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Complex and multiple anomalies of the aortic arch: Atypical origin of the vertebral artery of continuing interest among embryologists, anatomists, and clinicians[1]

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Abstract. Aortic arch branching anomalies are a relatively rare occurrence, observed in approximately 3-5% of cadavers. These anomalous branching patterns continue to be a topic of ongoing dialogue in embryological evolution and cervical region surgery. During dissection, it was discovered that the donor's left vertebral artery arose from the aortic arch between the left common carotid and subclavian arteries. In an earlier report that is included here, the right vertebral artery arose directly from the aortic arch (authors and journal expressed permission and attribution: Vasan et al., 2022). This paper not only discusses the embryological evolution of the vertebral artery and its anomalous branching but also emphasizes the need for careful examination of the aortic arch and its branches during clinical evaluation and surgical procedures.

Keywords: anomalous origin of vertebral arteries, altered preforaminal vertebral arteries, difference in vertebral artery length.

INTRODUCTION

The introduction includes a historical perspective that starts in the early 20th century and focuses on the number of primary branches of the aortic arch. The normal arch of the aorta has three branches: the right brachiocephalic trunk, also known as the innominate artery, which bifurcates into the right subclavian and right common carotid arteries, while the left common

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carotid and left subclavian artery follow the brachiocephalic trunk. This 'typical' pattern of aortic arch branches occurs in about 70% of the population (Rosen, 2023). To understand the multiple anomalies of the aortic arch, it is important to briefly discuss its embryological origin.

The development of the aorta and its branches in humans occurs during the third week of gestation (Schleich, 2002; Moore et al., 2020) and is a highly regulated and complex process that involves several synchronized events occurring sequentially or concurrently. Additionally, several intrinsic and extrinsic factors/molecules appear transiently with specific functions in normal development before disappearing (Moore et al., 2020). Due to the complexity of the development of the aorta and aortic arches, several congenital abnormalities are possible.

Some reports focused on the number of primary branches of the aortic arch (Poynter, 1916; Congdon, 1922; Iyer, 1927; Adachi, 1928; Windle et al., 1928; Lippert & Pabst, 1985). In some cases, however, the number of primary branches may be increased through other brachiocephalic arteries such as the thyroidea ima, internal and external carotid, right vertebral, internal thoracic, and inferior thyroid arteries. Infrequently, the right subclavian artery has been found to originate directly from the aortic arch as the last branch and to follow a retroesophageal course similar to the retroesophageal right subclavian artery (RRSA) (Haughton, 1974).

During weeks four to eight of embryonic development, the vertebral artery starts to form and the horizontal part of the 1-6 intersegmental arteries (ISA) begins to recede. By the development of longitudinal anastomoses that link the cervical ISA, the seventh ISA becomes the proximal subclavian artery. The adult vertebral artery usually originates from the subclavian artery and develops as a longitudinal channel connecting the cranial intersegmental arteries. If the left seventh intersegmental artery is incorporated into the developing aorta, it results in the left vertebral artery arising directly from the aortic arch. If one of the first six ISAs fails to involute (known as the persistent ISA), it can cause abnormal origins of the vertebral artery (Bordes et al., 2021; Dumitrescu et al., 2021).

Occasionally, the left vertebral artery arises directly from the aorta between the left common carotid and left subclavian arteries. This occurs when one of the proximal six intersegmental arteries (ISAs) fails to involute, resulting in abnormal origins of the vertebral artery (Lazaridis et al., 2018; Natsis et al., 2021). A persistent ISA located in the upper ISAs leads to an abnormal origin of the vertebral artery from the internal or external carotid artery (Lazaridis et al., 2018; Natsis et al., 2021). On the other hand, if it occurs in the lower 3-6 ISAs, it results in an abnormal origin of the vertebral artery from the aortic arch or the common carotid artery (Haughton, 1974.). In around 3-5% of individuals, the left vertebral artery arises directly from the aortic arch, which is clinically relevant during cervical region surgery (Matula et al., 1997).

The vertebral artery is separated into four segments based on its anatomical location. The first segment, the pre-foraminal or proximal segment, runs from its origin to the transverse foramen of C5/C6. The second segment, known as the intraforaminal segment, passes through the transverse foramen of the cervical vertebra. The third segment is the extradural segment; it runs from the second cervical transverse foramina to the base of the skull. The fourth and final segment, the intracranial segment, joins the vertebral artery from the other side to form the basilar artery (Matula et al., 1997). Bilaterally, the vertebral arteries show an expansion proximally at their origin and just before they enter the vertebral foramen (Vasan, 2022).

MATERIALS AND METHODS

The cadaveric specimens in the present study were obtained from the willed body program for medical student dissection. During routine cadaveric dissections of the thorax by medical students, we observed that both the right and left vertebral arteries atypically originated from the aortic arch (AA). The right vertebral artery originated from the right brachiocephalic trunk (Figs. 1, 3, and 4), while the left vertebral artery originated from the aortic arch between the left common carotid and the left subclavian arteries.

Donor cause of death

The donors were a 94-year-old Caucasian female who died of right femur fracture sequelae (Figs. 1, 2) (Case 1); a 73-year-old Caucasian female who died of renal failure following a complicated urinary tract infection (Fig. 3) (Case 2), and an 82-year-old Caucasian male with coronary artery disease and severe aortic stenosis (Fig. 4) (Case 3). Cases 2 and 3 and their related figures appeared in the authors' prior publication and, as such, are allowed to be used by including appropriate attribution for the work given.

Declaration

The authors state that every effort was made to comply with all the local and international ethical guidelines and laws that pertain to the use of human cadaveric donors in anatomical research.

RESULTS AND OBSERVATION

As beginners, the students did not perform a good-quality dissection in Case 1. However, upon our own further careful dissection, we observed that the right vertebral artery emerged from the brachiocephalic trunk (Fig. 1). The left vertebral artery emerged from the aortic arch between the left common carotid artery and the left subclavian artery (Fig. 2). Proximally at its origin, both the right and left vertebral artery exhibited recognizable distension, which was also noticed before entering the foramen transversarium (Figs. 1,2).

Figures 1 and 2 show clear differences in the length of the preforaminal section of the right (5.5 cm) and left (8.0 cm) vertebral arteries. It is important to note that the right and left vertebral arteries enter the foramen transversarium at the 5th and 6th cervical vertebrae, respectively. Additionally, both right and left vertebral arteries exhibit distension before entering the foramen transversarium.

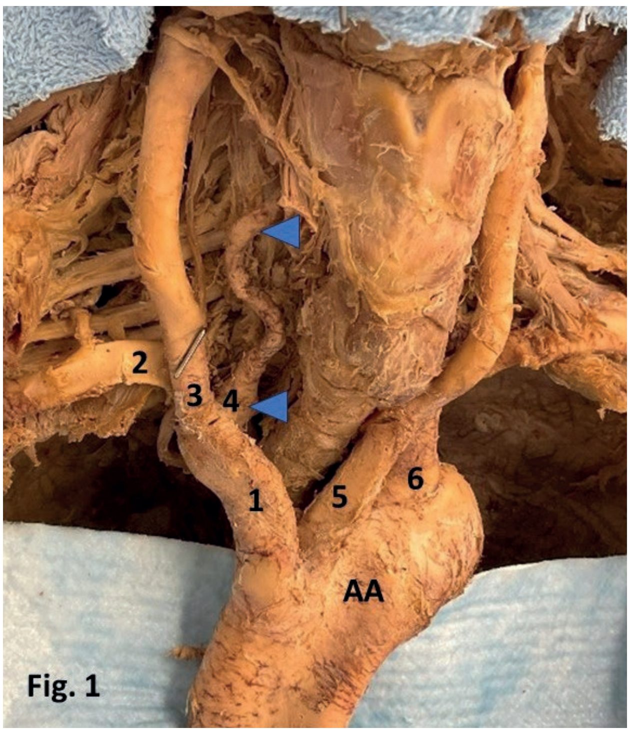


Figure 1. AA: Aortic Arch; 1: Right brachiocephalic trunk. 2: Right Subclavian Artery; 3: Right Common Carotid Artery; 4: Right Vertebral Artery; 5: Left Common Carotid Artery 6: Left Subclavian Artery. Blue arrowheads show the dilatations in the vertebral artery.

Noticeable differences in the preforaminal length of the vertebral arteries are significant. As seen in Cases 2 and 3 (Figs. 3, 4), the right vertebral artery measures 5.5 cm, while the left vertebral artery measures 7.0 cm. Additionally, the right and left vertebral arteries entered the foramen transversarium at the 5th and 6th cervical vertebrae, respectively. There was no difference either in the diameter or lumen size between the right and left distal parts of the vertebral arteries. Both right and left vertebral arteries showed a 'kink' and distension prior to entering the foramen transversarium.

DISCUSSION

The brain's blood supply comes from the left and right internal carotid arteries, known as anterior circulation, which comprises most of the cerebral hemispheres,

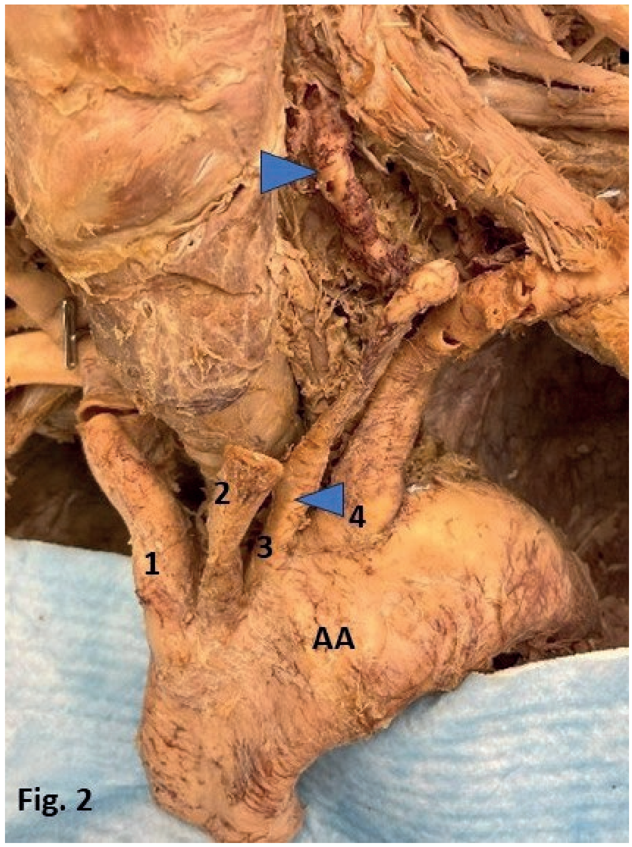


Figure 2. The Right (see Fig. 1) and Left Vertebral Arteries entered the foramen transversarium at C5 and C6, respectively. Before entering the foramen, the vertebral arteries exhibited dilatation, as indicated by the blue arrowheads. 1: Right brachiocephalic trunk. 2: Left Common Carotid Artery (trimmed to expose the Left Vertebral Artery. 3. Left Vertebral Artery. 4: Left Subclavian Artery.

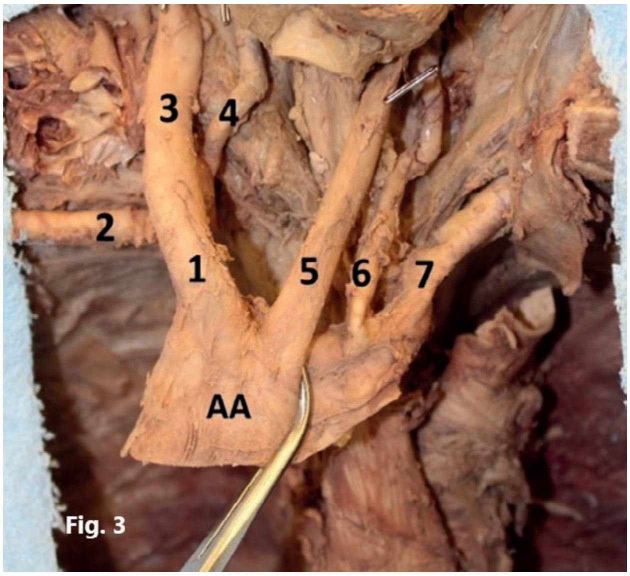
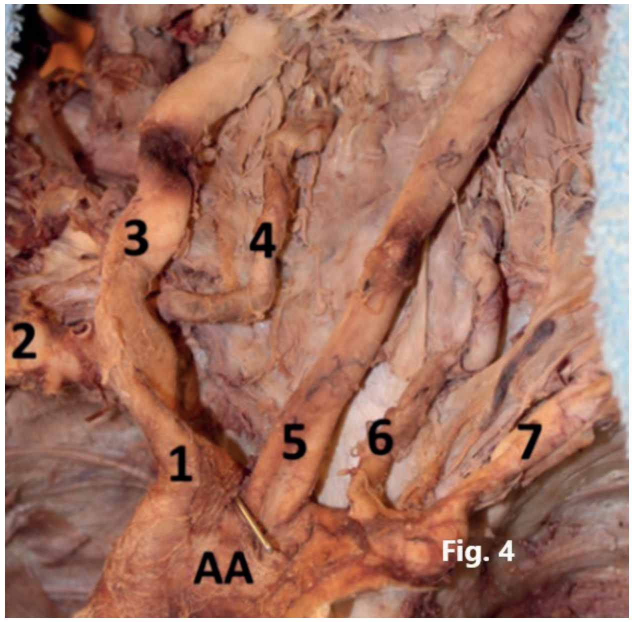


Figure 3. AA: Aortic Arch; 1: Right brachiocephalic trunk 2: Right Subclavian Artery 3. Right Common Carotid Artery 4: Right Vertebral Artery 5: Left Common Carotid Artery 6: Left Vertebral Artery, 7: Left Subclavian Artery.



Figures 3 and 4: Both the Right and Left Vertebral Arteries entered the foramen transversarium at C6 and C5, respectively. Prior to entering the foramen, the vertebral arteries exhibited dilatation. Figures 3 and 4 are from our earlier publication (approved by the journal policy): Int J Anat Res 2022, Vol 10(3):8426-8429. Https://doi.org/https://doi.org/10.16965/ijar.2022.17.

including frontal lobes, lateral temporal lobes, and the anterior part of deep cerebral hemispheres. The vertebral arteries are part of the posterior circulation of the brain that supplies the brainstem, cerebellum, occipital lobes, medial temporal lobes, and the back part of the deep cerebral hemisphere, specifically the thalamus. Regardless of their origin, the vertebral arteries contribute to the posterior brain circulation. The Circle of Willis connects the anterior and posterior circulations through anastomosis.

Individuals born with a left vertebral artery originating from the aortic arch may not experience any symptoms. However, there is a risk of the abnormal origin of the right vertebral artery becoming dilated, which can lead to cerebrovascular disorders and atherosclerotic changes due to increased blood flow (Tardieu et al., 2017). It is crucial to identify the anomalous origin and anatomical positioning of the left vertebral artery when considering anterior cervical spine surgery or other head-neck procedures that require retracting soft tissue structures such as nerves, arteries, veins, and muscles to reach the cervical spine (Tardieu et al., 2017). The prevertebral part of the vertebral artery, particularly the extracranial portion, is frequently affected by atherosclerosis and is a common site of stenosis (Imre et al., 2010). In Case 1, a sclerotic, narrower left vertebral artery was discovered, while the right vertebral artery was dilated due to increased blood flow, which helped protect the brain from ischemia (Melovitz-Vasan et al., 2015; Vasan et al., 2022).

Matula noted that the prevertebral vertebral artery tends to have a winding path in about 39% of cases, which is consistent with our observation (Figs. 1 and 2) and an earlier report (Matula et al., 1997; Freilich et al., 1986). Additionally, there is a difference in the twistiness of the right and left vertebral arteries, with 32% of right vertebral arteries being twisted versus 68% of left vertebral arteries. While the twists in the distal or preforaminal segment of the vertebral artery do not have any hemodynamic consequences, the loops of the proximal segments have been known to cause nerve root compressions, leading to radicular symptoms (Matula et al., 1997).

Previous studies confirmed that individuals with Down syndrome have a greater likelihood of having vascular anomalies; they also report a 40% occurrence rate of vertebral artery anomalies and a 36% occurrence rate of aberrant Right Subclavian Carotid Artery (RSCA) in these individuals (Rathore, 1989; Mishra et al., 2012). The deletion of Chromosome 22q11, also known as CATCH 22, is commonly associated with DiGeorge syndrome, conotruncal anomaly face syndrome, and velocardiofacial syndrome. Patients with this deletion are more likely to have anomalies of the aortic arch, aortic branches, ductus arteriosus, and pulmonary arteries than those without the deletion (Momma et al., 1999).

ANALYSIS

Anomalous origin of the right vertebral artery is less common than that of the left vertebral artery. The plausible embryologic explanation can only be speculative. Although these findings may be incidental in most cases, detailed information is required before any surgical/endovascular intervention to avoid any misinterpretation and inadvertent injury to the vertebral artery.

The following analysis pertains to the cases presented here and is based on our observations, findings, and published research studies on vertebral artery origin, malformations, and their effect on anatomy and physiology. In the analysis, we considered the age and gender of the donors and the cause of death. Any conclusion drawn in the analysis is the authors' or is based on available published materials. During routine cadaveric dissection of the thorax in Case 1, we observed that both the right and left vertebral arteries originated atypically. The right vertebral artery originated from the brachiocephalic trunk (Fig. 1), while the left vertebral artery originated between the left common carotid and the left subclavian arteries (Fig. 2).

In general, vertebral artery anomalies result from their development during embryonic stages, their path through the cervical region of the neck, and the morphology of the four individual segments. The vertebral artery begins to form during weeks four to eight of embryonic development, during which time the horizontal part of the 1-6 intersegmental arteries (ISA) starts to regress. The seventh ISA becomes the proximal subclavian artery by developing longitudinal anastomoses that link the cervical ISA. If the left seventh intersegmental artery is incorporated into the developing aorta, it results in the left vertebral artery, often arising directly from the aorta between the left common carotid and left subclavian arteries (Bordes et al., 2021).

Normally, the right vertebral artery arises as a branch from the right subclavian artery. However, it is possible that, while the right fourth arch is incorporated into the right subclavian artery, the dorsal aortic roots between the third and fourth arches persist and become the right vertebral artery.

Regardless of their origin, the vertebral arteries are significant because they form part of the brain's posterior circulation, and the two internal carotid arteries provide the anterior circulation. The Circle of Willis connects the anterior and posterior circulation.

Our present study revealed that the diameter, length, and tortuosity of the prevertebral segment of the left and right vertebral arteries varied (Figs 1-4). Additionally, based on the available literature, these observed variations in physical nature likely contributed to blood flow and hemodynamics. A significantly enlarged foramen transversarium was discovered incidentally during a cone-beam computed tomography scan. Upon further evaluation with magnetic resonance angiography, Omami (2021) discovered that the foramen enlargement was caused by a tortuosity in the vertebral artery's course.

Our report includes what was observed in the cases presented here, but our findings mirror earlier discoveries (Poynter, 1916; Congdon, 1922; Iyer, 1927; Adachi, 1928). Irrespective of when and who conducted the studies, the genesis of the vertebral artery occupied the interests of embryologists, anatomists, and clinicians alike.

CONCLUSION

The case report presented here gave the faculty a significant "teaching moment" in the dissection laboratory. It emphasized the anomaly as a valuable lifelong learning opportunity that the students could become acquainted with. The clinical cases presented an invaluable opportunity to educate aspiring physicians about the impact of malformations on affected individuals. Furthermore, studying these individuals with long life spans enables us to comprehend the crucial role of physicians in delivering effective treatment and care. This study provides an embryological elucidation of how and why the right and left vertebral arteries originate from the aortic arch and adds some historical context tracing back to the early last century with the works of Poynter (1916), Congdon (1922), Iyer (1927) and Adachi (1928). The study captures how the anomalous origin of vertebral arteries is clinically relevant in surgeries that involve the cervical region and supraaortic arch. The study also explores how the tortuosity of the proximal vertebral artery, the aortic origin of the left vertebral artery, and their impact on the hemodynamics of cerebral circulation are related. Unlike other studies that only report on this anomaly, this study delves into the clinical significance of this occurrence in other birth defects, such as Down syndrome.

ABBREVIATIONS

AA-Aortic arch; **ISA**-Intersegmental arteries; **RSCA**-Right Subclavian Carotid Artery

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The authors state that every effort was made to follow all local and international ethical guidelines and laws that pertain to the use of human donors in anatomical research.

For research using human subjects, the American Association for Anatomy endorses the protections embodied in the Basic Principles of the Declaration of Helsinki and their expansion in the regulations governing research supported by the U.S. Government (45 CFR Part 46; 56 FR 28003).

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DISCLOSURE

All authors were involved in the research and preparation process for the manuscript. CMV and Dr. Vasan performed the final part of the dissection and created the photographic images. CMV was responsible for conceiving the project idea, creating the initial draft with Dr. Vasan, and revising the manuscript with Ms. Huff until the final version was completed. Ms. Huff and Dr. Vasan conducted the literature search at the beginning, which was used to draft the manuscript and prepare the final format to be officially submitted. Ms. Huff is charged with formatting and submission of the manuscript.

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