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Original Research Article

Anatomical Variations of the Vertebral Artery: A Retrospective Record-Based Study Using Cadaveric and Radiological Data

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Abstract:

Background: The vertebral artery exhibits considerable anatomical variability in its caliber, course, transverse foramen entry, dominance, and branching pattern. Recognition of these variations is important for accurate radiological interpretation and safe cervical and craniovertebral procedures.

Aim: To evaluate the frequency and patterns of vertebral artery anatomical variations using existing cadaveric and radiological records.

Methodology: A retrospective record-based descriptive observational study was conducted in the Department of Anatomy, Darbhanga Medical College, Laheriasarai, Darbhanga, Bihar. Fifty eligible adult records were reviewed, comprising 25 cadaveric and 25 radiological records. Vertebral artery findings were extracted systematically and analyzed using SPSS version 27.0. Frequencies and percentages were calculated.

Results: Normal vertebral artery anatomy was observed in 32 (64%) records, while variations occurred in 18 (36%). Hypoplasia was the most frequent variation (14%), followed by tortuosity (10%), variation in transverse foramen entry level (8%), and duplication (4%). Left vertebral artery dominance was observed in 42%, right dominance in 28%, and co-dominance in 18%. Findings were broadly comparable between cadaveric and radiological records.

Conclusion: Vertebral artery variations were relatively common, emphasizing their importance in anatomical assessment, radiological interpretation, and procedural planning.

Keywords: Vertebral Artery; Anatomical Variation; Hypoplasia; Tortuosity; Cadaveric Study; Radiology; Vertebral Artery Dominance.

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Introduction

The vertebral artery is a significant part of the posterior cerebral circulation and supplies a significant amount of blood to the brainstem, cerebellum, spinal cord, and to the posterior portions of the brain [1]. It typically originates from the beginning of the subclavian artery and runs through the cervical vertebral transverse foramina, typically at the C6 level. It then passes superiorly through the transverse foramen of C1, curves medially around the posterior arch of the atlas, and enters the cranial cavity through the foramen magnum. In the cranial cavity, the right and left vertebral arteries merge close to the lower border of the pons to create the basilar artery [2]. This is the normal position, but the distribution of the vertebral artery in terms of the origin, course, level of its entry into the transverse foramina, size, branching, dominance and termination are all well recognised.

Vertebral artery anatomical variations are mainly associated with its embryology [3]. The development of the artery occurs by longitudinal anastomoses of cervical intersegmental arteries with selective persistence and regression of embryonic vascular channels. Variations in the final arterial origin and course can occur from abnormal persistence or regression of these vessels. These developmental anomalies can give rise to unusual origins, abnormal levels of entry into the cervical transverse foramina, tortuosity, duplication, fenestration and/or modified relationships with the cervical vertebrae. Knowledge of these developmental variants is significant because many of them have no clinical significance but can be important in diagnostic or surgical procedures of the cervical spine or craniovertebral junction.

The origin of the vertebral artery is one of the most common places of anatomical variation [4]. It usually comes from the subclavian artery but sometimes directly from the aortic arch (usually on the left) or the common carotid artery or other branches of the subclavian arterial system. Variations in the point of entry of the artery into the transverse foramen have also been reported, with the artery entering at C5, C4, or higher in the cervical spine in a certain number of people [5]. Importance of these variations: an artery that enters the transverse foramen at an atypical level might have an atypical relationship with the adjacent cervical structures and thus be more susceptible to injury during surgical procedures.

Other variations of the extracranial course of the vertebral artery are also important from an anatomical and clinical point of view [6]. A relatively vertical course is normally taken by the artery through the cervical transverse foramina, where it then turns laterally and posteriorly around the atlas. But tortuosity, looping, medial deviation, and asymmetrical courses can be present. From the normal anatomical description, an abnormal course could move the artery nearer to the spinal canal, neural foramina, uncovertebral joints, or to the operative field. This is especially important for cervical spine surgery (posterior instrumentation, screw fixation, decompression, atlantoaxial surgery, and surgery of the craniovertebral junction), where unexpected arterial anatomy can be a source of vascular injury.

The capability of identifying the variations of the vertebral arteries in living persons has greatly benefited from radiological investigations. The origin, diameter, course, transverse foraminal entry, and relationship of the artery to adjacent osseous structures are demonstrable by computed tomography angiography, magnetic resonance angiography, digital subtraction angiography, and multidetector computed tomography [7]. Computed tomography angiography will be helpful, especially when used to assess vascular and bony anatomy at the same time, which is critical preoperatively. Magnetic resonance angiography is a non-invasive technique for the assessment of the vertebrobasilar circulation and its intracranial structures. It is crucial to recognize normal anatomical variants on imaging to prevent misinterpretation and enhance procedural planning.

Vertebral arteries can also be quite unevenly sized from side to side. Often, one of these arteries is larger, and the other is smaller [8]. Vertebral artery hypoplasia and significant asymmetry of the diameters have been noted in an anatomical and radiological study, and may affect the hemodynamics of the posterior circulation. There are further variations such as duplication, fenestration, irregular termination, and differences in the origin or course of the posterior inferior cerebellar artery. In some cases, the vertebral artery may end as the posterior inferior cerebellar artery instead of as a major component of the basilar artery. These are important for understanding when interpreting vascular imaging and for planning endovascular or neurosurgical interventions.

The intracranial vertebral artery is in proximity to significant neurological structures such as the medulla, lower cranial nerves, posterior inferior cerebellar artery and anterior spinal artery. Thus, these variations in these vascular relationships may have relevance for posterior fossa surgery, aneurysm management, vascular reconstruction and endovascular interventions. The knowledge of these patterns helps differentiate anatomical variants from pathological conditions and in minimizing the risk of unintentional vascular injury.

Cadaveric studies continue to play a significant role in the understanding of vertebral artery anatomy due to the ability of direct dissection to dissect the vessel and observe its relationship with muscles, fascia, cervical vertebrae and neural structures, as well as its relationship with the surrounding tissues. Radiological studies, on the other hand, give information from living subjects and enable evaluation of the vascular morphology without dissection. Cadaveric and radiological data can therefore be used as complementary data and enable a more comprehensive evaluation of vertebral artery variability. A retrospective record-based approach also allows the evaluation of previous anatomical and imaging data in a systematic way without conducting further investigations on the subjects.

Vertebral artery variation exists across a variety of specialties, including anatomy, radiology, neurosurgery, orthopaedics, vascular surgery and interventional medicine, and is clinically meaningful. Unrecognized variations can pose the risk of vascular injury during surgery on the cervical spine and the craniovertebral junction, and can make endovascular surgery more difficult. Hence, it is imperative to record the incidence and morphologic types of VAVs both for anatomical knowledge and for clinical security. The present study "Anatomical Variations of the Vertebral Artery: A Retrospective Record-Based Study Using Cadaveric and Radiological Data" is aimed at systematically evaluating the variations in the origin, course, level of transverse foraminal entry, caliber, dominance, branching, and termination of the vertebral artery in available cadaveric and radiological records. These results could help in better understanding of anatomy, radiology and safer planning of procedures in and around the vertebral artery and cervical spine.

Methodology

Study Design: The present study was conducted as a retrospective record-based descriptive observational study to evaluate the anatomical variations of the vertebral artery using existing cadaveric dissection records and radiological imaging data. The study aimed to assess the frequency, pattern, and distribution of vertebral artery variations without any direct intervention or examination of subjects. Previously recorded anatomical and imaging findings were reviewed and analyzed to identify variations in the origin, course, entry level into the transverse foramen, dominance pattern, and other morphological characteristics of the vertebral artery.

Study Setting: The study was carried out in the Department of Anatomy, Darbhanga Medical College, Laheriasarai, Darbhanga, Bihar, India. The department maintains archived cadaveric dissection records and collaborates with the radiology department for the storage and retrieval of imaging data. These records served as the primary source of information for the present retrospective analysis.

Study Duration: The study was conducted over a period of three months.

Participants

Inclusion Criteria

- Cadaveric records with complete documentation of vertebral artery anatomy.
- Radiological records (CT angiography, MR angiography, or contrast-enhanced imaging) showing clear visualization of the vertebral arteries.
- Adult specimens or patients aged 18 years and above.
- Records containing adequate demographic and anatomical information.
- Records available within the study period and institutional archive.

Exclusion Criteria

- Incomplete or damaged records.
- Cadaveric specimens with evidence of traumatic injury or surgical alteration involving the neck vessels.
- Radiological images with poor quality or inadequate visualization of the vertebral arteries.
- Duplicate records.
- Pediatric cases below 18 years of age.

Study Sampling: A purposive sampling method was adopted. All available cadaveric and radiological records meeting the inclusion criteria during the study period were reviewed. Eligible records were selected consecutively until the required sample size was achieved.

Study Sample Size: A total of 50 records were included in the study. The sample comprised both cadaveric dissection records and radiological imaging records that fulfilled the predefined eligibility criteria. This sample size was considered adequate for describing the frequency and pattern of vertebral artery variations within the available institutional records.

Study Groups: For comparative analysis, the records were categorized into two groups:

- **Group A:** Cadaveric records (n = 25)
- **Group B:** Radiological records (n = 25)

The anatomical findings obtained from both groups were compared to assess similarities and differences in vertebral artery variations.

Study Procedure: Archived cadaveric and radiological records were retrieved from the departmental database. Each record was carefully reviewed for eligibility. Relevant anatomical information regarding the vertebral artery was extracted using a structured data collection form. Variations were classified according to standard anatomical descriptions. The collected data were subsequently compiled and organized for analysis.

Data Collection: Data were collected from departmental record registers, dissection reports, and radiological imaging archives. Information related to demographic characteristics and vertebral artery morphology was documented systematically. Confidentiality of all records was maintained throughout the study, and personal identifiers were removed during data extraction.

Data Analysis: The collected data were entered into Microsoft Excel and analyzed using Statistical Package for Social Sciences (SPSS) version 27.0. Descriptive statistics were applied to summarize the findings. Categorical variables were expressed as frequencies and percentages. The Chi-square test or Fisher's exact test was used for comparison between groups wherever applicable. A p-value of less than 0.05 was considered statistically significant.

Result

Table 1 shows the distribution of the 50 study records according to their source. Of the total records, 25 (50%) were obtained from cadaveric records, while an equal number of 25 (50%) were obtained from radiological records. Thus, both sources contributed equally to the study sample, ensuring a balanced representation of anatomical information from direct cadaveric observations and imaging-based records. The equal distribution allowed the study to incorporate findings from both anatomical and radiological perspectives. Overall, the study comprised 50 records, with each source accounting for exactly half (50%) of the total dataset.

Table 1: Distribution of Study Records According to Source		
Source of record	**Number (n)**	**Percentage (%)**
Cadaveric records	25	50
Radiological records	25	50
Total	**50**	**100**

Table 2 shows the distribution of vertebral artery findings according to their anatomical type among the 50 study records. A normal anatomical pattern was observed in 32 (64%) records, representing the most common finding. Vertebral artery hypoplasia was identified in 7 (14%) records, followed by tortuosity in 5 (10%) records. Variation in the transverse foramen entry level was observed in 4 (8%) records, whereas duplication was the least frequent finding, occurring in 2 (4%) records. Overall, the findings demonstrated that normal vertebral artery anatomy predominated, while anatomical variations collectively accounted for 18 (36%) of the examined records.

Table 2: Distribution of Vertebral Artery Findings According to Type		
Vertebral artery finding	**Number (n)**	**Percentage (%)**
Normal anatomical pattern	32	64
Hypoplasia	7	14
Tortuosity	5	10
Variation in transverse foramen entry level	4	8
Duplication	2	4
Total	**50**	**100**

Table 3 shows the side-wise distribution of vertebral artery variations among the 100 assessed sides. Variations were more frequently observed on the right side, where 10 (20.0%) sides demonstrated a variation and 40 (80.0%) showed a normal anatomical pattern. On the left side, variations were identified in 8 (16.0%) sides, while 42 (84.0%) exhibited a normal pattern. Overall, 18 (18.0%) sides showed vertebral artery variations, whereas 82 (82.0%) sides demonstrated normal anatomy. Thus, the findings indicated a slightly higher frequency of vertebral artery variations on the right side compared with the left side.

Table 3: Side-wise Distribution of Vertebral Artery Variations			
Side	**Variation present n (%)**	**Normal pattern n (%)**	**Total**
Right	10 (20.0)	40 (80.0)	50 (100.0)
Left	8 (16.0)	42 (84.0)	50 (100.0)
Total	**18 (18.0)**	**82 (82.0)**	**100 (100.0)**

Table 4 shows the distribution of vertebral artery dominance patterns among the 50 study records. Left vertebral artery dominance was the most frequently observed pattern, occurring in 21 (42%) records. Right vertebral artery dominance was identified in 14 (28%) records, while a co-dominant pattern was observed in 9 (18%) records. A hypoplastic vertebral artery pattern was present in 6 (12%) records, representing the least common pattern. Overall, the findings demonstrated a predominance of left-sided vertebral artery dominance, followed by right-sided dominance, co-dominance, and hypoplastic patterns. This distribution indicated considerable variation in vertebral artery dominance among the examined records.

Table 4: Distribution of Vertebral Artery Dominance Pattern		
Dominance pattern	**Number (n)**	**Percentage (%)**
Left vertebral artery dominant	21	42
Right vertebral artery dominant	14	28
Co-dominant	9	18
Hypoplastic vertebral artery pattern	6	12
Total	**50**	**100**

Table 5 compares vertebral artery findings between cadaveric and radiological records. A normal anatomical pattern was the most common finding in both cadaveric records, 17 (68.0%), and radiological records, 15 (60.0%), with an overall frequency of 32 (64.0%). Hypoplasia was observed in 3 (12.0%) cadaveric and 4 (16.0%) radiological records, while tortuosity occurred in 2 (8.0%) and 3 (12.0%), respectively. Variation in transverse foramen entry level was equally distributed, with 2 (8.0%) records in each group. Duplication was the least frequent finding, occurring in 1 (4.0%) record from each source. Overall, the distribution was broadly comparable between the two record types.

Table 5: Comparison of Vertebral Artery Findings Between Cadaveric and Radiological Records

Vertebral artery finding	Cadaveric records n (%)	Radiological records n (%)	Total n (%)
Normal anatomical pattern	17 (68.0)	15 (60.0)	32 (64.0)
Hypoplasia	3 (12.0)	4 (16.0)	7 (14.0)
Tortuosity	2 (8.0)	3 (12.0)	5 (10.0)
Variation in transverse foramen entry level	2 (8.0)	2 (8.0)	4 (8.0)
Duplication	1 (4.0)	1 (4.0)	2 (4.0)
Total	**25 (100.0)**	**25 (100.0)**	**50 (100.0)**

Discussion

The present retrospective study based on a record collection aimed to assess the vertebral artery anatomy with 50 records, including 25 cadaveric and 25 radiological records. The level of contribution from both sources meant that the direct anatomical observations could be taken together with imaging-based observations. In this study, normal vertebral artery anatomy was seen in 64% (32 records), and an anatomical variation was seen in 36% (18 records). The proportion of variation is relatively high, which agrees with the fact that the anatomy of the vertebral arteries is highly variable, but differs depending on population, anatomical segment studied, diagnostic method, and definition of variation. In a review of 250 MRI scans, Eskander et al. 2010 [9] stressed that there is significant inter-individual variation in the vertebral artery, specifically in terms of caliber and course, as well as its relationship with the cervical vertebrae. Abd El Gawad et al. (2019) [10] on the other hand, by radiological and dry-bone evaluation, found the relationship of the vertebral arteries with the atlas and other neighboring structures to be far from uniform."

In the present work, hypoplasia was the most common variation (7/50 records, 14%). This prevalence rate is greater than a pooled prevalence of 7.94% found in a systematic review and meta-analysis of the prevalence of vertebral artery anatomy; however, these differing results could be due to differences in the diagnostic criteria used or the study populations. However, a high prevalence was reported by Jeng and Yip, 2004 [11], who found that ultrasonographic evaluation showed that vertebral artery hypoplasia existed in a large number of the subjects they examined, suggesting that asymmetry in the caliber of the vertebral artery may be common. This was also clinically significant as shown by Perren et al. (2007) [12], who found that 4.6% of patients with infarction in vascular territories other than the posterior circulation had vertebral artery hypoplasia (defined as <2.5 mm in diameter) compared with 13% in those with posterior circulation infarction. The 14% prevalence in the present study is therefore of anatomical interest and supports the need for accurate recording of vessel size when assessing a patient's radiological evaluation, especially in the presence of a suspicion of posterior circulation pathology.

The second commonest variation in the current study was tortuosity found in 5 records (10%. This prevalence is lower than the one reported in the systematic review and meta-analysis based on the same literature base, which estimated tortuosity to be approximately 25.9% overall. There may be differences due to the small number of patients in the present study, the different definition of tortuosity, or that only selected retrospective records were available for review. The tortuous course of the vertebral arteries may be relevant to surgery, as changes in the usual vascular course can lead to vessel injury in cervical spine, craniovertebral junction and/or endovascular surgery. Moreover, Sheth et al. [13] noted some changes in the shape of the vertebral artery with rotation and showed that the shape of the artery in clinically significant areas may vary during rotation, thus highlighting the dynamic nature of the vertebral artery anatomy. So although tortuosity was found in just 10% of the current records, it still has clinical significance.

In 4 records (8%) there was variation in the level of entry of the transverse foramen. These findings are similar to those that have been reported radiologically. Using MRI and contrast-enhanced CT, Bruneau et al. (2006) [14] examined 500 vertebral arteries, and 93.0% of the arteries entered the transverse foramen at C6, with 7.0% showing a variation in entry level. Among these abnormalities, C5 entry accounted for 5.0%, C4 for 1.0%, C7 for 0.8%, and C3 for 0.2%. Thus, the prevalence of the present study (8%) seems similar to the prevalence reported by Bruneau et al. (2006) (7%). A study by Uchino et al. also found 7.0% of left vertebral and 6.2% of right vertebral arteries to enter the abnormal transverse foramina [15]. These findings corroborate the present observation, and suggest that abnormal entry levels, though not common, are an important and reproducible anatomical variant compared to normal C6 entry.

Duplication was also found in 2 records (4%) from the present study. Similar variations were noted in angiographic and cadaveric studies, and although not frequently seen, duplication was also described. Zhu et al. (2018) [16] identified 26 patients with 29 distal vertebral artery variants that included duplicated vertebral arteries (13), C2-origin PICA variants (10), and aberrant V3 variants (6). The findings of the present study replicate those of previous studies, which documented the variability of these anatomic structures, but because the previous study was conducted specifically on distal vertebral artery and radiculomuscular artery variants, the frequencies of these variants cannot be compared as a direct comparison. The relatively low prevalence in the current dataset might be due to the small sample size.

When assessed side-wise, there were variations in 18 of 100 sides assessed (18%), and slightly more on the right side (10/50; 20%) than on the left side (8/50; 16%). This difference was small but has been shown in previous studies to be prevalent with vertebral artery asymmetry and side predominance. In particular, the left vertebral artery is frequently larger or dominant. In the present series 21 records (42%) were left-sided dominant, 14 (28%) were right-sided dominant, 9 (18%) were co-dominant, and 6 (12%) were hypoplastic. The results of this study are consistent with the overall findings of pooled studies that report that the left vertebral artery is dominant in about 36.1% of patients and the right vertebral artery is dominant in about 25.3% of patients. This left-sided predominance might therefore be the anticipated left-sided dominance and could explain the higher left-sided dominance observed in the present study.

The findings were further illustrated by the similarity when comparing cadaveric records with radiological records. In cadaveric records, 68% and in radiological records, 60% were normal. A total of 12% and 16% of cadaveric and radiological records, respectively, showed hypoplasia, and 8% and 12% showed tortuosity, respectively. The variation at entry level was the same in both groups (8%), as was duplication (4%) in both. The similarity in results implies that both sources of records could recognise the principal types of vertebral artery variations. The higher prevalence of hypoplasia and tortuosity in radiological records may be related to the fact that modern imaging techniques can assess the caliber and course of the vessels in living people. On the other hand, cadaveric examination offers a direct view of the artery and its bony and surrounding relationships.

These findings support the clinical relevance of the study reported by Lazaridis et al. 2018 [17] who reported that the distribution of the VAO was mainly unilateral, and left VAO from the aortic arch was present in about 3.6% of patients. In the present data set, the vertebral artery was not specifically categorized with regard to its abnormal origin, but the present evidence shows that the origin of the artery is not limited to variations in caliber or course. Likewise, Omotoso et al. (2023) in their systematic review of 17 studies with 10,820 patients found that 1.8% had persistent first intersegmental artery, 1.6% extradural PICA origin, and 0.7% vertebral artery fenestration [18]. These variants are relatively uncommon compared to hypoplasia and tortuosity, which were more common in this study.

In total, the results of the present study confirm that normal vertebral artery anatomy prevailed (64%), but a significant proportion of records (36%) exhibited some degree of variation. The most common variation was hypoplasia (14%), followed by tortuosity (10%), abnormal transverse-foramen entry (8%) and duplication (4%). Left vertebral artery (VA) dominance (42%) was more common than right dominance (28%) and co-dominance (18%). A broad comparison of the results of cadaveric and radiological studies supports the importance of combining cadaveric and radiological studies to investigate the anatomy of the vertebral artery. These differences need to be recognised, as, although relatively uncommon, vascular anatomy can affect radiological interpretation and may contribute to the risk of vascular injury during cervical spine and craniovertebral procedures.

Conclusion

The present retrospective record-based study demonstrated that although normal vertebral artery anatomy was predominant, anatomical variations were relatively common. Among the 50 records evaluated, 64% showed a normal pattern, while 36% demonstrated variations, with hypoplasia (14%) being the most frequent, followed by tortuosity (10%), variation in transverse foramen entry level (8%), and duplication (4%). Left vertebral artery dominance (42%) was more common than right dominance (28%) and co-dominance (18%). Variations were slightly more frequent on the right side than the left. Cadaveric and radiological records showed broadly comparable findings, highlighting the complementary value of both approaches. These findings emphasize the importance of recognizing vertebral artery variations during anatomical assessment, radiological interpretation, and planning of cervical spine and craniovertebral surgical or endovascular procedures to minimize the risk of vascular complications.

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