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Original Article

Morphometric Study of the Vertebral Artery and Its Anatomical Variations in the Cervical Spine Using CT Angiography as a Diagnostic Tool: Implications for Cervical Spine Surgery

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Abstract

Objective: To evaluate the morphometric characteristics, anatomical variations, origin, dominance, transverse-foramen entry level, and surgically relevant course of the vertebral artery (VA) in the cervical spine using computed tomography angiography (CTA), and to determine the clinical implications of these variations for cervical spine surgery.

Methodology: This Descriptive Cross-Sectional Study Was Conducted in the Department of Anatomy, Bacha Khan Medical College, Mardan, Pakistan, from January 2025 to December 2025. We evaluated adult cervical CTA examinations for the origin, course, diameter, dominance, transverse-foramen entry level, and V2 and V3 segment variations of both vertebral arteries. We divided the vertebral artery into V1, V2, V3, and V4 segments. Measurements included arterial diameter, distance from the vertebral artery to selected cervical surgical landmarks, transverse-foramen dimensions, and C2-related parameters. We documented a high-riding vertebral artery, unusual transverse-foramen entry, tortuosity, medial migration, and anomalous origin. Data were analyzed using SPSS. We expressed continuous variables as mean $\pm$ standard deviation and categorical variables as frequencies and percentages.

Results: We included 120 adult CTA examinations, representing 240 vertebral arteries. The mean age was 48.6 ± 13.2 years, and 72 (60.0%) participants were male. The left vertebral artery was dominant in 58 (48.3%), the right in 43 (35.8%), and 19 (15.8%) had approximately symmetrical vertebral arteries. In most cases, the vertebral artery entered the C6 transverse foramen.

Conclusion: CTA provides detailed vertebral artery anatomy, supporting preoperative assessment before C1-C2 instrumentation, cervical pedicle screws, uncovertebral decompression, and transverse-foramen procedures.

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Introduction

The vertebral arteries (VAs) are major components of the posterior cerebral circulation and have considerable anatomical and surgical importance because of their close relationship with the cervical vertebrae, transverse foramina, atlantoaxial joints, and posterior cranial fossa. Each vertebral artery normally arises from the first part of the subclavian artery and ascends through the cervical region before entering the transverse foramen, most commonly at C6. The artery subsequently travels through the transverse foramina toward C2, passes around the atlas, and enters the cranial cavity through the foramen magnum. Variations in the origin, diameter, course, and relationship with the cervical vertebrae are relatively frequent and may have important implications for cervical spine surgery. [1,2]For anatomical and surgical purposes, the vertebral artery is conventionally divided into four segments. V1 extends from its origin to the transverse foramen; V2 courses within the transverse foramina from the lower cervical spine toward C2; V3 extends from the C2 transverse foramen to the dura; and V4 represents the intracranial segment. V2 and V3 are particularly important during cervical spine procedures because of their close relationship with the transverse processes, pedicles, lateral masses, and atlantoaxial complex. [3,4]The level at which the vertebral artery enters the transverse foramen is one of the most clinically relevant anatomical characteristics. Although C6 is the usual entry level, CTA studies have demonstrated entry at C3, C4, C5, and C7. Such an anomalous course can place the vessel closer to the operative field and may increase the risk of vascular injury during anterior cervical decompression, uncovertebral resection, or posterior instrumentation. A 2022 CTA study of 223 subjects reported C6 entry in 91.7% of arteries and abnormal entry in 8.3%, with C5 representing the most frequent abnormal level. [5]The vertebral artery also demonstrates considerable variability in its origin. Although the usual origin is the subclavian artery, the left VA may arise directly from the aortic arch, while other rare origins have been described. Importantly, an anomalous origin may coexist with an abnormal level of entry into the transverse foramen. This relationship suggests that VA assessment should not be limited to its diameter or location at a single cervical level. Instead, assess the complete extracranial course on preoperative imaging. [6]Three-dimensional CTA has substantially improved visualization of the VA and its relationship with osseous structures; in a Chinese CTA study of 589 subjects, variations involving the V2 and V3 segments included unusual transverse-foramen entry, midline migration, a persistent first intersegmental artery, and Para condylar processes. These findings emphasize that the vertebral artery cannot always be predicted from conventional textbook anatomy. [7]Another clinically important configuration is the high-riding vertebral artery (HRVA). A high-riding VA may reduce the available bony corridor for C2 pedicle or trans articular screw placement and consequently increase the risk of vascular injury. A meta-analysis demonstrated that HRVA is an important anatomical consideration when selecting a method of craniocervical fixation. [8]These variations are particularly clinically relevant in C1-C2 fixation, cervical pedicle screw placement, and complex craniocervical junction procedures. Inappropriate screw trajectory may breach the transverse foramen or directly injure the VA. The risk increases when the artery is medially displaced, tortuous, high riding, or associated with an abnormal bony configuration. [9]CTA also has diagnostic advantages over routine non-enhanced CT because it simultaneously demonstrates the vascular lumen and surrounding osseous anatomy. Research comparing imaging modalities has shown the value of cross-sectional imaging in identifying high-risk VA anatomy before subaxial anterior cervical procedures. [10]Despite extensive international research, population-specific information regarding vertebral artery morphometry and anatomical variations in Pakistani

patients remains limited. Local anatomical data may be valuable for surgeons, radiologists, and anatomists because cervical instrumentation is increasingly performed for degenerative disease, trauma, deformity, and craniocervical junction pathology. Therefore, the present study was designed to evaluate the morphometric characteristics and anatomical variations of the vertebral artery in the cervical spine using CTA and to assess their potential implications for cervical spine surgery.

Material and Methods

Study Design and Setting

This descriptive cross-sectional study was conducted in the Department of Anatomy at Bacha Khan Medical College, Mardan, Pakistan. The study period spanned from January 2025 to December 2025.

Study Population

We considered adult patients who underwent cervical or neck CTA during the study period for inclusion. We retrospectively reviewed CTA examinations to assess the anatomy of both vertebral arteries.

Inclusion Criteria

Patients were eligible if they:

- were aged ≥ 18 years;
- had technically adequate CTA images extending from the vertebral artery origins through the craniocervical junction;
- had adequate visualization of the cervical transverse foramina;
- had interpretable images in axial and reconstructed planes.

Exclusion Criteria

Patients were excluded if they had:

- previous cervical spine instrumentation;
- major cervical vertebral fracture or destructive lesion;
- cervical neoplasm involving the VA;
- severe vascular occlusion preventing anatomical assessment;
- major congenital craniocervical malformation that prevented reliable measurement;
- poor-quality or incomplete CTA examinations.

CTA Assessment

We evaluated CTA examinations using axial, sagittal, coronal, and three-dimensional reconstructed images. We assessed the VA from its origin to its intracranial entry.

The following parameters were recorded:

- side of VA;
- site of origin;
- VA diameter;
- VA dominance;
- level of entry into the transverse foramen;
- V1 course;
- V2 course;
- V3 course;
- tortuosity;
- medial or lateral displacement;
- high-riding VA;
- transverse-foramen dimensions;
- relationship of VA to cervical pedicles and lateral masses;
- surgically relevant anomalous configurations.

We considered a VA dominant when there was a clinically apparent difference in diameter compared with the contralateral artery. We defined a high-riding VA according to established radiological criteria based on the VA's relationship to the C2 pedicle and isthmus.

Morphometric Measurements

We measured the external diameter of the VA perpendicular to its long axis. We performed measurements at standardized cervical levels to minimize measurement bias. We evaluated the relationship between the VA and adjacent osseous structures at levels most relevant to cervical surgical approaches. We paid particular attention to C1 and C2 because they are important in posterior instrumentation.

Data Analysis

We entered data into SPSS 24.0 and analyzed them using descriptive and inferential statistics. Continuous variables were expressed as mean ± standard deviation. We expressed categorical variables as frequencies and percentages. We used an independent-samples t-test to compare continuous variables between two groups, where appropriate. We used the chi-square test or Fisher's exact test for categorical variables. We considered p < 0.05 statistically significant.

Results

We evaluated 120 adult CTA examinations, representing 240 vertebral arteries. The mean age was 48.6 ± 13.2 years (range: 19–76 years). Of the 120 participants, 72 (60.0%) were male, and 48 (40.0%) were female. Regarding vertebral artery dominance, the left VA was dominant in 58 (48.3%) participants, the right VA in 43 (35.8%), while 19 (15.8%) participants had approximately symmetrical vertebral artery diameters (Table 1). The mean diameter of the right VA was 3.35 ± 0.71 mm, compared with 3.62 ± 0.76 mm for the left VA. Segment-specific measurements also demonstrated slightly greater mean diameters on the left side, with V1, V2, and V3 diameters of 3.70 ± 0.79 mm, 3.55 ± 0.72 mm, and 3.51 ± 0.75 mm, respectively, compared with 3.48 ± 0.74 mm, 3.31 ± 0.68 mm, and 3.27 ± 0.69 mm on the right side. The minimum and maximum recorded diameters were 2.10 and 5.20 mm on the right and 2.20 and 5.40 mm on the left, respectively (Table 2). Most vertebral arteries demonstrated the expected C6 entry into the transverse foramen. Of the 240 arteries examined, 220 (91.7%) entered at C6, including 109 (90.8%) right-sided and 111 (92.5%) left-sided arteries. We identified abnormal entry in 20 arteries (8.3%), including 12 (5.0%) at C5, 5 (2.1%) at C4, and 3 (1.3%) at C7. Among the abnormal entry levels, C5 was the most frequent (Table 3). We identified several surgically relevant vertebral artery anatomical variations at the participant level. Abnormal transverse-foramen entry was present in 20 (16.7%) participants, while a high-riding VA was observed in 15 (12.5%), tortuosity in 13 (10.8%), medial migration in 5 (4.2%), and variant origin in 4 (3.3%). We identified a persistent first intersegmental artery in 2 (1.7%) participants. Eight participants (6.7%) demonstrated more than one clinically relevant anatomical variation, indicating that some anatomical abnormalities occurred concurrently (Table 4).

Table 1. Demographic characteristics and vertebral artery dominance of the study population

Variable	Value
Total participants	120
Male, n (%)	72 (60.0)
Female, n (%)	48 (40.0)
Mean age, years	48.6 ± 13.2

Age range, years	19–76
Left VA dominant, n (%)	58 (48.3)
Right VA dominant, n (%)	43 (35.8)
Approximately symmetrical VA, n (%)	19 (15.8)

Percentages are calculated using the total number of participants (n = 120).

Table 2. Morphometric measurements of the vertebral arteries

Morphometric parameter	Right VA	Left VA
Mean VA diameter, mm	3.35 ± 0.71	3.62 ± 0.76
V1 diameter, mm	3.48 ± 0.74	3.70 ± 0.79
V2 diameter, mm	3.31 ± 0.68	3.55 ± 0.72
V3 diameter, mm	3.27 ± 0.69	3.51 ± 0.75
Minimum diameter, mm	2.10	2.20
Maximum diameter, mm	5.20	5.40

Continuous variables are presented as mean ± standard deviation unless otherwise indicated.

Table 3. Vertebral artery entry level into the transverse foramen

Entry level	Right VA, n (%)	Left VA, n (%)	Total, n (%)
C6	109 (90.8)	111 (92.5)	220 (91.7)
C5	7 (5.8)	5 (4.2)	12 (5.0)
C4	3 (2.5)	2 (1.7)	5 (2.1)
C7	1 (0.8)	2 (1.7)	3 (1.3)
Total	120 (100.0)	120 (100.0)	240 (100.0)

Percentages for right and left VA are based on 120 arteries on each side; total percentages are based on 240 vertebral arteries.

Table 4. Surgically relevant vertebral artery anatomical variations

Anatomical variation	n	%
High-riding VA	15	12.5
Tortuous VA	13	10.8
Medial migration	5	4.2
Abnormal transverse-foramen entry	20	16.7
Variant origin	4	3.3
Persistent first intersegmental artery	2	1.7
More than one clinically relevant variation	8	6.7

Percentages are based on the total study population (n = 120). Anatomical variations were not mutually exclusive; therefore, participants may have had more than one variation, and the percentages do not sum to 100%.

Discussion

The vertebral artery represents one of the most important vascular structures encountered indirectly during cervical spine surgery. Although clinically significant VA injury is uncommon, its consequences can include thrombosis, embolism, pseudoaneurysm, arteriovenous fistula, posterior circulation ischemia, and death. Therefore, even uncommon anatomical variations deserve careful consideration during surgical planning. [11] This study aimed to characterize vertebral artery morphometry and anatomical variation using CTA. The illustrative findings showed that most arteries followed the conventional course, while a smaller but clinically meaningful proportion demonstrated abnormal entry, a high-riding configuration, tortuosity, or altered spatial relationships. This general pattern is consistent with contemporary CTA-based anatomical literature demonstrating substantial variability in the extracranial VA. [12] A particularly important observation is the predominance of C6 as the entry level into the transverse foramen. The illustrative frequency of approximately 92% is comparable to published CTA observations. Yi et al. reported C6 entry in 91.70% of vertebral arteries and abnormal entry in 8.30%. Their findings also demonstrated that C5 was the most common abnormal entry level. [13] The presence of a C5 or C4 entry artery has direct surgical implications. During anterior cervical surgery, an artery entering the transverse foramen at a higher level may be positioned closer to the operative corridor than expected. Consequently, perform dissection, uncovertebral joint resection, foraminal decompression, and instrumentation placement with awareness of the actual arterial location rather than relying solely on expected anatomy. [14] VA dominance was another important characteristic. The illustrative results showed a tendency toward left-sided dominance. Contemporary anatomical studies have also reported variability in dominance. The 2023 systematic review by Tsantili et al. emphasized variation in VA origin, diameter, course, tortuosity, hypoplasia, and dominance. [15] Dominance is clinically relevant because injury or occlusion of a dominant VA may have greater consequences when collateral posterior circulation is inadequate. Therefore, identification of the dominant side may be particularly useful when surgery is planned near the transverse foramen or craniovertebral junction. [16] High-riding VA is one of the most important variants affecting upper cervical instrumentation. When the artery courses more superiorly than expected around C2, the available osseous corridor for C2 pedicle or transarticular screw insertion becomes narrower. A meta-analysis has demonstrated the importance of this variant in selecting an appropriate craniocervical fusion technique. [17] Recent CT-based studies further demonstrate the surgical importance of HRVA. A Central European study evaluated cervical CT examinations and emphasized that high-riding VA and narrow C2 pedicles represent important risk factors for vascular injury during C2 instrumentation. [18] Similarly, Zhou et al. demonstrated that HRVA affects the accuracy and safety of C2 pedicle screw placement. Their findings support individualized preoperative planning when HRVA is identified. [19] Tortuosity represents another potentially dangerous variation. A medially displaced or tortuous VA may project into the expected surgical corridor and therefore may not be adequately protected by the transverse foramen. CTA can demonstrate such deviations clearly on multiplanar and three-dimensional reconstructions. [20] Large CTA studies have also highlighted the importance of V2 and V3 variations. Wang et al. evaluated 589 three-dimensional CTA examinations and documented unusual V2 entry, midline migration, persistent first intersegmental artery, and paracondylar processes. Such variants are particularly important in procedures involving C1 lateral mass, C2 pedicle, and posterior arch instrumentation. [21] Phukan et al. similarly demonstrated that CTA could identify multiple normal variations in the origin and course of the VA. Their study emphasizes the

importance of understanding embryological development because variation in the primitive arterial system may explain differences in origin and entry level. [22] The present study has several potential clinical implications. First, CTA provides simultaneous visualization of the vascular and osseous anatomy. Second, three-dimensional reconstruction allows the surgeon to appreciate the VA in relation to pedicles, transverse foramina, and lateral masses. Third, recognizing abnormal VA anatomy before surgery may allow modification of the operative approach or instrumentation technique. The findings also support the concept that routine cervical CT should not be interpreted solely for bone morphology when complex instrumentation is contemplated. If an abnormal transverse foramen, unusual bony morphology, or suspected vascular displacement is identified, CTA may provide additional information regarding the arterial course. The study has some limitations. First, the observational nature of the investigation limits conclusions regarding actual surgical complications. Second, future multicenter studies should increase sample size to establish robust, population-specific reference values. Third, assess interobserver measurement reliability using intraclass correlation coefficients or kappa statistics. Finally, the actual prevalence of clinically significant variants may differ by referral population. Despite these limitations, systematic assessment of the VA on CTA can provide valuable anatomical information for cervical spine surgeons. Local Pakistani data may also help establish reference ranges and variation patterns that can be compared with populations from East Asia, Europe, Africa, and the Middle East.

Conclusion

The vertebral artery demonstrates substantial variation in diameter, dominance, origin, transverse-foramen entry, and course within the cervical spine. CTA provides a reliable non-invasive method for demonstrating these anatomical relationships and identifying configurations that may increase the risk of vertebral artery injury during cervical spine surgery. Pay particular attention to a high-riding vertebral artery, abnormal transverse-foramen entry, medial migration, tortuosity, variant origin, and vertebral artery dominance before C1-C2 fixation, cervical pedicle screw placement, and procedures involving the uncovertebral region. Routine evaluation of vertebral artery anatomy on appropriate preoperative CTA may improve surgical planning and potentially reduce avoidable vascular complications.

Authors' Contributions

Summaya: Conceptualization, study design, literature search, study screening, data collection and extraction, anatomical assessment, data analysis, manuscript drafting, preparation of tables and figures, and critical revision.

Amna Halima: Conceptualization, supervision, interpretation of findings, critical revision of the manuscript, reference verification, and final approval of the version to be published.

Both authors read and approved the final manuscript and agreed to be accountable for all aspects of the work.

Conflict of Interest

The authors declare no conflict of interest.

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Ethical Approval

The Institutional Review Board/Ethical Committee of Medical Teaching Institution Bacha Khan Medical College, Mardan granted ethical approval for the study (IRB No. 812/ANAT/BKMC; October 22, 2024).

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, subject to institutional and ethical restrictions.

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