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Original Article

Microvascular anatomy of the lateral spinal artery: Origins, collateral channels, and other anatomical variations

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ABSTRACT

Background: The lateral spinal artery (LSA) corresponds to the posterolateral arterial axis of the craniocervical junction. Although implicated in various pathologies and injury risks during treatments, the existence and anatomical characteristics of the LSA are debated. We aim to demonstrate the characteristics of the LSA, including its origins, collateral channels, and anatomical variations.

Methods: Neurosurgeons performed far-lateral craniotomies and cervical laminectomies on 18 cadaver heads (36 sides). Neurovascular structures associated with the LSA were examined in epidural, subdural, and subarachnoid spaces.

Results: The main origins of the LSA were the V3 segment of the vertebral artery (VA) (n = 18), the V4 segment of the VA (n = 12), and the posterior inferior cerebellar artery (PICA) (n = 6). The PICA originated from V3 in 6 cases; in 5, the main LSA origin was the intradural PICA. In the 30 cases where the PICA originated from V4, only one main LSA originated from the PICA. In addition to the main origin, we identified supplementary origins, averaging 1.7 per case. In 4 cases, the LSA and posterior meningeal artery (PMA) shared an origin at V3. Twenty-seven cases had anastomosis between the LSA and PICA on the pial surface. Collateral channels at the C2 level through posterior radicular arteries were observed in 13 cases.

Conclusion: The main origins of the LSA are around the dural ring of the VA and are associated with the PICA's origin. Other potential channels supplying the LSA were also identified. The LSA and PMA may share an origin from the VA.

Keywords: Anatomical study, Lateral spinal artery, Posterior inferior cerebellar artery, Posterior meningeal artery, Vertebral artery

INTRODUCTION

Various pathological entities, such as arteriovenous malformations, arteriovenous fistulas, aneurysms, and tumors, occur at the craniocervical junction (CCJ), which has a unique and complex vascular anatomy. A thorough understanding of the vascular anatomy surrounding the CCJ is important to treat these conditions. Unlike other vascular structures, such as the anterior spinal artery, vertebral artery (VA), and posterior inferior cerebellar artery (PICA), the lateral spinal artery (LSA) is not well understood, and it is often confused with the posterior spinal artery

(PSA). Lasjaunias *et al*.[10] defined the LSA as a component of the PSA, which corresponds to the posterolateral arterial axis of the CCJ junction and upper cervical spinal cord.[13] Typically, LSAs originate from the extradural segment of the VA (V3), the intradural segment of the VA (V4), or the PICA. They run parallel to the eleventh nerve, positioned anterior to the cervical dorsal nerve rootlet and posterior to the dentate ligament, and they usually end at the C4 level.[10] Conversely, the PSAs, which are predominantly found caudal to the LSA's termination point, traverse the surface of the spinal cord posterior to the posterior nerve rootlets.

Pathological lesions in the VA or PICA, such as atherosclerotic occlusion or VA dissection, can obstruct the LSAs, leading to infarctions in the posterolateral part of the lower medulla and upper spinal cord.[3,4,15,17] Moreover, iatrogenic LSA injury may occur during neurosurgical procedures aimed at addressing VA aneurysms, dissections, dural arteriovenous fistulas (DAVFs), arteriovenous malformations, and tumors.[1,2,5,8,12,21,23] LSA damage or blockage typically induces symptoms related to infarction of the posterior column and posterior horn. However, motor weakness associated with infarction of the lateral funiculus occurs more frequently than initially anticipated.[24]

LSAs are difficult to identify using conventional angiography due to their relatively small diameters and varied origins. It is unclear whether each LSA has a single origin from the VA or PICA or if they have multiple origins and anastomotic channels with other arteries. This unfamiliarity with LSAs can complicate clinical decisions and escalate the risk of complications during neurosurgical interventions for pathologies around the posterolateral aspect of the CCJ. In this cadaveric study, we investigated the origins and course of the LSA, its anastomotic connections with other vessels, and its association with the dura mater.

MATERIALS AND METHODS

This cadaveric anatomical study was exempt from the Institutional Review Board's review and approval.

We examined 18 embalmed cadaveric heads (36 sides) after injecting the arteries and veins with red and blue colored silicone. On each side, we performed a far-lateral craniotomy with condylectomy and laminectomies at C1, C2, and C3. All dissection procedures were performed using an operating microscope (Pentero, Carl Zeiss AG, Oberkochen, Germany). We thoroughly examined neurovascular structures in the cisterna magna, cerebellomedullary cistern, cerebellopontine cistern, and the intradural space of the upper cervical spine. In addition, we focused on studying the dura mater and the V3 segment of the VA to elucidate the anatomical characteristics of the LSA.

We initially defined the LSA as the artery that corresponds to the posterior lateral aspect of the CCJ and the upper spinal cord.[10,13] The main origin of the LSA was classified as 1 of 3 potential locations: the V3, V4, or PICA. Branches arising from the V3 between the axis and the transverse process of the atlas were defined as radicular arteries. Simultaneously, branches that arose from the V3 segment between the dura and the transverse process of the atlas were identified as the LSA origin from the VA. If an artery coursed from its origin, progressed through the subarachnoid space and was directly connected to the LSA, its main origin was labeled as the LSA. In the case of an artery with multiple origins, the main LSA origin was ascertained by the origin of the thickest vessels connected to the LSA. When the origin of the LSA was found in the V3, the LSA's trajectory through the dura was analyzed. We also identified the pial anastomotic channel of the LSA, confirming the connection channels formed on the pial surface between LSA branches and branches from other arteries. We also attempted to identify extracranial collateral flow that originated from radicular arteries that extended from the VA and ran adjacent to the C2 and C3 nerve roots. In addition, because the posterior meningeal artery (PMA) commonly originates from the VA, we investigated potential relationships between the LSA and the PMA.[22]

RESULTS

We identified the LSA in all 36 sides of the 18 cadaveric brains. The locations of the main origin of the LSA, as defined earlier, were the V3 segment of the VA (18 of 36 sides, 50%), the V4 (12 of 36 sides, 33%), and the PICA (6 of 36 sides, 17%) [Figures 1a-d and Table 1]. In the 30 cases in which the main origin of the LSA was from the V3 or V4, all were situated within 10 mm of the dural ring of the VA [Figures 1-3a and b].[6,11,18,20] For the cases in which the main origin of the LSA was from the V3 segment, the LSAs emerging from the main LSA origin ran parallel to the VA. These vessels closely followed the VA and passed through the dura near the dural ring of the VA. After it entered the dura, the LSA diverged from the VA within the subarachnoid space [Figure 3c]. In cases in which the main origin of the LSA stemmed from the PICA, the origin location appeared to correlate with the location of the PICA's origin. In six cases, the PICA originated extradurally from the V3. In five of these cases (5 of 6, 83%), the main origin of the LSA was the intradural PICA. Conversely, only one main LSA origin came from the PICA among the 30 cases in which the PICA arose intradurally from the V4 (1 of 30, 3.3%) [Figure 2]. In ten cadaveric heads, the main LSA origin locations differed on the 2 sides. However, in the remaining eight cadavers, the primary origin locations were consistent between the right and the left side. Beyond the main LSA origin, multiple additional LSA origins were noted, averaging 1.7 origins per case: four origins in two cases, three in two cases, two in 14 cases, and one in 18 cases. The V4 was the most common

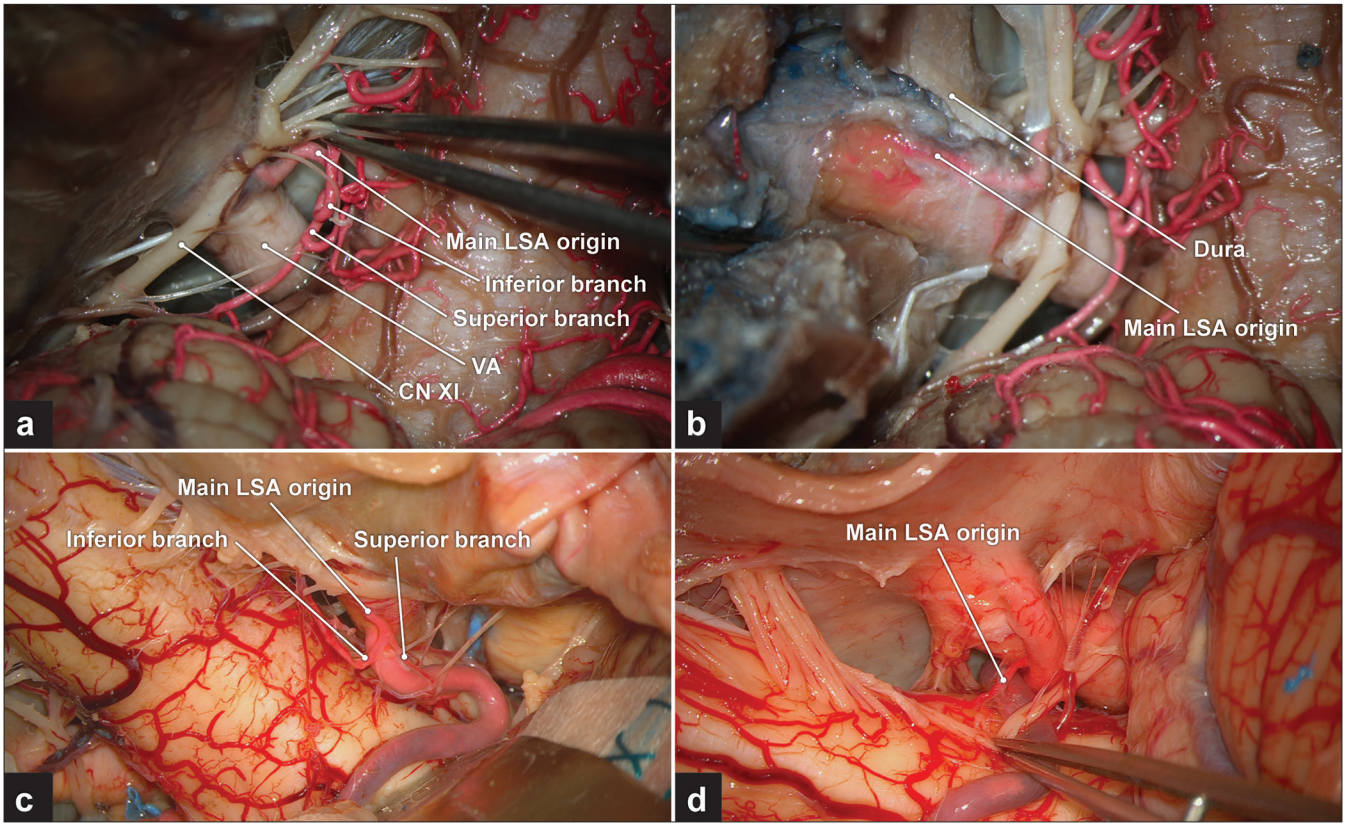

Figure 1: The main origin of the lateral spinal artery (LSA) emanates from the extradural segment of the vertebral artery (VA). (a) Intradural view of the main origin of the LSA from V3 and its branches. The inferior and superior branches of the LSA are visible, as well as the accessory nerve (cranial nerve XI). (b) The extradural origin of the LSA was identified after the partial removal of the dura mater around the dural ring of the VA. (c) The main origin of the LSA from the intradural segment of the VA and the superior and inferior branches of the LSA. (d) The main origin of the LSA from the posterior inferior cerebellar artery, which originates from the extradural segment of the VA. *Used with permission from Barrow Neurological Institute, Phoenix, Arizona.*

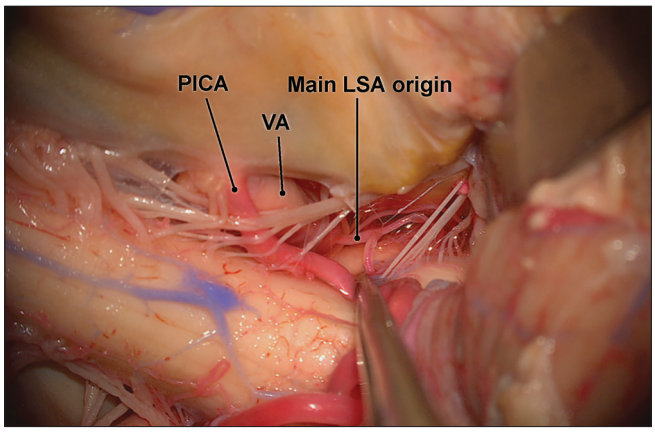

Figure 2: In this specimen, the lateral spinal artery (LSA) originated from the intradural segment of the vertebral artery (VA), with the posterior inferior cerebellar artery (PICA) originating from the extradural segment of the VA (V3). Previous studies have demonstrated that the main origin of the LSA usually comes from the PICA in cases where the PICA originates from the extradural segment of the VA.[6,11,18,20] Our study corroborates these findings, but we note this case as an exception. *Used with permission from Barrow Neurological Institute, Phoenix, Arizona.*

Table 1: Origins of the lateral spinal artery

Origin of the Lateral Spinal Artery	Main Origin (*n*=36)	Additional Origin (*n*=24)
Extradural segment of the vertebral artery	18 (50)	1 (4)
Intradural segment of the vertebral artery	12 (33)	21 (88)
Posterior inferior cerebellar artery	6 (17)	2 (8)

Data are shown as number of cases (%).

site of these additional LSA origins (21 of 36 cases), with the other two origin locations being the PICA (two of 36 cases) [Figure 4] and V3 (one of 36 cases).

In four cases, there was a concomitant origin of the LSA and PMA [Figure 4]. In all four cases, the concomitant origins of the LSA and PMA were identified at the V3. The arteries from this concomitant origin ran parallel to the VA and were closely adjacent to it, and they passed through the dural

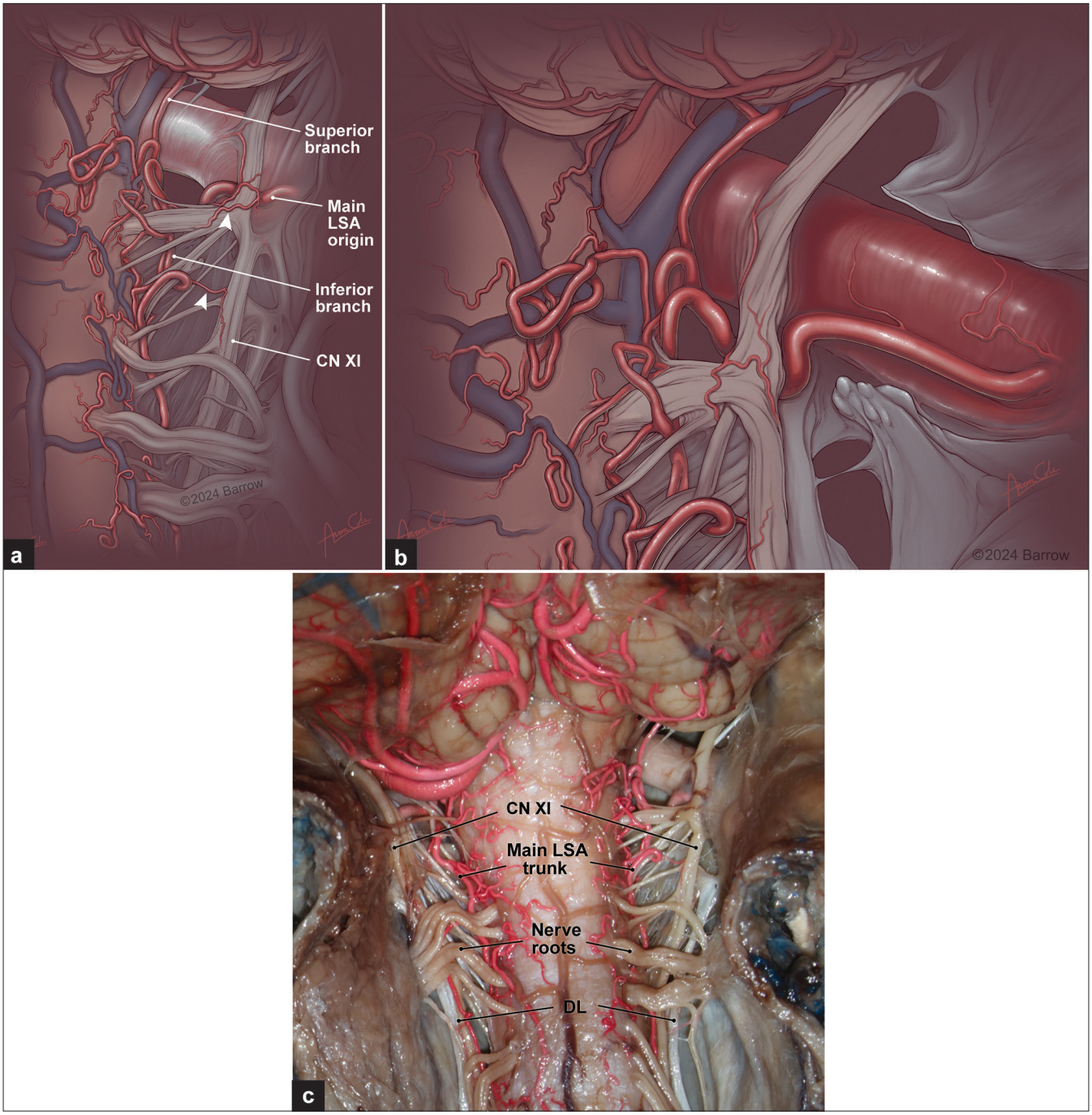

Figure 3: Illustrations showing an overview of lateral spinal artery (LSA) anatomy. (a) Intradural overview of the LSA and its branches. The *white arrowheads* indicate the blood supply to the accessory nerve (cranial nerve [CN] XI). (b) Enlarged illustration of the LSA origin after removal of the dura mater around the dural ring of the vertebral artery (VA). (c) Overview of the intradural course of the LSAs. The inferior branches form the main LSA trunk and continue posteriorly along the posterolateral side of the medulla and spinal cord, parallel to the accessory nerve (CN XI). Some branches from the LSA supply blood to the accessory nerve. The main LSA trunks also run continuously anteriorly to the posterior spinal nerve roots and posteriorly to the dentate ligaments (DL) in the subarachnoid space. They extend branches toward the dorsal column, forming a vascular network on the pial surface of the dorsal column. *Used with permission from Barrow Neurological Institute, Phoenix, Arizona.*

ring, similar to the main LSA origin from V3. Two arteries have a concomitant origin at the V3 segment of the vertebral artery and then split into the LSA and the PMA. In each of these four cases, the concomitant origin at the V3 segment was the main LSA origin. Following its bifurcation, the LSA proceeded directly to the posterolateral surface of the CCJ. In contrast, the PMA ran in the opposite direction of the LSA, supplying the dura from within.

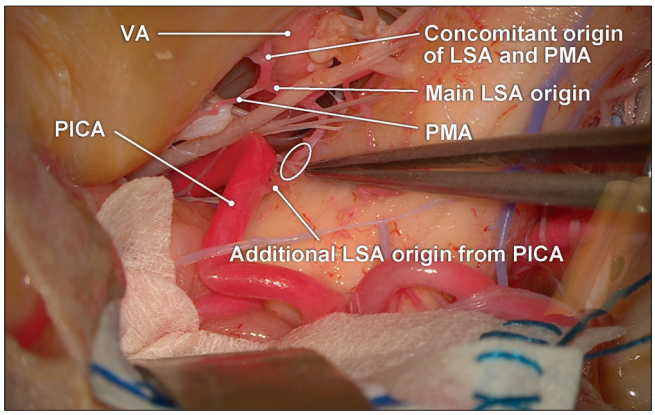

Figure 4: Specimen showing concomitant origin of the lateral spinal artery (LSA) and posterior meningeal artery (PMA) from the extradural segment of the vertebral artery (VA). An additional origin of the LSA from the posterior inferior cerebellar artery (PICA) also occurred in this specimen. A direct anastomosis exists between the superior branch from the main LSA origin and a branch from the additional LSA origin from the PICA (white oval). The concomitant origin of the LSA and PMA passes through the dural ring. The artery from this concomitant origin subsequently divides into the LSA and PMA in the subarachnoid space. *Used with permission from Barrow Neurological Institute, Phoenix, Arizona.*

In the 30 cases in which the main origin of the LSA was situated at the V3 or V4, the artery arising from the main origin bifurcated within the subarachnoid space to yield a superior branch and an inferior branch [Figure 1a and c]. The inferior branch constituted the main LSA trunk and descended along the posterolateral side of the medulla, running parallel to the accessory nerve [Figure 3a and c]. Moreover, several branches from the LSA trunk provided blood to the accessory nerve [Figure 3a]. Echoing findings from a previous study by Lasjaunias *et al*.,[10] the main LSA trunk also extended downward anteriorly to the posterior spinal nerve roots and posteriorly to the dentate ligament. This trunk branched onto the posterolateral surface of the medulla and the upper cervical spine. The superior branch, being relatively short, ascended along the posterolateral aspect of the medulla and predominantly supplied blood to the posterolateral surface of the medulla near the obex of the fourth ventricle. Of the 30 cases with the main LSA origin located at the VA, pial anastomoses between the superior branch of the LSA and branches of the PICA were observed in 23 cases [Figure 5]. Typically, these anastomoses develop on the posterolateral pial surfaces of the medulla rather than within the subarachnoid space.

In six cases where the main origin of the LSA stemmed from the PICA, the inferior branch of the LSA typically arose from the PICA shortly after it passed through the dural ring and descended like that of the LSAs that originated from the VA [Figure 1d]. The perforating arteries that originated from the lateral medullary segment of the PICA supplied the posterolateral surface of the medulla, mirroring the function of the superior branch of the LSA from the VA.

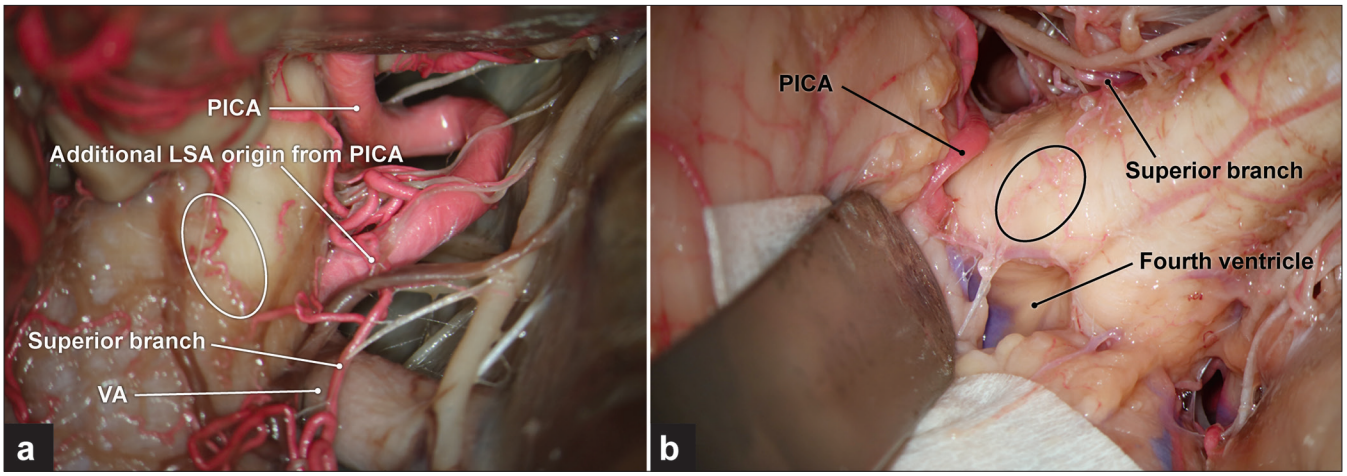

Figure 5: Pial anastomosis between the superior branch of the lateral spinal artery (LSA) and the posterior inferior cerebellar artery (PICA). (a) The superior branch of the LSA has a direct anastomosis with the PICA in the subarachnoid space and a pial anastomosis with cortical branches from the PICA (*oval*). (b) The superior branch usually supplies blood to the posterolateral surface of the medulla near the obex of the fourth ventricle. This figure illustrates the pial anastomoses between the superior branch of the LSA and the cortical branch of the PICA (*oval*). VA = vertebral artery. *Used with permission from Barrow Neurological Institute, Phoenix, Arizona.*

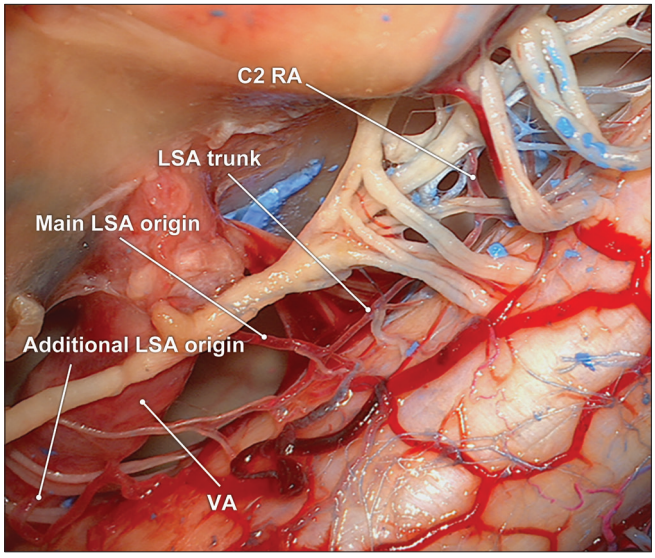

Figure 6: Posterior radicular artery of C2 supplying the lateral spinal artery (LSA) trunk. This figure depicts several channels supplying the main LSA trunk, including the main LSA origin, an alternate LSA origin at the distal vertebral artery (VA), and the C2 posterior radicular artery (C2 RA). *Used with permission from Barrow Neurological Institute, Phoenix, Arizona.*

Of the six cases with the main LSA originating at the PICA, anastomoses were observed between distal branches of the LSA trunk and smaller branches of the PICA in four instances. These anastomoses also form on the posterolateral pial surfaces of the medulla.

We also found other collateral channels between the LSA trunk and extradural arteries at the upper cervical spine. In 13 of the 36 cases examined, posterior radicular arteries ran alongside the C2 dorsal nerve root and were directly connected to the main LSA trunk [Figure 6]. No cases were found of the posterior radicular arteries running adjacent to the C3 nerve root.

DISCUSSION

Anatomy of the VA

The vascular anatomy surrounding the CCJ may not be overly familiar to the neurosurgeon compared with other brain or spine vascular territories. Nonetheless, vascular anatomy is foundational information for treating conditions in the region. Understanding the vascular anatomy of the CCJ must begin with structures well below the area. The VA is divided into four segments. The V1 (preforaminal) segment starts at the origin of the VA in the subclavian artery and ends before entering the transverse foramen of the sixth cervical vertebra (C6). The V2 (foraminal) segment ascends through the transverse foramina from the sixth to the second cervical vertebrae (C2). The V3 (atlantic or extradural) segment starts as the VA exits the transverse foramen of C2, ascends through the transverse foramen of the first cervical vertebra (C1), loops posteriorly and medially in the groove for the VA in the superior surface of the posterior arch of C1, and ends as it penetrates the posterior atlanto-occipital membrane to start its intradural course. The V4 (intradural) segment runs superiorly anterior to the medulla and joins with the contralateral V4 to form the basilar artery.

Debate over the distinction between the LSA and PSA

In this study, we found the LSA to represent the posterolateral arterial axis of the CCJ junction and upper cervical spinal cord, consistent with previous studies [Figure 3a and b].[10,13] The main trunks of the LSAs in this study coursed anteriorly to the posterior spinal nerve roots and posteriorly to the dentate ligament up to the level of the C3-4 disc space [Figure 3]. Lasjaunias *et al.*[10] noted that the LSA terminates at the C4 or C5 level. Beyond this, it has been found to shift more posteriorly, coursing behind the dorsal nerve roots where it merges with the ipsilateral PSA, which typically has a more posterior trajectory than the LSA.[20] In addition, we found that the LSA does not generally adhere to the pia mater while descending from the medulla to the upper cervical spinal cord. Instead, it mainly progresses within the subarachnoid space and sends branches to the pia mater on the posterolateral surface of the spinal cord [Figure 3].

However, the distinction between the LSA and the PSA remains a point of contention for many researchers and physicians. Lasjaunias *et al.*[10] conducted anatomical and angiographic studies and found distinct anatomical features of the arteries on the posterolateral surface of the medulla and upper cervical spinal cord. Their findings invite controversy regarding the PSA, which is traditionally understood to follow the same anatomical path from the medulla to the conus.[10,13] Thus, they began to refer to this specific artery as the LSA. Similarly, Parke *et al.*[14] detailed the posterolateral spinal arterial complex in the upper cervical spinal cord and termed this arterial complex the lateral cervical spinal artery. This designation aligns with the characteristics of the LSA as described by Lasjaunias *et al.*[10]

Siclari *et al.*[20] approached the study of the LSA from a different perspective. They believed that certain specific characteristics of the arteries on the posterolateral surface of the medulla and upper cervical cord arise due to variations in the development of the PSA in conjunction with the PICA and VA rather than being attributable to the LSA. Similarly, Gregg and Gailloud[7] proposed that the PSA comprises two components: The posterolateral spinal artery and the posteromedial spinal artery. They further asserted that previous studies mislabeled the posterolateral spinal artery as either the LSA or the lateral cervical

spinal artery. However, in our study, the LSA exhibited characteristics distinct from those of the PSA, aside from the vessel's path, as previously described. Typically, the PSA is discontinuous, travels on the pia mater instead of in the subarachnoid space, and occasionally crosses over to supply the opposite side, resembling a ladder.[9] However, our study showed that the LSA runs down continuously in the subarachnoid space, rather than on the pia mater, down to the level of the C3–4 disc space. As the LSA descends, it sends out branches toward the dorsal column, and these offshoots create a vascular network on the dorsal column's surface, mirroring the PSA as referenced in other works, as described above [Figure 3c].

Debate over the main LSA origin and its trajectory

Seçkin *et al*.[18] noted that the primary origin of the PSA, which we term the main origin of the LSA, has not been identified on the intradural PICA when the PICA arises from the V4. Their finding is consistent with the findings of previous studies.[6,11,18,20] They proposed that the main origin of the LSA is intimately linked with the PICA's origin, suggesting that the main LSA origin stems from the PICA in instances where the PICA originates from the V3 segment or the extradural VA.[18] Our findings corroborate these observations, although we did identify some exceptions. We found that out of six cases where the PICA originated from the extradural VA, the main origins of the LSA were from the intradural PICA in five cases. Furthermore, in 29 of 30 cases in which the PICA originated from the V4, the main origin of the LSA was from either the V3 or V4, not the PICA. However, there was 1 exceptional case in which the main origin of the LSA was from the V4, whereas the PICA originated from the V3 [Figure 2]. In addition, we observed another exception where the main origin of the LSA was from the intradural PICA, but the PICA, in this case, originated from the V4. Notably, in these two atypical instances, there were no other LSA origins; only a singular origin was discerned in each case.

Our findings indicate that when LSAs originate from the VA, the main origin of the LSA is usually located near the dural ring of the VA. In the 30 cases in which the main origin of the LSA was from the V3 or V4, every main origin of the LSA was located within 10 mm of the dural ring. All additional LSA origins also emerged within 15 mm of the dural ring. Seçkin *et al*.[18] also found that the main origin of LSA was consistently located within 10 mm of the dural ring. However, Rojas *et al*.[16] found some cases in which the LSA had a far more proximal origin, specifically from the V3 between the transverse processes of C1 and C2. We also identified similar arterial branches that emanated from the proximal part of the V3 that linked with the main trunk of the LSA. As detailed in our results, we labeled these branches as posterior radicular arteries that run alongside the C2 dorsal nerve root [Figure 6]. Among the 36 cases, we found 13 with collateral channels through the posterior radicular artery leading to the LSA trunk. However, in these 13 cases, the main LSA trunk was more substantial than the collateral branch connected through the posterior radicular artery.

Correlation between the LSA and PMA and clinical implications

The PMA predominantly originates from the V3 and V4. Occasionally, it may arise from the cervical internal carotid artery, PICA, ascending pharyngeal artery, or occipital artery.[22] The PMA provides blood supply to the medial and paramedian regions of the dura, covering the cerebellar convexity between the transverse sinus and the posterior margin of the foramen magnum.[22] Both the PMA and LSA could arise from the V3 or V4 segment of the VA, and the origins of the 2 arteries may be very close to each other. Nevertheless, no studies have reported the relationship between the PMA and LSA. In our study, we identified four cases of concomitant origin of the LSA and PMA among 18 cadaveric heads with 36 sides, suggesting the presence of a type of radiculomeningeal artery at the CCJ. A radiculomeningeal artery that originated from the V3 between the dura and the transverse process of the atlas ran parallel to and was attached to the VA. This artery passed through the dural ring and bifurcated into the main LSA and PMA trunks within the subarachnoid space.

The presence of a concomitant origin of the LSA and PMA has significant clinical implications [Figure 4]. The PMA frequently serves as a feeding artery to form DAVFs in the posterior fossa and CCJ.[5,19,22] Choi *et al*.[5] shared their treatment experiences of DAVFs at the CCJ and highlighted several cases in which the PMA served as a primary feeder to the DAVF and originated from a concomitant origin of the LSA and PMA. They termed this artery a feeder stemming from the radiculomeningeal artery at the CCJ. Unfortunately, they also documented two instances of posterolateral spinal cord infarction attributed to LSA occlusion during embolization using a liquid embolic material. In addition, other studies have described iatrogenic LSA injury after embolization of DAVFs in the posterior fossa or CCJ.[1,23] Besides the main origin of the LSA, we found several channels that might supply the main LSA trunk, including an additional LSA origin from the VA and PICA that connected directly to the LSA trunk, pial anastomoses between the pial branch of the superior branch of the LSA and PICA branches, and radicular arteries that run alongside the C2 dorsal nerve root. However, our findings also indicate that the concomitant origin is the main LSA origin. Consequently, if the concomitant origin were damaged or obstructed, it would be challenging to ascertain whether the blood flow through other collateral channels was adequate. Furthermore, the arteries that constitute the main

LSA trunk and various collateral channels tend to be thin, making them hard to identify and differentiate using standard angiography. When embolizing DAVFs in which the PMA is the main feeding artery, it is a challenge to determine whether the PMA originates from the concomitant origin and whether adequate collaterals exist.

CONCLUSION

The LSA can be defined as a component of the PSA that is responsible for the posterolateral arterial blood supply to the CCJ and upper cervical spinal cord. However, the LSA is distinct from the PSA in other locations regarding direction, running location, and continuity of blood vessels. Our study showed that the main origin of the LSA is typically situated near the dural ring of the VA when these origins derive from the VA. Furthermore, the main origin of the LSA may be associated with the location of the origin of the PICA. In addition to the main origin of the LSA, we found multiple vascular channels that feed the LSA. We also observed an anatomical variation in which the LSA and PMA share a common origin from the VA. However, due to the small size of the LSA and other vascular channels linked to the LSA from the VA and PICA, these anatomical variations are challenging to discern angiographically. Given the susceptibility of the LSAs to injury during neurosurgical procedures, neurosurgeons should be well-acquainted with their anatomical features.

Ethical approval: The Institutional Review Board approval was not required because, as a cadaveric anatomical study, it was exempt from the Institutional Review Board's review and approval.

Declaration of patient consent: Patient consent was not required as there were no patients in this study.

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Conflicts of interest: There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation: The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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