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Review Article

Anatomical variants of the vertebral artery: insights from cadaveric and radiological studies - a review

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ABSTRACT

Vertebral artery (VA) anatomical variations pose significant clinical challenges in neurosurgical, diagnostic, and endovascular interventions. This review aims to consolidate cadaveric and radiological evidence to map the morphologic spectrum and prevalence of such variants. A comprehensive search strategy was applied to PubMed using Boolean terms, retrieving 446 articles. Following strict inclusion criteria, 31 studies were selected. The most common variant identified was the origin of the left VA from the aortic arch, observed in 13 studies with a frequency range of 0.79%–9.3%. Entry level variations at cervical vertebrae C3–C7, hypoplasia (16.1%–59.3%), duplication (~0.16%), fenestration (~0.4%), and other anomalies such as triplication and abnormal origins from the brachiocephalic or common carotid artery were also reported. Course-related anomalies including tortuosity and anomalous trajectories further highlight the importance of preoperative imaging. Radiological studies offered population-level data, while cadaveric studies revealed detailed morphological nuances. Geographic variation in findings underscores the role of ethnicity and embryological development. The findings emphasize the need for standardized nomenclature, enhanced imaging protocols, and greater awareness among clinicians to mitigate intraoperative risks and improve patient outcomes.

Keywords: Vertebral artery, Anatomical variation, Hypoplasia, Fenestration, Cadaver, Radiological imaging

INTRODUCTION

The vertebral arteries (VAs) are key vessels supplying the brain through the posterior circulation. Their anatomy is well known to vary, and such differences may involve the site of origin, the path taken through the cervical spine, or the point of entry into the transverse foramina. These changes are not just of academic interest; they may complicate surgical procedures, create difficulties during cervical spine instrumentation, or alter the risk of posterior circulation stroke.[1-4] Among the commonly reported variants, the left VA taking its origin directly from the aortic arch is most frequent. Other changes, including high or low entry levels at C3–C7, duplication, fenestration, and hypoplasia, are also described with differing rates in various studies.[5-8] With the wide use of multidetector computed tomography angiography (MDCTA) and magnetic resonance angiography (MRA), large-scale surveys are now possible, while cadaveric work continues to add finer morphological details not always seen in radiological studies.[9,10]

Recent studies have added new insights. Tasdemir and Cihan showed distinctive patterns of VA origin and V2 segment morphology in a Turkish sample, and Chao et al reported new vertebrobasilar subtypes in Chinese patients using three-dimensional reconstructions.[3,4] Takata et al described a rare C5 segmental artery detected only by high-resolution MRA, highlighting the role of newer techniques in uncovering rare anomalies. Despite these reports, there is still no agreement on definitions such as hypoplasia or dominance, which explains why prevalence figures differ widely.

Population differences also stand out. Omotoso et al found clear racial differences in proximal VA anatomy in South Africans, while Wang et al described embryologically persistent arteries in Chinese groups not usually seen elsewhere.[6,10] These variations raise questions about genetic and developmental influences that remain insufficiently studied.

Although many reports are available, several gaps persist. There is no standard system to classify VA variants, making comparisons difficult. Some studies focus only on measurements, while others emphasize clinical links such as stroke or intraoperative injury.[11-15] Radiological and cadaveric findings are rarely combined, which limits a full understanding of the spectrum.

The present review brings together evidence from 31 radiological and cadaveric studies. By comparing recent imaging data with anatomical observations, it aims to provide an updated view of vertebral artery variants, highlight their clinical importance, and suggest the need for uniform reporting systems in future research.

METHODS

A search was conducted following preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 guidelines. We used the Boolean search string: ((variations [Title/Abstract] OR anatomical variations [Title/Abstract]) AND (vertebral artery [Title/Abstract] OR vertebral artery branches [Title/Abstract])).

Searches were conducted on PubMed, initially yielding 446 results. Filters for the last 10 years, English language, and human studies narrowed the results to 126. Following title and abstract screening, 55 studies were evaluated in full text. Thirty-one studies met the inclusion criteria and were included in the review. Inclusion criteria were: human cadaveric or radiological studies; clearly reported anatomical variations of the vertebral artery; use of validated imaging or dissection methods; and sufficient demographic and methodological information. Exclusion criteria included studies on animals, non-original studies (except one systematic review), and studies lacking clear anatomical descriptions (Figure 1).

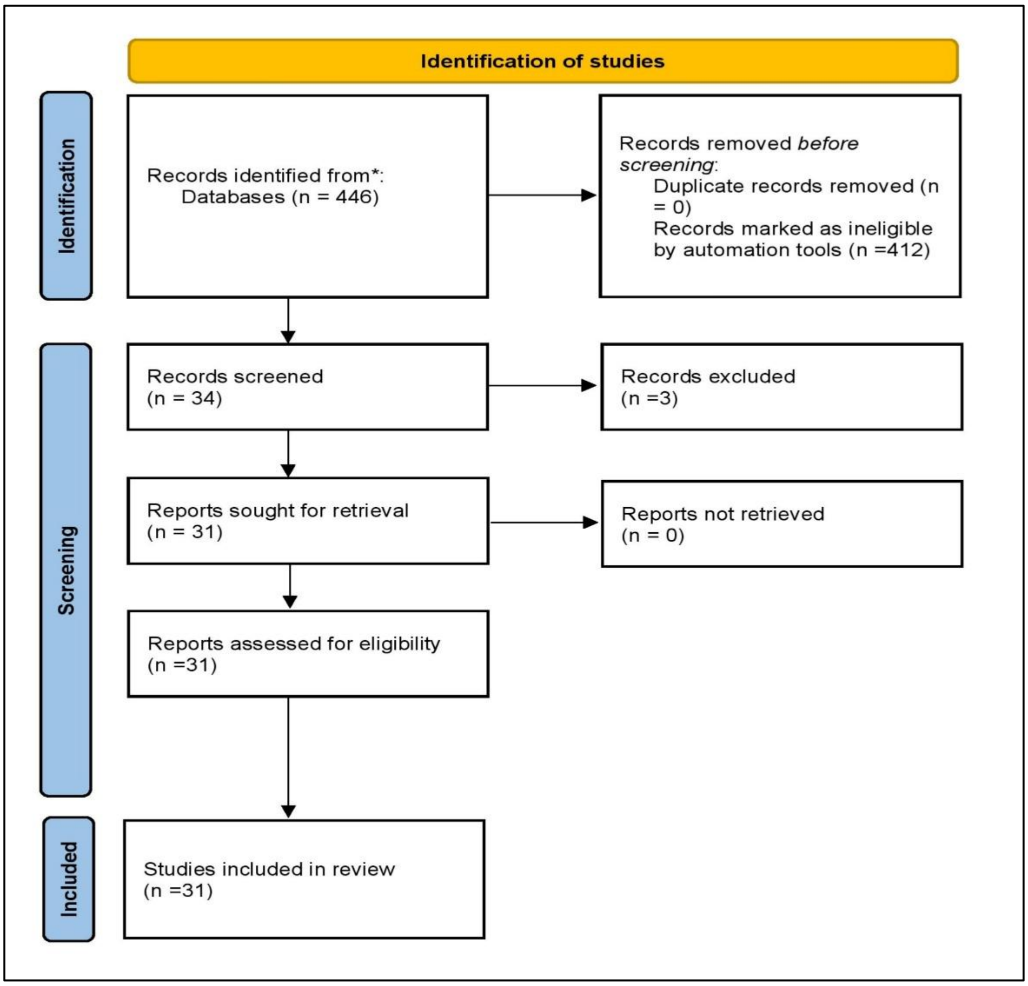

Figure 1: PRISMA flow chart.

Study selection and data extraction were performed independently. Two independent reviewers screened and extracted data. Disagreements were resolved by consensus. Data collected included study design, imaging modality, sample size, demographics, variant type, side prevalence, and clinical significance.

Risk of bias in radiological studies was assessed using the Newcastle–Ottawa scale. Cadaveric case reports were acknowledged for qualitative contributions but excluded from bias scoring. Data synthesis was narrative and thematic.

RESULTS

The study characteristics are listed in Table 1.

Risk of bias

Of the 31 studies, 25 were retrospective radiological studies and 6 were cadaveric (including 4 case reports). Radiological studies scored moderate to low risk of bias. Case reports were excluded from formal scoring.

A key limitation was heterogeneity in definitions and diagnostic thresholds across studies (Table 2).

Table 1: Study characteristics table.

S. no.	Author, year	Study type	Sample size	Population	Focus
1	Dzierżanowski et al, 2017[1]	Radiological	104	Caucasian	Intracranial VA morphometry
2	Tellioglu et al, 2017[2]	Radiological	141	Turkish	VA entry level and FT anatomy
3	Chao et al, 2025[3]	Radiological	199	Chinese	Vertebrobasilar artery types
4	Tasdemir and Cihan, 2022[4]	Radiological	322	Turkish	Origin and V2 segment variants
5	Pasao Glu, 2017[5]	Radiological	249	Turkish	VA and BA variants in vertigo
6	Omotoso et al, 2021[6]	Radiological	554	South African	V4 segment anatomy
7	Bueno and Nimchinsky, 2023[7]	Radiological	460	US	Origin/course variants
8	Li et al, 2019[8]	Cadaveric	119	Chinese	V1 origin and dominance
9	Zhang et al, 2018[9]	Radiological	200	Chinese	Persistent FIS artery
10	Wang et al, 2021[10]	Radiological	589	Chinese	V2/V3 segment anomalies
11	Li et al, 2016[11]	Radiological	12,826	Chinese	Duplication of VA
12	Omotoso et al, 2021[12]	Radiological	554	South African	Proximal VA morphometry
13	Buffoli et al, 2021[13]	Cadaveric (case)	1	Caucasian	Aortic arch/VA branching
14	Dean et al, 2022[14]	Cadaveric (case)	1	Female	Bilateral C4 entry
15	Magklara et al, 2020[15]	Systematic review	>1000	Mixed	VA origin and embryology
16	Wang et al, 2016[16]	Radiological	2370	Chinese	Aortic arch and VA features
17	Park and Park, 2024[17]	Radiological	189	Korean	Vertebrobasilar infarction
18	Eid et al, 2015[18]	Cadaveric (case)	1	Japanese	Aberrant VA and thoracic duct
19	Takata et al, 2025[19]	Radiological (case)	1	Japanese	C5 segmental artery
20	Tapia-Nañez et al, 2020[20]	Radiological	220	Mexican	Aortic/VA variants
21	Rusu et al, 2021[21]	Radiological	52	Romanian	Combined head/neck variants
22	Czuba et al, 2020[22]	Radiological	57	Polish	Posterior circulation and aneurysm
23	Ostrowski et al, 2022[23]	Radiological	44	Polish	Occipital-vertebral anastomosis
24	Tatit et al, 2022[24]	Cadaveric	23	Brazilian	VA-PICA anatomy
25	Wang et al, 2021[25]	Radiological	109	Chinese	Microvascular decompression
26	Mohan et al, 2021[26]	Radiological (case)	1	US	Spinal infarction due to VA
27	Vitošević et al, 2022[27]	Cadaveric (case)	1	Polish	Right VA from RCCA
28	Peng et al, 2024[28]	Radiological	21	Chinese	Revision surgery risks
29	Lee et al, 2017[29]	Radiological/ surgical	1	Korean	Hybrid aortic arch repair
30	Keser et al, 2018[30]	Radiological	114	Turkish	Occipital artery variants
31	Kandregula and Guthikonda, 2021[31]	Not stated	—	Not stated	Surgical injury prevention

Continued.

Table 2: Risk of bias table.

S. no.	Author, year	Study type	Risk of bias assessment	Risk level	No.
1	Dzierżanowski et al, 2017[1]	Radiological (retrospective)	NOS: representative sample, clear outcome, no comparability	Moderate	1
2	Tellioglu et al, 2017[2]	Radiological (retrospective)	NOS: good selection, unclear comparability, objective outcome	Moderate	2
3	Chao et al, 2025[3]	Radiological (retrospective)	NOS: adequate size, clear exposure, unclear bias control	Moderate	3
4	Tasdemir and Cihan, 2022[4]	Radiological (retrospective)	NOS: Clear protocol, selection bias low, lacks confounding control	Moderate	4
5	Pasao Glu, 2017[5]	Radiological (case-control)	NOS: selection well-defined, control adequate, possible recall bias	Moderate	5
6	Omotoso et al, 2021[6]	Radiological (retrospective)	NOS: strong outcome reporting, racial analysis, lacks confounder control	Moderate	6
7	Bueno and Nimchinsky, 2023[7]	Radiological (retrospective)	NOS: well-structured, large cohort, no external validation	Moderate	7
8	Li et al, 2019[8]	Cadaveric	Clear methodology, representative sample, no bias control needed	Low	8
9	Zhang et al, 2018[9]	Radiological (retrospective)	NOS: balanced groups, clear imaging criteria, limited generalizability	Moderate	9
10	Wang et al, 2021[10]	Radiological (retrospective)	NOS: large size, but unclear protocol transparency	Moderate	10
11	Li et al, 2016[11]	Radiological (retrospective)	NOS: massive sample, objective measurement, minimal bias	Low	11
12	Omotoso et al, 2021[12]	Radiological (retrospective)	NOS: duplicate population to #6, similar design	Moderate	12
13	Buffoli et al, 2021[13]	Cadaveric (case report)	Single case, narrative description, high bias potential	High	13
14	Dean et al, 2022[14]	Cadaveric (case report)	Rare variant, anatomically valid, but not generalizable	High	14
15	Magklara et al, 2020[15]	Systematic review	AMSTAR 2: broad inclusion, lacks PROSPERO reg., no meta-analysis	Moderate	15
16	Wang et al, 2016[16]	Radiological (retrospective)	NOS: objective imaging, poor comparability control	Moderate	16
17	Park and Park, 2024[17]	Radiological (retrospective)	NOS: imaging-based outcome, small size, lacks confounding control	Moderate	17

Continued.

S. no.	Author, year	Study type	Risk of bias assessment	Risk level	No.
18	Eid et al, 2015[18]	Cadaveric (case report)	Single case, no generalizability	High	18
19	Takata et al, 2025[19]	Radiological (case report)	Unique case, valid method, lacks replication	High	19
20	Tapia-Nañez et al, 2020[20]	Radiological (retrospective)	NOS: adequate sample, lacks subgroup stratification	Moderate	20
21	Rusu et al, 2021[21]	Radiological (descriptive)	NOS: Narrative report, selective focus, small sample	Moderate	21
22	Czuba et al, 2020[22]	Radiological (case-control)	NOS: matched groups, objective outcome, well-structured	Low	22
23	Ostrowski et al, 2022[23]	Radiological (retrospective)	NOS: moderate sample, single-center, limited external validation	Moderate	23
24	Tatit et al, 2022[24]	Cadaveric (prospective)	Well-defined approach, small size, fair description	Moderate	24
25	Wang et al, 2021[25]	Radiological (retrospective)	NOS: intervention outcome study, clear imaging endpoint	Moderate	25
26	Mohan et al, 2021[26]	Radiological (case report)	Unique anomaly, single patient, lacks external validity	High	26
27	Vitošević et al, 2022[27]	Cadaveric (case report)	Rare finding, no systematic design	High	27
28	Peng et al, 2024[28]	Radiological (retrospective)	NOS: small sample, high relevance, limited generalizability	Moderate	28
29	Lee et al, 2017[29]	Radiological/surgical (case report)	Valid imaging, clinical follow-up, but anecdotal	High	29
30	Keser et al, 2018[30]	Radiological (retrospective)	NOS: reasonable cohort, objective outcome, lacks comparative stratification	Moderate	30
31	Kandregula and Guthikonda, 2021[31]	Descriptive review	Not systematically structured, lacks methods section	High	31

NOS: Newcastle–Ottawa scale

DISCUSSION

This review synthesizes findings from 31 cadaveric and radiological studies to delineate the spectrum of anatomical variants of the vertebral artery (VA), their prevalence, and clinical implications. Variations in VA origin, entry level, course, and branching patterns were comprehensively characterized.

The most commonly reported variant across studies was the left vertebral artery originating directly from the aortic arch, noted in 13 studies.[1,4-6,8,12-15,20,21,27,29]

Frequencies ranged from 0.79% to 9.3%, although Magklara et al reported a much higher rate (97.4%) among aberrant cases.[15] This variation is particularly important for surgical planning in endovascular and cervical procedures.

Entry level variations into the transverse foramina, particularly at levels C4–C7, were observed in at least nine studies.[2,4,6,13,14,19,24,27,30] Tellioglu et al and Dean et al highlighted cases of bilateral C4 entry and segmental VA entries, with implications for cervical spine instrumentation.[2,14] These variants may increase the risk of iatrogenic injury, particularly during procedures involving pedicle screws or lateral mass fixation.

Hypoplasia, a critical factor in vertebrobasilar insufficiency and stroke, was reported in eight studies with prevalence ranging from 16.1% to 59.3%.[5,6,9,12,16,17,22,25] Omotoso et al noted significant racial differences in the distribution of hypoplasia and atresia, while Czuba et al found a strong correlation with basilar artery aneurysms.[6,22]

Fenestration and duplication, while less common, carry substantial clinical risk due to their association with turbulent flow and aneurysm formation. These were identified in four studies with low prevalence (~0.16–0.4%).[1,6,11,13] Li et al reported the largest duplication prevalence in a sample of over 12,000 Chinese patients.[11]

Rare variants including triplication, persistent first intersegmental artery, aberrant origin from the brachiocephalic trunk or common carotid artery, and vertebral artery bifurcation were reported in at least 12 studies.[3,9,10,13,14,19,20,23,26-28,30] These rare patterns, though individually uncommon, may carry high surgical significance. For example, Vitošević et al described a case of a right VA arising from the right common carotid artery, requiring alternative surgical routes.[27]

Geographic and population differences were notable across studies. Chinese cohorts dominated the radiological datasets, with distinctive distributions of hypoplasia and embryologically persistent vessels.[3,4,9,10,16,25,28] South African and Turkish studies provided comparative insights into racial and ethnic variability.[2,4,6,12,30]

From a methodological perspective, radiological studies provided large population-based estimates but often lacked anatomical precision, especially regarding smaller branches.

Cadaveric reports added essential detail, especially for rare or variant courses, though were limited by small sample sizes and lack of generalizability.[13,14,18,24,27]

Clinical implications extend beyond vascular surgery. Several studies discussed associations between anatomical variants and conditions such as central vertigo, spinal infarction, failed posterior fossa decompression, and microvascular decompression complications.[5,25,26,28] Omotoso et al, Kandregula and Guthikonda, and Wang et al emphasized the need for comprehensive preoperative imaging to prevent inadvertent vascular injury.[6,12,25,31]

Despite its strengths, this review is limited by variability in definitions—particularly for hypoplasia and dominance—and inconsistency in reporting across studies. No unified morphometric criteria were applied across studies, which complicates inter-study comparisons. Furthermore, many included studies were retrospective, introducing potential selection bias.

Future directions should include prospective, multicenter imaging studies using standardized definitions and protocols, combined with detailed anatomical validation through dissection where possible. Establishing a consensus on reporting standards for VA anomalies would enhance comparability and clinical applicability.

CONCLUSION

Anatomical variations of the vertebral artery are both common and clinically significant. The left VA arising from the aortic arch is the most frequent variant, followed by entry-level deviations, hypoplasia, and rare anomalies such as duplication and aberrant origins. These findings emphasize the need for meticulous preoperative imaging, especially in neurosurgical and vascular interventions. Standardization in reporting and classification of vertebral artery variants is essential to ensure patient safety and improve clinical outcomes. Future work should prioritize classification frameworks and standard reporting protocols for vertebral artery variants.

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