Anatomical Correlation of the Arterial Blood Supply to the Spinal Cord in Human and Experimental Animals: A Review

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Abstract

Several animal models exist to examine physiological and functional changes after the spinal cord injury with aim to explain knowledge about the spinal cord injury in human. Before the appropriate animal model is chosen, many aspects must be considered to eliminate the wrong interpretation of the results. The knowledge of the arterial blood supply to the spinal cord is very important in planning the procedures of the spinal cord treatment as well as in animal experiments. As the literature on the topic is disarranged, the aim of this review is to summarize the available literature into one coherent format. This chapter compares the arterial spinal cord blood supply of the frequently used species (pig, dog, cat, rabbit and rat) in experimental spinal cord injury and in human. A complete understanding of the anatomy of the arterial blood supply to the spinal cord is critical for the anatomists and clinicians to determine the advantages and disadvantages of each animal model for next studies.

Keywords: anatomy, arterial blood supply, experimental animal, human anatomy, spinal cord injury

1. Introduction

Various pathological conditions, including surgical treatments, traumatic injuries, embolism, malformations and tumors, result in severe changes in the arterial blood supply to the spinal cord [1]. The degree and type of present symptoms depend on the affected part of the spinal cord. Spinal cord injury is associated with sustainable disability and results in loss of bladder, respiratory, cardiac, or sexual functions, and in varying degree of paralysis [2]. The superficially located fine arterial system of the spinal cord predisposes the induction of the spinal cord ischemia by spinal cord injuries.

The arterial blood supply to the spinal cord is most profusely documented in human [1, 3, 4]. Several animal species serve in different experimental studies of spinal cord injury as models: pig [5–7], dog [8–10], cat [11–13], rabbit [14–16], guinea pig [17–19], rat [20–22] and mouse [23–25]. To understand the physiologic and pathophysiologic mechanisms of various spinal cord diseases and the effects of several neuroprotective drugs, the detailed knowledge of the spinal cord arterial blood supply is necessary. The following review discusses the current knowledge, principles, peculiarities, variations and known differences in the arterial blood supply to the spinal cord in the most frequently used species of experimental animals and in human.

2. Pattern of the arterial blood supply to the spinal cord

The spinal cord is mainly supplied by the segmental spinal branches. The majority of them originate in the cervical part from the vertebral arteries, in the thoracic part from the dorsal intercostal arteries and in the lumbar part from the lumbar arteries.

2.1. Cervical part of the spinal cord

The cervical part of the spinal cord is except the spinal branches arising from the vertebral artery also supplied by numerous small branches originating from the posterior inferior cerebellar artery. They supply the most cranial part of the first cervical segment of the spinal cord.

The vertebral artery belongs to the branches of the subclavian artery. Through the thoracic inlet leaves the vertebral artery the thoracic cavity. After it's leaving of the thoracic cavity continues towards the transverse foramen of the sixth cervical vertebra in the craniodorsal direction. Inside the transverse canal of the cervical vertebrae, it continues cranially. The vertebral artery reaches the lateral foramen of the atlas through which it enters the vertebral canal. On the floor of the vertebral canal, both vertebral arteries unite together to form the basilar artery, which continues cranially and connects to the arterial circle of the brain. The segmental spinal branches are arising from the vertebral artery along its course inside the transverse canal. They enter the vertebral canal at each segment through the lateral vertebral or intervertebral foramina.

2.2. Thoracolumbar part of the spinal cord

The thoracolumbar part of the spinal cord receives the arterial blood from the spinal branches originating from the paired segmental arteries: the dorsal intercostal and lumbar arteries.

The paired dorsal intercostal arteries originate from the thoracic aorta and/or from some branches of the subclavian artery. The number of dorsal intercostal arteries and the number of the intercostal spaces is the same. The last dorsal intercostal artery is designated as the dorsal costoabdominal artery. They convey the arterial blood to the caudal cervical segments and thoracic part of the spinal cord.

Each dorsal intercostal artery is directed towards the corresponding vertebral body. After it crosses the vertebral body, it gives off the dorsal branch which runs caudoventrally to the transverse process. The main continuation of the artery is directed to the corresponding intercostal space. After the passage of the intercostal space, the interspinal branch to the muscles, interspinal ligaments and spinous processes arise. The spinal branch originates at the level of the intervertebral foramen [26].

The segmental paired lumbar arteries give off the spinal branches supplying the lumbar part of the spinal cord. In almost all cases, the lumbar arteries arise from the dorsal surface of the abdominal aorta.

Each lumbar artery runs on the lateral surface of the corresponding lumbar vertebral body, is directed to the caudal margin of the transverse process and thereafter gives off a branch designed for the vertebral body. The spinal branch arises from the lumbar artery as the second branch. The main continuation of each lumbar artery follows the transverse process of the corresponding lumbar vertebra [26].

2.3. Spinal branches

The majority of the spinal branches supplying the spinal cord originate from the vertebral arteries, dorsal intercostal arteries, and lumbar arteries. At each segment, they enter the vertebral canal passing through the intervertebral foramen. Their passage through the foramen is associated with the corresponding nerve root where they are superficially covered by the perineurium. The spinal branches are loosely attached to the nerve root inside the subarachnoidal cavity. Each of the spinal branches divides into the dorsal or ventral branch, or in some cases in both of them.

The spinal branches are divided into three types:

1. The spinal braches supplying the nerve root or dura mater. They do not reach the spinal cord.
2. The spinal branches ending in the superficial arterial system of the spinal cord.
3. The spinal branches reaching and supplying the spinal cord.

The spinal branches convey the arterial blood to the corresponding nerve root, spinal ganglion, dura mater, dorsal spinal arteries and ventral spinal artery [27]. The calibre of the spinal branch determines which structures are supplied. The spinal branch with smaller diameter very often supplies only the nerve root [28].

On the dorsal and ventral surface of the spinal cord are present the dorsal and ventral branches arising from the spinal branches divided into the small cranial and caudal branches. In some cases, these branches are recognizable and their fusion constitutes the dorsal spinal arteries and the ventral spinal artery.

The dorsal and ventral branches occurring at the same level and side, give off small superficial branches which constitute the spinal arterial ring [28, 29] or the *vasa coronae* [30]. The pial arterial plexus is formed by a network of anastomoses encircling the spinal cord. The majority of branches arising from the pial arterial plexus enter the midline of the dorsal surface of the spinal cord, supplying the outer part of the spinal cord including the major part of the dorsal horns [28].

2.4. Extrinsic arteries

The majority of the intrinsic arteries (central arteries) arise from the ventral spinal artery. In place of fusion of bilateral vertebral arteries, the ventral spinal artery is in cranial connection with both of them or only with one of them. The ventral spinal artery is located in the ventral median fissure and continues throughout the whole length of the spinal cord [28]. To the level of the thoracic part of the spinal cord decreases the diameter of the ventral spinal artery. It is constant in the thoracic part and more caudally is the artery hardly recognizable. At the level of joining of the artery of Adamkiewicz, the ventral spinal artery reaches its smallest diameter. Caudally to this junction, the ventral spinal artery becomes larger in diameter.

The lower thoracic, lumbar and sacral part of the spinal cord are supplied by a spinal branch with larger diameter which is known as the artery of Adamkiewicz (*arteria radicularis magna*, great radicular artery). The typical hairpin curve of the artery of Adamkiewicz is caused by a different speed of growth of the spinal cord and vertebral column [31]. Before accompanying the corresponding nerve root, the artery courses cranially form an oblique angle. After giving off a small cranially directed branch, the artery reaches the ventral median fissure. The artery of Adamkiewicz is continuing vertically, turns caudally in an acute angle and reaches the ventral median fissure. This anatomical arrangement predisposes the direction of the blood flow into the caudal segments of the spinal cord [32].

In the dorsal lateral grooves of the spinal cord, the longitudinal dorsal spinal arteries run. The cranial connection of the dorsal spinal arteries is to the posterior inferior cerebellar arteries or to the vertebral arteries. The diameter of the arteries varies according to the part of the spinal cord.

2.5. Intrinsic arteries

The vascular network formed by the intrinsic arteries consists of the central and peripheral system. The central system supplies the ventral two-thirds of the spinal nervous tissue. The blood flow is centrifugal from the ventral spinal artery. The blood of the central system supplies the base of the dorsal columns of the white matter, the ventral grey matter, dorsal columns of the white matter, ventral part of the dorsal grey matter and inner half of the ventral and lateral columns of the white matter. The peripheral system conveys the blood through the pial arterial plexus and dorsal spinal arteries centripetally. Dorsal columns of the white matter, dorsal part of the dorsal grey matter and outer part of the ventral and lateral columns of the white matter are supplied by the peripheral system [28].

The ratio of blood supply to spinal cord by central and peripheral system is variable according to the part of the spinal cord. The central system is large in the lumbar and cranial sacral segments, the central and peripheral system are large in the cervical segments and the peripheral system is large in the thoracic segments [28].

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3. Human

To the most important factors affecting the severity of degree and clinical results of the spinal cord injury belongs the spinal cord ischemia. The planning of surgical and endovascular interventions cannot be successful with the detailed knowledge of the arterial system of the spinal cord [28].

3.1. Cervical part of the spinal cord

The cervical spinal cord is supplied by segmental spinal branches arising from the vertebral, deep cervical and ascending cervical arteries [33]. The cranial three to five spinal branches in the cervical part originate from the vertebral arteries and in the caudal part from the deep cervical, ascending cervical arteries and the supreme intercostal artery [34]. Occasionally some caudal spinal branches in the cervical part may arise as direct branches from the subclavian artery [32]. The branches of the ascending cervical artery fuse together with the branches of the vertebral and deep cervical artery before giving of the spinal branches [35].

In the literature, high variability in the origin of the vertebral artery was described [36]. The vertebral arteries originate from the first parts of the subclavian arteries. After they leave the thoracic cavity through the thoracic inlet, they enter the transverse canal at the level of the sixth cervical vertebra and continue inside the canal to the head. They enter the vertebral canal via the transverse foramen of the atlas.

The arterial blood to the cervical spinal cord convey eight to ten unpaired ventral spinal branches originating from dorsal segmental branches [32]. One of them is located at the level of the sixth cervical vertebra, and one to three cranially and caudally to this spinal branch [37]. They enter the ventral spinal artery. The largest of them is located at the cervical enlargement at the level of the sixth or fifth cervical segment (rarely at the fourth or seventh cervical segment) [27, 34] and it is arising from the deep cervical artery (in case of rare location from the ascending cervical artery or costocervical trunk). The second largest spinal branch is positioned at the level of the third cervical segment (rarely at the second or fourth cervical segment) [34].

The ventral spinal artery is cranially connected to the both vertebral arteries [38, 39]. It has a form of an uninterrupted trunk located in the ventral median sulcus, will often bifurcate and vary in size [40].

Two plexiform dorsal spinal arteries are cranially connected to the vertebral arteries or posterior inferior cerebellar arteries [41–43]. Their diameter is the largest in the cervical region [32].

3.2. Thoracolumbar part of the spinal cord

The thoracic part of the spinal cord is supplied by spinal branches originating from the intercostal arteries [33]. From the dorsal surface of the thoracic aorta, nine pairs of segmental intercostal arteries and one pair of subcostal arteries arise [34]. Two to four small spinal branches enter the ventral spinal artery in the thoracic part [32].

The segmental spinal branches supplying the lumbar part of the spinal cord are branches of the paired lumbar arteries, iliolumbararteries, and the lowest lumbar artery. In the sacral part convey the arterial blood the lateral sacral arteries [33]. The lumbar arteries are present in four pairs with origin from the dorsal surface of the abdominal aorta. The iliolumbar artery branches either from the abdominal aorta and median sacral artery [34].

The arterial system in the middle segments of the thoracic part is poorly developed. In the majority of cases, it is supplied only by one spinal branch originating from the seventh intercostal artery. The ventral spinal artery is discontinuous in this region [44].

The second spinal branch participating on the blood supply of the thoracic and lumbar part is the artery of Adamkiewicz [45]. It is the largest spinal branch with variable level of its origin [46–48]. In 75% of cases, its origin is located at the level between ninth and twelfth thoracic segment, in 15% of cases between the fifth and eighth thoracic segment and in 10% of cases between the first and second lumbar segment [42, 47]. As left-sided artery, it was described in 80% of cases [49]. The artery of Adamkiewicz supplies 68% of perfusion to the caudal thoracic and cranial lumbar part of the spinal cord [50]. This artery forms a typical hairpin curve and thereafter reaches the ventral spinal artery [47, 51]. In the case of the origin of the artery of Adamkiewicz at the level between the fifth and eighth thoracic segment, an accessory artery known as the Desproges-Gotteron artery (cone artery) can be present. Its ordinary position is at the level between the second and fifth lumbar segment [52]. Most frequent level is the second lumbar segment, but it may vary between the eighth thoracic and fourth lumbar segment [42].

The spinal branches in the sacral part of the spinal cord originate from the lateral sacral arteries and the median sacral artery. They supply the nerve roots and sacral nerves. The extensive anastomosis on the ventral surface of the sacrum is formed by spinal branch directed to the first ventral sacral foramen and spinal branches, which enter the second, third and fourth ventral sacral foramina [34].

Along the whole length of the spinal cord, the ventral spinal artery receives six to eight significant ventral branches. The ventral branches have a larger diameter and are less numerous as the dorsal branches [32, 33]. The bifurcation is formed when the ventral branches enter the ventral spinal artery from both sides at the same segment. Such bifurcation forms a diamond-shaped pattern. The diameter of the ventral spinal artery correlates to the relative amount of the grey matter [34]. Its widest point is at the junction with the artery of Adamkiewicz and the second widest at the cervical enlargement. The ventral spinal artery is narrowest in the middle segments of the thoracic part of the spinal cord [32].

Two dorsal spinal arteries are located on the dorsal surface of the spinal cord and they receive eight to sixteen significant dorsal branches. They join at the caudal level of the *conus medullaris* with the ventral spinal artery to form the conus basket which extends to the *filum terminale* [53]. The ventral spinal artery gives off two dorsally directed terminal branches which anastomose with each dorsal spinal artery at the level of the fifth sacral segment [54]. The diameter of the dorsal spinal arteries is smaller in the thoracic region than in lumbar region [32].

4. Experimental animals

4.1. Pig

Despite the widespread and intensive use of the pig as an animal model in the experimental spinal cord injury, there is a gap in the information of its spinal cord arterial supply [55, 56].

4.1.1. Cervical part of the spinal cord

The vertebral arteries arise uniformly as the first branches on both sides from the costocervical trunk [57] or variably [26]. The right vertebral artery is the second branch arising from the right costocervical trunk and the left vertebral artery is the third branch with the origin from the left subclavian artery [26].

The spinal branches supplying the cervical part of the spinal cord are arising segmentally from the bilateral vertebral arteries [57]. The ventral spinal artery is cranially connected by means of two ventral branches to the vertebral arteries in the place of formation of the basilar artery [57, 58]. The ventral spinal artery is uninterrupted and entered on average by six ventral branches [58].

4.1.2. Thoracolumbar part of the spinal cord

In the literature, the variable arrangement of the dorsal intercostal arteries is described. The first dorsal intercostal artery has origin from the vertebral artery [57], supreme intercostal artery [59] or it is not present [26]. The second dorsal intercostal artery is absent in generally [26] or it arises in some cases from the dorsal scapular artery or regularly from the vertebral artery [59]. The third, fourth and the fifth dorsal intercostal arteries are arising from the supreme intercostal artery [26] or from the dorsal surface of the thoracic aorta as independent branches [59]. The rest of the dorsal intercostal arteries of the same level originate from the dorsal surface of the thoracic aorta as individual branches [55, 56, 60] or they form a common trunk of origin [59].

The arrangement of the lumbar arteries is more constant. They are present as six [55, 56, 60] or five pairs [26, 59] with independent origin from the dorsal surface of the abdominal aorta. In the case of presence of five pairs, the sixth pair of the lumbar arteries branches from the median sacral artery [26].

In the thoracic part, the ventral spinal artery receives on average eight ventral branches and in the lumbar part five ventral branches [58]. In the majority of cases, the artery of Adamkiewicz originates from the caudal part of the abdominal aorta [61]. The range of origin of the artery of Adamkiewicz is from the first lumbar to the first sacral segment. In 87% of cases, the origin is from the third to the fifth lumbar artery [62].

In the pig, the arterial blood supply to the thoracolumbar part of the spinal cord is enriched by the collateral blood flow, which consists of two parts. The first part is coming from the internal thoracic and subscapular artery through the wall of the chest and abdomen. The second part presents the blood coming from the median sacral artery through its spinal branches to the most caudal part of the spinal cord [55].

4.2. Dog

In studies of several spinal cords, diseases serve as an animal model the dog. In the research area, a lot of papers dealing with experimental ischemia in the dog have been published [29].

4.2.1. Cervical part of the spinal cord

The origin of the vertebral artery is located on the subclavian artery before the origin of the costocervical trunk on both sides [26, 63]. The collateral blood flow is formed by connections between four to five muscular branches of the costocervical trunk and each vertebral artery and between the bilateral superficial cervical artery and vertebral artery [64].

The spinal branches originating segmentally from the vertebral artery at each of the seven intervertebral foramina supply the cervical spinal cord. To the largest spinal branches belongs the first [65] and the third [63, 65], and in some cases also the fourth branch [66]. From the dorsal scapular artery that branches from the costocervical trunk originates the eighth spinal branch [66].

The unpaired ventral spinal artery extending the whole length of the spinal cord is formed by the fusion of the ventral branches of the spinal branches [65, 66]. In 67% of cases, the ventral spinal artery is in some segments of the cervical spinal cord doubled [65, 67]. The ventral spinal artery is high variable in its cranial connection: in 20% of cases, it is the point of fusion of bilateral vertebral arteries; in 20% of cases, it is from the bilateral vertebral arteries in the place of formation of the basilar artery; in 40% of cases, it is from the right vertebral artery and in the last 20% of cases, it is from the left vertebral artery [29]. The cranial connection of the ventral spinal artery in the area of formation of basilar artery is also described as constant [63, 68]. The ventral spinal artery is joining 88% of all the possible ventral branches. The diameter of the ventral spinal artery is larger in the cervical than in the thoracic part [65].

From the spinal branches arising dorsal branches form on the dorsolateral surface of the spinal cord an irregular arrangement [66] or continuous dorsal spinal arteries [65] throughout the entire spinal cord. On the dorsal surface of the spinal cord, four dorsal spinal arteries are present. The larger lateral dorsal spinal arteries are located in the dorsal lateral grooves and the smaller medial dorsal spinal arteries in the dorsal intermediate grooves. The dorsal spinal arteries are cranially connected to the basilar artery (60% of cases) or to the rostral cerebellar artery (40% of cases) [29]. The dorsal spinal arteries are formed throughout the whole length of the spinal cord and they receive 88.1% of all the possible dorsal branches. The dorsal branches in the cervical part are originating from the ventral branches [65].

The several anastomoses between the dorsal and ventral spinal arteries form the spinal arterial ring which is higher density in cervical than in the thoracic part of the spinal cord [29].

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4.2.2. Thoracolumbar part of the spinal cord

The dorsal intercostal arteries are present in a number of twelve pairs [66]. The first dorsal intercostal artery branches from the costocervical trunk [26, 66]. The second, third [26, 66] and in some cases the fourth dorsal intercostal artery are coming from the thoracic vertebral artery, which originates from the costocervical trunk [66]. One study described the second, occasionally the third and the fourth dorsal intercostal artery as branches of a common trunk with the fifth right dorsal intercostal artery [69]. The rest of dorsal intercostal arteries originate from the dorsal surface of the thoracic aorta, by which the left-sided arise more cranially than the right-sided [66].

The total number of lumbar arteries is seven pairs. The first and second pair of lumbar arteries are arising from the thoracic aorta because of the attachment of the diaphragm to the third and fourth lumbar vertebrae. The next five pairs are originating from the dorsal surface of the abdominal aorta whereby the left-sided arise cranially to the right-sided. More caudally, the origins of the arteries at the same level become closer and the last pairs of the lumbar arteries originate by means of a common trunk. The last seventh pair arises from a common trunk with the median sacral artery from the terminal part of the abdominal aorta [26, 66]. The median sacral artery represents the caudal continuation of the abdominal aorta. From the median sacral artery originating sacral branches give off spinal branches which enter the ventral spinal artery [66].

The spinal branches with corresponding nerve root enter the vertebral canal on the right side in 72% of cases and on the left side in 62% of cases. The diameter of the ventral spinal artery becomes smaller caudally to the lower cervical part of the spinal cord [29, 65] and it is smaller in the thoracic part in comparison with the lumbar part of the spinal cord. In the thoracic part enter the ventral spinal artery 31.2% from all the possible ventral branches and in the lumbar part 45% of them [65].

In 50% of cases, the artery of Adamkiewicz arises from the left fifth lumbar artery and in 50% of cases, it is absent. It represents the arterial supply to the ventral two-thirds of the caudal half of the spinal cord. In the place of fusion with the ventral spinal artery, it gives off a cranially directed branch to the thinned ventral spinal artery [29]. The arrangement, the side and the level of origin of the artery of Adamkiewicz was observed as high variable [65].

The dorsal spinal arteries in the thoracic part receive 49.6% all the possible dorsal branches and in the lumbar part 60% of them. The diameter of the dorsal spinal arteries is smaller in comparison with the cervical and lumbar part [65].

In the lumbar part, the density of the spinal arterial ring is higher than in the thoracic part [29, 65].

4.3. Cat

Despite the cat does not belong to the most frequently used experimental model in the study of the spinal cord injuries, it has an important place as an animal model in such studies.

4.3.1. Cervical part of the spinal cord

The vertebral artery is bilaterally the first branch arising from the subclavian artery [26, 57, 70].

The ventral spinal artery is cranially connected to the both vertebral arteries in place of their fusion and runs throughout the entire length of the spinal cord [68, 70, 71]. On some distance, it is positioned deeper in the ventral median fissure [70]. 80.6% of all possible ventral branches enter the ventral spinal artery. The first ventral branch has the largest diameter [65].

Two longitudinal dorsal spinal arteries run on the dorsal surface [65, 70]. 95.6% of all possible dorsal branches enter the dorsal spinal arteries [65].

4.3.2. Thoracolumbar part of the spinal cord

The total number of dorsal intercostal arteries is twelve pairs. The first dorsal intercostal artery originates from the costocervical trunk, and the second and third arise from the supreme intercostal artery. The remaining pairs originate independently from the dorsal surface of the thoracic aorta [26].

There are present six pairs of lumbar arteries with origin from the dorsal surface of the abdominal aorta [26, 57, 71]. The median sacral artery gives off the last seventh pair [26, 71].

The diameter of the ventral spinal artery in the thoracic part is smaller in comparison with the lumbar and cervical part [65, 70]. From all possible ventral branches enter the ventral spinal artery in the thoracic part 55.4% and in the lumbar part 42.8% of them [65]. The frequency of the left-sided ventral branches is doubled in comparison with the frequency of the right-sided [71].

Till now, it was described the different anatomical arrangement of the artery of Adamkiewicz in the literature. The origin from the left fourth lumbar artery is designated as uniform [70]. Another one source describes in 80% of cases only a larger ventral branch connecting the ventral spinal artery. In 80% of cases, it arises from the fourth lumbar artery and in 20% of cases from the third lumbar artery. As left-sided artery, it is present in 70% of cases [65]. The similar arrangement describes other work. In 70% of cases, a larger ventral branch originates from the fourth lumbar artery and in 30% of cases from the third lumbar artery. An accessory large ventral branch is formed in 50% of cases [71].

The dorsal spinal arteries in the thoracic part are smaller in diameter than in the cervical and lumbar part. 56.9% of possible dorsal branches enter the dorsal spinal arteries in the thoracic part and 70.7% in the lumbar part [65]. Bradshaw [70] described four dorsal spinal arteries located caudally to the level from the fifth to the seventh cervical vertebra. One pair is located medially and one pair laterally. In the lumbar part, also two dorsolaterally positioned dorsal spinal arteries with no side predominance are observed [71].

The spinal arterial ring is formed only in one-half of cases [71]. The density of the spinal arterial ring in the thoracic part is smaller in comparison with the cervical and lumbar part of the spinal cord [65, 72].

4.4. Rabbit

The rabbit is one of the most used species of experimental animals serving for the study the pathophysiology of the spinal cord diseases and neuroprotective drugs effect on damaged nervous tissue [73].

4.4.1. Cervical part of the spinal cord

Till now, not only constant origin of the vertebral artery from the subclavian artery [74, 75] is described but also variations. In 86% of cases, the left-sided vertebral artery arises from the left subclavian artery, in 10% of cases from the aortic arch and in 4% of cases from a common trunk with the left descending scapular artery with the origin from the aortic arch. In 98% of cases, the right-sided vertebral artery originates from the right subclavian artery. In the remaining 2% of cases, it is formed by the fusion of two branches. The first branch originates from the right subclavian artery and the second branch from the common trunk with the right superficial cervical artery from the common carotid artery [76]. The fusion of both vertebral arteries is in 50% of cases without a gap, in 30% of cases with one longitudinal gap and in 20% of cases with two oval gaps [77].

The unpaired and continuous ventral spinal artery is connected in the area of both vertebral arteries fusion to the right vertebral artery in 40% of cases, to the left vertebral artery in 35% of cases or to the bilateral vertebral arteries in 25% of cases [77]. Another study describes the cranial connection of the ventral spinal artery to the bilateral vertebral arteries in all studied specimens [68]. The left-sided ventral branches enter the ventral spinal artery in 53.8% of cases and the right-sided in 46.2% of cases [77]. The doubled ventral spinal artery without recording its cranial connection is described too [67].

On the dorsal surface of the spinal cord are located two or none dorsal spinal arteries, but the frequency of the presence or absence is not noted [77]. Cranially they are connected to the corresponding vertebral artery, or posterior inferior cerebellar artery [67] or none [77]. The dorsal branches entering the dorsal spinal arteries are present in the same frequency as the ventral branches which are joining the ventral spinal artery [77].

4.4.2. Thoracolumbar part of the spinal cord

The thoracic part of the spinal cord receives the arterial blood from the spinal branches originating from 12 pairs of the dorsal intercostal arteries and from the costoabdominal artery. The dorsal intercostal arteries with the origin from the dorsal surface of the thoracic aorta are present as nine pairs in 70% of cases, as eight pairs in 20% of cases and as 10 pairs in 10% of cases. The rest of them is coming from the supreme intercostal artery. The arrangement of the dorsal intercostal arteries of the same level is high variable [78]. The dorsal intercostal arteries originate as paired segmental branches arising from the dorsal surface of the thoracic aorta [74, 75, 79].

The lumbar arteries originating from the dorsal surface of the abdominal aorta which are supplying the lumbar part of the spinal cord are present in a number of six pairs in 90% of cases and in a number of five pairs in 10% of cases [78]. The last seventh pair branches from the median sacral artery [78, 79]. The lumbar arteries of the same level arise as independent branches in 60% of cases and in 40% of cases is their origin high variable [78]. Also, seven pairs of segmental lumbar arteries with origin from the abdominal aorta in all the studied specimens are possible [74, 75].

The continuous and unpaired ventral spinal artery is positioned in the ventral median fissure [78]. In the lumbar part of the spinal cord is possible the presence of three parallel longitudinal ventral spinal arteries [68]. In the thoracic part of the spinal cord, the left-sided ventral branches joining the ventral spinal artery are present in 71% of cases and the right-sided in 29% of cases. In the lumbar part in 62.5% of cases are formed the left-sided ventral branches and in 37.5% of cases the right-sided [78].

The artery of Adamkiewicz originates in 50% of cases from the right-sided and in 50% of cases from the left-sided sixth lumbar artery [78]. In the other work, the presence and the level of the origin of the artery of Adamkiewicz is not recorded [68].

In 70% of cases, two dorsal spinal arteries are present, in 20% of cases no one and in 10% of cases three. The left-sided dorsal branches joining the dorsal spinal arteries are present in the thoracic part in 60.5% of cases and right-sided in 39.5% of cases, in the lumbar part the left-sided in 52.5% of cases and right-sided in 47.5% of cases [80].

4.5. Rat

The rat is matchless the most frequently used experimental animal in the study of spinal cord injury and absolutely in the study of the spinal cord ischemia.

4.5.1. Cervical part of the spinal cord

The both vertebral arteries arise from the subclavian arteries as the second branches after the origin of the costocervical trunks [81, 82]. The cranial connection of the ventral spinal artery is by means of two ventral branches to the bilateral vertebral arteries in the place of the formation of the basilar artery [81, 83].

Two ventral spinal arteries [67, 82] are in connection with the corresponding vertebral artery [82] or without cranial connection [67]. Three to four ventral branches join the ventral spinal artery in the cervical part of the spinal cord [68, 83]. The last cervical segments have rich arterial blood supply by means of the ventral branches [84]. On each side originates from the vertebral artery the corresponding dorsal spinal artery [81].

4.5.2. Thoracolumbar part of the spinal cord

The dorsal intercostal arteries are present in a number of twelve pairs. The first, second and third pair arise from the supreme intercostal artery which originates from the costocervical trunk. From the dorsal surface of the thoracic aorta, nine pairs of the dorsal intercostal arteries arise independently. The dorsal costoabdominal artery represents the last segmental pair [82]. The origin of the dorsal intercostal arteries at the same level from the dorsal surface of the thoracic aorta was described also by means of a common trunk [85].

Five pairs of lumbar arteries with independent origin [82] or with origin by means of a common trunk [85] arise from the dorsal surface of the abdominal aorta.

The cranial thoracic part is supplied by means of a poor arterial system formed by segmental branches in this area [84]. The unpaired and uninterrupted ventral spinal artery runs subdurally in the ventral median fissure from the level of the tenth thoracic to the fourth lumbar vertebra [86]. Two to three [84] or three to four ventral branches enter the ventral spinal artery. The majority of them are located at the level from the tenth thoracic to the second lumbar vertebra [81]. Three ventral branches are present in 58% of cases, four ventral branches in 27% of cases and five ventral branches in 15% of cases. For the ventral branches, the left-sided predominance is typical [86]. The ventral spinal artery continues to the beginning of *filumterminale* [83, 84].

The artery of Adamkiewicz is relatively constant in topography with right-sided predominance and it is accompanied in the cranial region of the lumbar part of the spinal cord with one or two small branches [84]. The caudal thoracic, lumbar and sacral part of the spinal cord [68, 72, 83, 86] are supplied at the level of the second or third lumbar vertebra [83, 86] by a large segmental artery (the artery of Adamkiewicz).

On the dorsal surface of the spinal cord, two irregular dorsal spinal arteries with irregular loops between each other are formed [83]. On the dorsal surface of the spinal cord, except the cervical part, three additional dorsal spinal arteries are located: two lateral dorsal spinal arteries and one median dorsal spinal artery. The additional arteries are interconnected by means of the transverse anastomotic circle [81]. The dorsal branches are higher in number and equally distributed, but of a smaller diameter than the ventral branches. They are more frequently present at the cervical and lumbar enlargements [84].

In the most caudal segments, the arterial plexuses are present on the surface of the spinal cord [84]. The arterial anastomoses are present in half of cases and the arterial network is of lesser density in thoracic part than in the cervical and lumbar part [72].

5. Conclusions

Detailed knowledge of the anatomy of the arteries contributing to the spinal cord blood supply plays an important role in the management of treatments of several diseases of the thoracic and/or thoracolumbar aorta, which may impact the spinal cord blood supply [87]. The possible present collateral arterial system is of great importance as a compensatory mechanism of the spinal cord blood supply in the cases of large arteries occlusion. The supply from one source can decrease when another one is increased or the other way [88]. A high risk of the spinal cord ischemia can be caused by the occlusion of the segmental arteries and rupture of a possible collateral system of the spinal cord blood supply [89].

In the pig, each dorsal intercostal and lumbar artery conveys the blood into the ventral spinal artery. In less than quarter of studied pigs was monitored, the manifested paraplegia after the ligation of the descending aorta [90] or segmental arteries was known as critical. The arteries intended for another spinal cord segments replace the arterial blood flow to the segments with interrupted arterial supply. All dorsal intercostal and lumbar arteries participate on the arterial blood supply of the spinal cord and on the formation of the collateral blood flow [91]. The differences in arterial pattern concerning the collateral blood circulation must also be considered by the interpretation of the results of the experimental studies [59]. Several arteries with the variable place of their origin supply the spinal cord in the pig. The median sacral artery represents an important source of the pig spinal cord arterial supply which differentiates it from the human spinal cord blood supply.

The use of the dog in the study of experimental spinal cord ischemia predetermines: the blood supply of the ventral two-thirds of the spinal cord in the caudal cervical part by main arteries with a greater diameter and the right-sided predominance of the segmental arteries [29, 92]. In comparison with the rabbit, the spinal cord blood supply in the dog is more similar to the humans. The clamping of the thoracic aorta is an adequate method to induce a spinal cord ischemia of respective spinal cord segments [29, 90].

In cat, the abdominal aorta gives rise to one or more branches with larger calibre, which convey the arterial blood to the lumbar and sacral part of the spinal cord [93]. This arterial pattern resembles that in human.

The effect of numerous neuroprotective drugs and postoperative outcomes is studied in rabbit, which serves as a better experimental model for such experiments. The homosegmental blood supply from the abdominal aorta caudally to the origin of renal arteries with minimal or no intraspinal collateral arterial system and that the neurological outcomes do not differ significantly from the neurological signs in other species of experimental animals predetermine the use of the rabbit in neurological research [93, 94]. To induce the spinal cord ischemia in rabbit, it is necessary to ligate only the abdominal aorta [90].

In rats, the heterosegmental blood supply is formed in the lower thoracic, lumbar and sacral spinal cord. To obtain the spinal cord ischemia in rat, it is necessary the ligation of the descending aorta [90].

Before the appropriate animal model is chosen, several aspects must be considered. It is very difficult to find an ideal animal model because of different occurrence of variable advantages and disadvantages [93]. Each aspect and step before starting an experimental model must be considered. It is recommended to perform a pilot study which helps the scientist to determinate what is awaiting from each animal model and identifies the optimal way for reduction of the animal use and necessary experimental time [95].

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