerve, anterior and posterior spinal axis and the cornu dorsalis.[11]



Vertebral level	Right side, *n* (%)	Left side, *n* (%)
4th cervical	3 (1.5)	1 (0.5)
5th cervical	13 (6.5)	55 (7.5)
6th cervical	179 (89.5)	179 (87)
7th cervical	5 (2.5)	10 (5)
Total	200	245

Figure 5. The structure of arterial supply of the encephalon and the spinal cord shows a rather similar pathways in terms of the anatomoses and fusions, as well as the bifurcations that make the centrifugal appearance surrounding the brain and along the neural tube derivative of the segmental spinal cord (long open curved arrow) (VA: vertebral artery, ASA: anterior spinal artery, RMA: radiculomedullary artery, PN: pial network, CA: circumferential artery, CWA: circulus arteriosus of Willis, F: fusion, ICA: internal carotid artery, ASCA: anterior superior cerebellar artery, ACA: anterior cerebral artery, MCA: middle cerebral artery, PCA: posterior cerebral artery, SP: sulcal perforator artery, BP: basilar perforator artery, TP: Thalamo perforator artery, AchA: anterior choroidal artery). The below table shows variations of the vertebral artery entrance into vertebral canal.[11]

Histology

The arterial wall has layers, from superficial to the deeper parts are tunica adventitita formed by fibrous and loose connective tissue, nerves and vasa vasorum whilst tunica media composed predominantly by the smooth muscle and fibrous tissue, and tunica intima composed of a layer of flat epithelium. However, in the arteries of CNS, sparse external elastic lamina and relative lack of tunica media and adventitia are observed. The landmark of first intradural branch in the anterior is the ophthalmic artery; and the posterior cerebellar artery (PICA) of the V4 at the dorsal part (figure 6).[2,3,7]

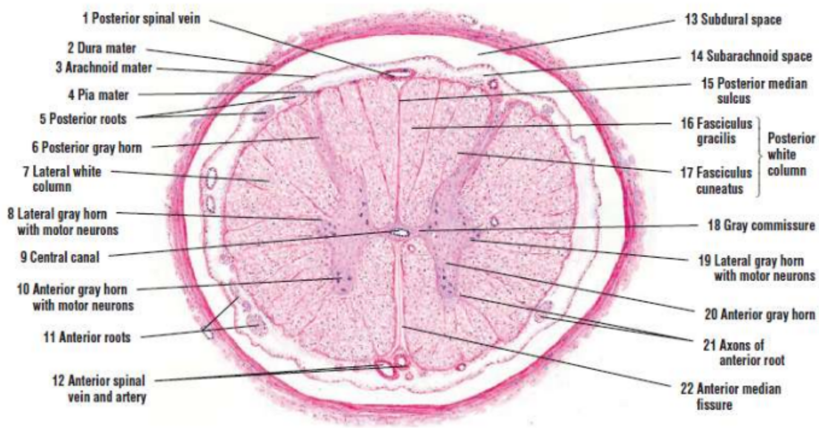


Figure 6. The histology of the coronal section of the midthoracic spinal cord in H/E staining shows the funiculum at the peripheral part whilst the horn or cornu at the ventral, dorsal and lateral side of the deeper part surrounding the central canal of the spinal cord.[7]

Vascular Anatomy of The Spinal Cord

There are 4 parts of vertebral arteries, V1-V4, the first part is origin of the right and left subclavian artery, although in 80-90% is running cranially to enter the C6 or C7 transverse foramen whilst in 2-6% of cases the origin of the left vertebral artery comes from the aortic arch between the left common carotid artery and left subclavian artery. Other variation includes VA from the aortic arch then runs into the transverse foramen of C5; the left VA is from the left common carotid artery or external carotid artery; the right vertebral artery is from the aorta, carotid arteries, or brachiocephalic trunk, and the findings of rami musculares in the cervical part. The VA2 runs cranially from C2-C6, where A. Meningeal Anterior sprouts approximately at C2-C3, whereas falx cerebelli and occipital posterior fossa medial duramater are supplied by the posterior meningeal artery. The VA3 is a wide external cervical loop at C2-C1 that is prone to pseudoaneurysm or dissection. This part passes away at the superior of atlas (C1) transverse foramen, then located superior to the C1 corpus before goes posteromedially around the atlantooccipital articulation to posterior and acutely turn anterosuperiorly and penetrates duramater at the foramen magnum. Several variations reported are the persistent 1st intersegmental artery resides at the inferior of C1 arch, just after exiting the C2 transverse foramen (3-4%).

The VA4 is the last one and located intracranially via the foramen magnum, where the branches include the anterior spinal artery (ASA), two posterior spinal arteries (PSAs), and the rami perforantes. The ASA and two PSAs branch off at the distal vertebral arteries at foramen magnum, whilst ASA then resided on the median ventral sulcus, the PSAs run parallel to each other in a dorsal paramedian area.[2,3,11] Posterior Inferior Cerebellar Arteries (PICA) that might be from the VA4, has several variations include vertebral arteries are not fused to form the basilar artery rather to end in PICA. The ASA may also from the PICA, and is supported by segmental feeders where its central branches supply the anterior 2/3 of the cord (cornu ventralis, spinothalamic and corticospinal tracts).[2,3,11] Approximately 2-3 anterior and posterior radiculomedullary arteries arise from the vertebral arteries in the cervical segment, largest is the artery of intumescentia cervicalis starts at the C4-C8 (most common at C6 nerve root) (figure 4-5).[5,9,11] The ASA and PSAs are supported by 8 to 10 Aa. Medullares Segmentale (from A. Spinalis Segmentalis); the largest is A. Radicularis Magna (of Adamkiewicz) usually developes at the left thoracolumbar segments to support the inferior part of the spinal cord including the intumescentia lumbalis (figure 7). A copy of ASA untill the C5-C6 level are reported often, the branches supply the lamina VIII-IX of the ventral horn, lamina VII of the lateral horn, the central grey matter of lamina X, the ventrolateral funiculi and the anterior part of the dorsal horn.[1,2,11] Meanwhile the vasocorona arteries supply piamater spinalis, whilst the

PSAs and the pial arterial plexus (vasocorona) supply dorsal funiculi e.g. the I – VI Rexed laminae.[1-3]

Table 1. The arterial supply of the spinal nerves.[11]

Spinal nerve root	Peripheral nerves	Source of supply (usual → to → unusual)
C1 – C2		Ocipital – Vertebral – PICA
C3	Phrenic nerves	Asc. pharyngeal – ASC. cervical – Vertebral
C4		Asc. cervical – Vertebral
C5	Brachial plexus	Asc. cervical – Vertebral – Costocervical
C6		Vertebral – Costocervical – Asc. cervical
C7		Costocervical
C8		Costocervical
T1 – T2		Costocerival – Supreme intercostal
T3 – T4 – T5		Supreme intercostal – Costocervical
T6 – T12		Corresponding intercostal
L1 – L4	Lumbosacral plexus and sciatic nerve	Corresponding lumbar
L5		Iliolumbar – Middle sacral
S1		Lateral sacral – Iliolumbar – Middle sacral
S2 – S5		Lateral sacral

The posterior spinal arteries (PSAs), which are more redundant than the ASA, form a plexiform network and supply posterior 1/3 of the cord (dorsal horn and columns, with variable supply to the lateral corticospinal tracts). Together with ASA, PSAs run inferiorly to conus medullaris, where the diameter of ASA is the largest. After passing the conus and filum terminale, these vessels end as a group of rami cruciantes (figure 8).[2,3,11]

Table 2. The morphological extrinsic arterial variation of the spinal cord.[11]

	Cervical	Upper $^2/_3$ thoracic	Lower $^1/_3$ thoracic	Lumbo-sacral
Radicular arteries	Cervical enlagement 400 – 600 μm		Thoracic-lumbar enlargement 550 – 1200 μ	
	Anterior N = 2 – 4	N = 2 – 3		N = 0 – 4
	Posterior N = 3 – 4	N = 6 – 9		N = 0 – 3 (150 – 400 μm)
Anterior spinal artery	200 – 500 μm	Could be discontinued 200 – 400 μm		500 – 800 μm filum artery
Posterolateral spinal artery	100 – 200 μm	< 250 μm Midline posterior spinal artery	200 μm	100 – 400 μm
Fenestration duplication	– Frequently > 50% – Sulcal artery = pseudoduplication – Descending sulcal trunk	Rare	Rare	Exceptional

Table 3. The internal arterial supply of the spinal cord.[11]

	Cervical	Upper $^{2}/_{3}$ thoracic	Lower $^{1}/_{3}$ thoracic	Lumbo-sacral
Sulcal arteries N = 200–240	100–200 µm N = 60–80 n = 3–10/cm	Territory 15–20% 80–200 µm N = 70–100 n = 1–3/cm	Ascending course	Territory 30%–50% 250 µm N = 80–100 n = 6–10/cm
Radial arteries and vasa corona	Perforators 50 µm	Transparenchymatous Pial ascending and descending anastomoses		60 µm
Intrinsic branching	Horizontal	Ascending and descending		Horizontal

N, overall number of arteries; n, density of arteries.

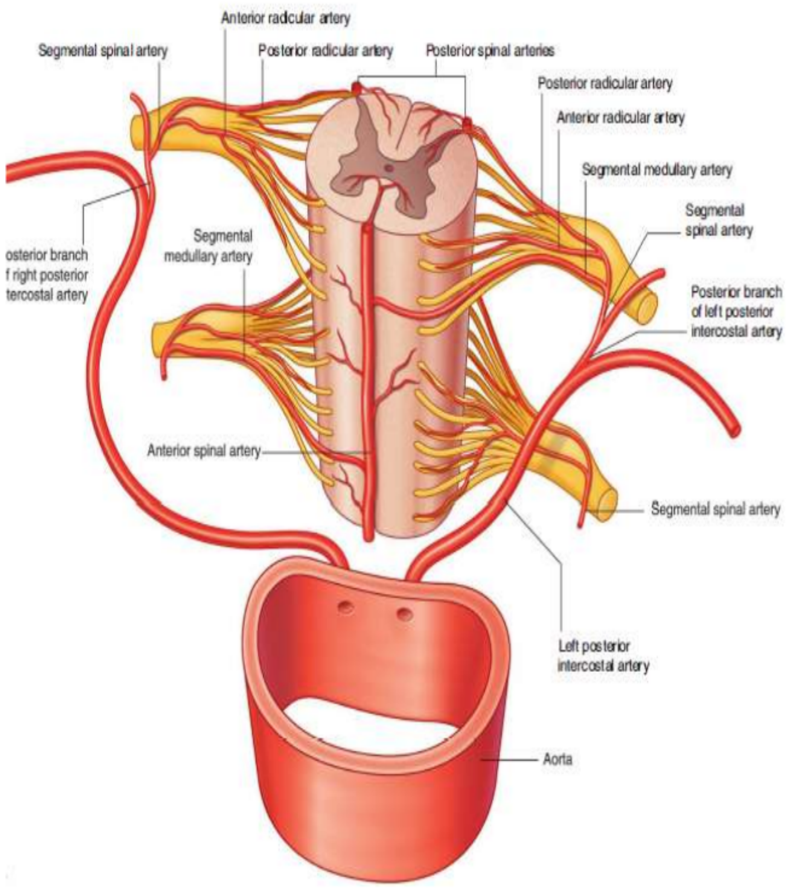


Figure 7. The segmental arterial supply of the spinal cord.[9]

The number and diameter of anterior segmental vessels are paradoxical. These arteries come from various sources i.e. in the cervicothoracic region the intercostal arteries come from the aorta or costocervical trunk, a branch of the subclavian artery; the 1st and 2nd posterior intercostal arteries of supreme intercostal artery (a branch of the costocervical trunk of the subclavian artery). Branches of dorsal side of the thoracic aorta and the subcostal artery, together with small segmental arteries from the aorta at 1 to 2 vertebral levels inferior to their perfusion area are sometimes traveling cranially of their site of origin to supply the lower part.[2,3,11]

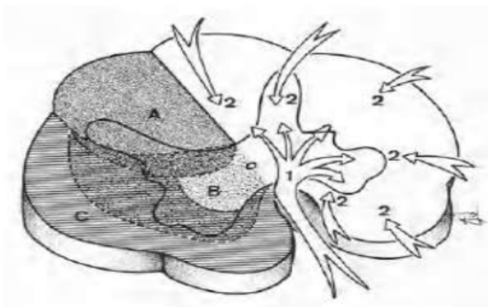


Figure 9. The axial distribution of the sulcocommissural (1), radial (2) arteries. The dorsal (A) and the lateral (C) areas overlap with the ventral area of the sulcal aretry (B).[11]

The ASA in thoracic level is smaller than the other regions, and the longitudinal artery system is supported by radiculomedullary arteries at each segment i.e. by Artery of Lazorthes at C5-C7 levels, Artery of Adamkiewicz at the thoracolumbar region which often found at the left-side (75%). This artery arises from T9-T12 (60%), from lumbar region (25%) and 10% from T6-T8 to L2. Artery of von Haller, a hairpin loop as it branches into ascending and larger descending rami to join the ASA, can be found at the T5.[1-3] A collateral blood supply can also be found as a Basket artery of the conus medullaris whilst the internal iliac artery gives off inferior and superior lateral sacral branches, which branches supported spinal arteries via the anterior sacral foramen for conus medullaris as conus artery or Artery of Desproges-Gotteron. The posterior intercostal arteries that enter the neural foramen and penetrating the dura as the radiculomeningeal (dural) artery supply both the nerve root and its dura, the radiculomedullary artery, the anterior and posterior radicular artery supply the anterior and posterior nerve roots, and medullary artery also support the ASA and PSAs (figure 9). [1,3,11]

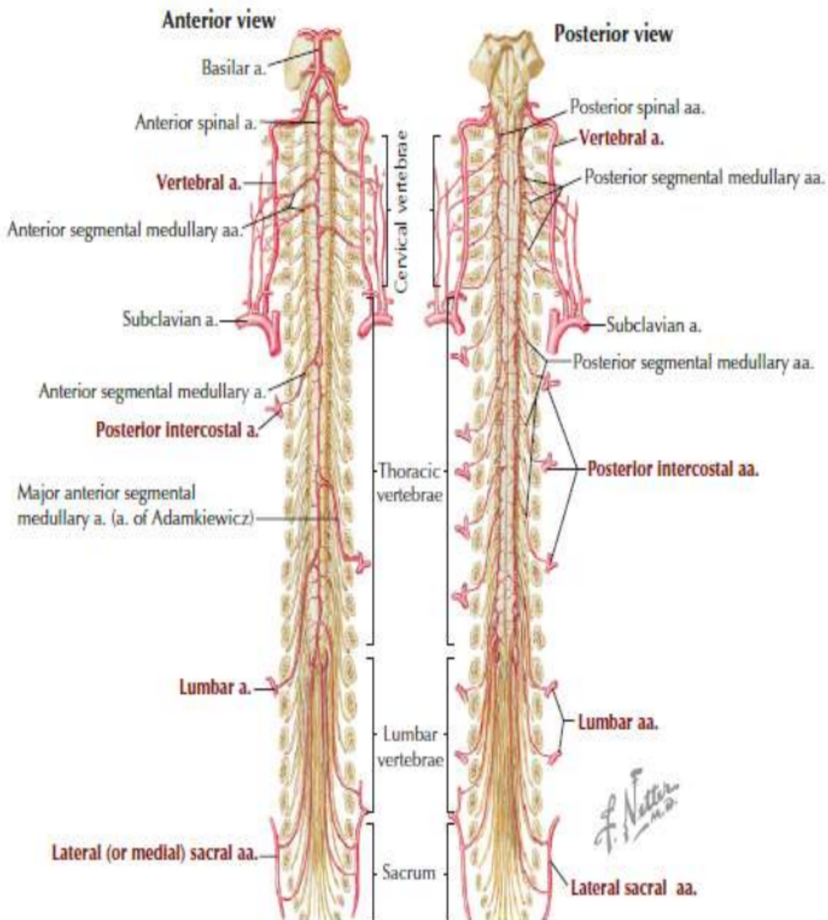


Figure 8. The diagram of arterial structure from the ventral and dorsal side of the spinal cord.[9]

In the spinal cord, the veins are more symmetric and vast than the arterial system with less variation of ventral to dorsal and right to left segments. The anterior median vein runs at the ventral median fissure receiving drainage from the ventral horn and funiculus, to the filum terminale at the terminal thecal sac. The median veins drain into the radiculomedullary veins, leaving the intradural space at the root sheath.[11,12,15]

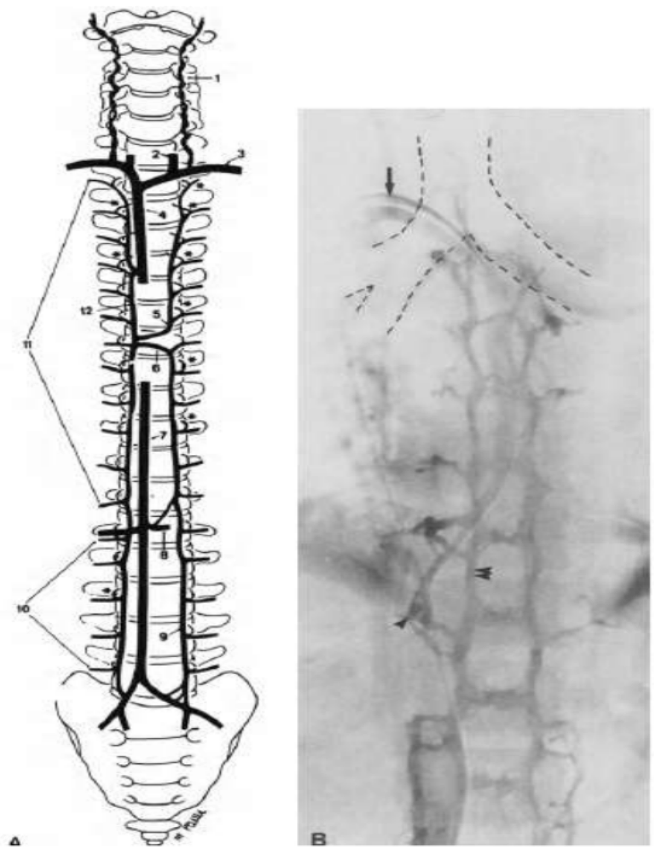


Figure 10. The structure of the veins of the spinal cord from anterior (A) and catheteriztion of the azygos veins (arrow) to its confluence (arrowhead) (B). (1. vertebral vein, 2. jugular vein, 3. subclavian vein, 4. superior vena cava/ SVC, 5. left sided-superior azygos vein, 6. left sided- inferior azygos vein, 7. inferior vena cava, 8. left renal vein, 9. ascending lumbar vein, 10. lumbar veins, 11. intercostal veins, 12. azygos vein. Opacification of the epidural venous plexus is pointed by the double arrow.[11]

Plexus venosus epidurale (of Batson) receives drainage from the peripheral and dorsolateral cord together with the radial venous plexus and the coronal venous plexus at the dorsal side. The plexiform venous system at the medial and lateral-anterior and posterior sides of the dorsal and ventral rootlets formed a continuous system from sacrum to the cranial base. Two pairs of longitudinal veins run in the length of each ventral and dorsal root to the cord, and drain into internal vertebral plexus in the extradural (epidural) space of the vertebral canal. From there, segmental veins are connected to the systemic veins, i.e. azygos/ hemiazygos veins. The radicular veins receive tributaries from the internal vertebral veins (which also connect to the intracranial veins) that run in the vertebral canal, and connected with segmental veins which then drain into the superior and inferior vena cava, azygos and hemiazygos veins, deep cervical veins, the intercostal-segmental vein and the ascending lumbar vein. At the dorsal side, the basivertebral veins, ventral plexus of vertebral body and dorsal plexus have connection with sinus venosus duraematris, the superior and inferior vena cava, and azygos/ hemiazygos system (figure 10).

The Veins of Vertebrae

The vertebral veins composed of vast valveless vein plexus in the vertebral column run from hiatus sacralis to foramen magnum. These veins are in anastomoses with the clival plexus, the suboccipital sinus, the internal and external venous plexus and Vv. Basivertebrales.[1-3]

Epidural plexus

This plexus is ended at the thecal sac, where the medullary veins run from the sacrum to the cranial base with plexiform venous channels, the ventral and dorsal midline veins, antero- and posterolateral veins at the dorsal and ventral radix attachments; these veins drain into the SVC, IVC, azygos/ hemiazygos system with anastomoses to sinus venosus duraematris.[1,3,11]

CONCLUSION

The anterior and posterior spinal arteries assisted by radiculomedullary arteries of supply the arterial blood of the spinal cord. Variation of the vessels of the spinal cord are reported amongst individuals thus comprehension of the complexity of these structures must be well understood whilst this needs to be elucidated in the future research.

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