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ORIGINAL ARTICLE

Vertebral artery origin variations and their association with vertebral artery diameter and hypoplasia: A computed tomography angiography study

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ABSTRACT

Objectives: Direct aortic arch origin of the left vertebral artery (VA) is the most common VA origin variation; however, its relationship with vessel caliber and hypoplasia remains unclear. This study aimed to evaluate VA origin patterns and whether direct aortic arch origin is associated with VA diameter and hypoplasia.

Patients and methods: This retrospective cross-sectional study included 360 consecutive adults who underwent computed tomography angiography (CTA) between January 2020 and May 2026. Vertebral artery origin, diameter, hypoplasia, aplasia, and dominance were evaluated; hypoplasia was defined as a V2-segment diameter < 2.5 mm. Origin analyses were restricted to subjects with a visible left VA (n = 351). Predictors of VA diameter and hypoplasia were assessed by multivariable linear and logistic regression adjusted for age and sex; Firth penalized regression and a stricter threshold (< 2.0 mm) served as sensitivity analyses.

Results: The median age was 72 years (IQR, 62 to 78 years); and 220 (61.1%) participants were male, and 140 (38.9%) were female. The left VA arose directly from the aortic arch in 18 (5.1%) patients and from the left subclavian artery in 333 (94.9%). Aortic arch origin was associated with a smaller left VA diameter (3.07 ± 0.98 *vs.* 3.70 ± 0.85 mm, $p = 0.006$) and a higher prevalence of hypoplasia (< 2.5 mm: 33.3% *vs.* 9.3%, $p = 0.007$). In the primary model (aplastic arteries excluded), aortic arch origin was independently associated with a 0.705-mm reduction in left VA diameter ($\beta = -0.705$, 95% CI: −1.107 to −0.302; $p < 0.001$) and was the strongest predictor of hypoplasia (OR = 5.78, 95% CI: 1.85 to 16.74; $p = 0.002$). Firth penalized regression and the stricter threshold (< 2.0 mm) gave consistent results.

Conclusion: Direct aortic arch origin of the left VA is independently associated with smaller VA diameter and a substantially higher prevalence of hypoplasia, consistent across sensitivity analyses. Recognition on CTA may inform assessment of VA morphology and anatomical variation.

Keywords: Anatomic variation, aorta, thoracic, computed tomography angiography; subclavian artery, vertebral artery.

The vertebral arteries (VAs) constitute the principal arterial supply of the posterior cerebral circulation and play a critical role in perfusion of the brainstem, cerebellum, thalami, and occipital lobes. In the typical anatomical configuration, each VA originates from the ipsilateral subclavian artery and ascends through the transverse foramina of the cervical vertebrae before joining to form the basilar artery.[1,2] However, variations in VA origin, course, and caliber are common and represent some of the most frequently encountered vascular anatomical variants in the cervicocerebral circulation.[1,2]

Among these variations, direct origin of the left VA from the aortic arch is the most frequently reported anomaly, with a prevalence ranging from approximately 2 to 8% in angiographic and computed tomography angiography (CTA) studies.[1,3,4] Embryologically, this variation is thought to result from persistence of the sixth

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cervical intersegmental artery with regression of the normal proximal VA segment.[5] Although generally considered a benign developmental variant, previous studies have suggested potential associations with altered vascular geometry, hemodynamic changes, arterial dissection,[6] aneurysm formation, and posterior circulation ischemic events.[3,7,8]

Recognition of VA variations is increasingly important, as they may influence diagnostic angiography, VA catheterization, cervical spine surgery, carotid and vertebral revascularization, and neuroendovascular interventions in the posterior circulation.[3,9] Anomalous anatomy may increase procedural complexity, influence catheter selection, prolong procedure time, and occasionally necessitate alternative access, making accurate identification increasingly relevant with the widespread use of CTA.[2,4]

While numerous studies have investigated the prevalence and anatomical characteristics of VA origin variations, relatively little attention has been paid to their potential relationship with VA caliber. Vertebral artery hypoplasia is a common vascular variant that has been associated with altered vertebrobasilar hemodynamics and, in some studies, increased susceptibility to posterior circulation ischemia.[8,10-14] Whether direct aortic arch origin predisposes to smaller VA diameter and hypoplastic development remains incompletely understood. Moreover, quantitative data evaluating this relationship while accounting for potential confounding factors such as age and sex remain limited.

A recent study suggested that anomalous VAs may be more frequently hypoplastic; however, available evidence remains sparse and largely descriptive.[15] Therefore, further investigation is needed to clarify whether VA origin variation is independently associated with vessel caliber and hypoplasia.

The aim of the present study was to evaluate VA origin patterns, vessel diameter, hypoplasia, aplasia, and dominance characteristics in a large clinical CTA cohort, with particular emphasis on the relationship between direct aortic arch origin of the left VA and vessel morphology. In addition, we sought to determine whether direct aortic arch origin of the left VA is independently associated with reduced VA caliber and an increased likelihood of VA hypoplasia.

PATIENTS AND METHODS

This retrospective cross-sectional study examined CTAs performed at the Niğde Ömer Halisdemir University Faculty of Medicine between January 2020 and May 2026. Images were retrieved from the institutional Picture Archiving and Communication System (PACS). Consecutive adult patients who underwent cervical or cerebral CTA for various clinical indications were screened for eligibility. Patients aged 18 years or older with CTA examinations of sufficient image quality for evaluation of VA anatomy were included. Exclusion criteria were: *(i)* severe motion or reconstruction artifacts impairing vascular assessment; *(ii)* inadequate arterial opacification; *(iii)* previous cervical vascular surgery or major cervical trauma; *(iv)* vascular malformations, tumors, or other pathologies substantially altering VA anatomy; *(v)* complete occlusion of the VA origin preventing anatomical assessment; and *(vi)* duplicate examinations from the same patient. When multiple examinations were available, only the earliest eligible CTA study was included. After applying the eligibility criteria, 360 patients were included in the study. Given the retrospective study design and the use of anonymized imaging data, the requirement for written informed consent was waived by the ethics committee. The study protocol was approved by the Niğde Ömer Halisdemir University Faculty of Medicine Non-Interventional Clinical Research Ethics Committee (Date: June 24, 2026, Approval No: 2026/120). The study was conducted in accordance with the principles of the Declaration of Helsinki.[16]

All CTA examinations were performed using a 64-slice multidetector CT scanner (Somatom; Siemens Healthineers, Erlangen, Germany). Following intravenous administration of iodinated contrast material, image acquisition was performed according to the institution's standard CTA protocol.

Typical acquisition parameters included tube voltage of 120-130 kV, automatic tube current modulation, gantry rotation time of 0.33 sec, field of view of approximately 220 mm, and reconstructed slice thickness of 0.6-1.0 mm. Multiplanar reconstruction, maximum intensity projection, and three-dimensional volume-rendered images were generated as needed for anatomical assessment.

All CTA examinations were reviewed using the institutional PACS workstation by an investigator experienced in cerebrovascular anatomy. Measurements were performed by a single observer

who was blinded to the statistical analyses at the time of image evaluation. The origin of each VA was classified as arising either from the subclavian artery or directly from the aortic arch. Vertebral artery aplasia was defined as complete congenital absence of the vessel.

Because VA origin cannot be reliably classified in cases of complete congenital aplasia, all analyses involving left VA origin were restricted to subjects with a visible left VA. Accordingly, subjects with left VA aplasia (n = 9) were excluded from analyses evaluating the association between VA origin and vessel morphology, resulting in a primary analytical cohort of 351 participants. Vertebral artery diameter measurements were obtained from the V2 segment using multiplanar reconstructed CTA images. Measurements were performed perpendicular to the long axis of the vessel at a representative nonstenotic segment and recorded in millimeters. Vertebral artery dominance was determined according to the relative diameters of the paired VAs. In cases with unilateral aplasia, the contralateral VA was classified as dominant. For descriptive analyses, VA hypoplasia was evaluated using diameter thresholds of < 2.0 mm and < 2.5 mm. Consistent with the primary study objective and multivariable analyses, VA hypoplasia was primarily defined as a V2 segment diameter < 2.5 mm. Aplastic arteries were analyzed separately and were not classified as hypoplastic. The following variables were recorded for each subject: *(i)* age, *(ii)* sex, *(iii)* right VA diameter, *(iv)* left VA diameter, *(v)* VA origin pattern, *(vi)* VA dominance, *(vii)* VA hypoplasia, and *(viii)* VA aplasia.

To assess intraobserver reproducibility, 30 CTA examinations were randomly selected and re-evaluated by the same observer after a one-week interval. Intraclass correlation coefficients were calculated using a two-way mixed-effects model with absolute agreement for single measurements. Agreement between repeated measurements was additionally assessed using Bland-Altman analysis.

Statistical analysis

Statistical analyses were performed using R statistical software version 4.6.1 (R Foundation for Statistical Computing, Vienna, Austria).[17] Continuous variables were assessed for distributional characteristics using graphical methods and normality testing. Continuous data were presented as mean ± standard deviation (SD) or median and interquartile range (IQR), as appropriate. Categorical variables were presented as frequencies and percentages. Comparisons between groups were performed using the Wilcoxon rank-sum test for continuous variables and Fisher's exact test for categorical variables. Paired comparisons between right and left VA diameters were restricted to patients with bilaterally patent VAs and performed using the Wilcoxon signed-rank test. Correlations between age and VA diameter were assessed using Spearman's rank correlation coefficient.

To evaluate independent predictors of left VA diameter, multivariable linear regression analysis was performed including age, sex, and VA origin as covariates. The primary regression model was performed after exclusion of aplastic left VAs. Since the origin of an aplastic artery cannot be established, aplastic left VAs were excluded from all origin-based regression analyses. Independent predictors of VA hypoplasia were evaluated using multivariable logistic regression analysis after exclusion of aplastic arteries. Effect estimates are reported as beta (β) coefficients or odds ratios (ORs) with corresponding 95% confidence intervals (CIs).

Because of the relatively small number of subjects with direct aortic arch origin, Firth penalized logistic regression was additionally performed as a sensitivity analysis to assess the robustness of the observed associations and reduce the risk of small-sample bias. A further sensitivity analysis was conducted using a stricter definition of VA hypoplasia (< 2.0 mm). Because the analyses were exploratory in nature, no formal correction for multiple comparisons was applied. Therefore, secondary findings should be interpreted cautiously. All statistical tests were two-sided, and a p-value < 0.05 was considered statistically significant.

RESULTS

Of the 360 consecutive subjects included in the study (median age, 72 years [IQR, 62 to 78 years]), 220 (61.1%) were male and 140 (38.9%) were female. Excluding aplastic arteries from diameter measurements, the mean right VA diameter was 3.54 ± 0.82 mm (n = 353), and the mean left VA diameter was 3.67 ± 0.87 mm (n = 351). Among subjects with bilaterally patent VAs (n = 344), the paired right and left diameter comparison did not reach statistical significance (Wilcoxon signed-rank test, p = 0.0609).

Vertebral artery aplasia was identified in 16 arteries overall. Right VA aplasia was observed

in seven patients (1.9%), whereas left VA aplasia was observed in nine (2.5%). After excluding aplastic arteries from the denominator, a VA diameter < 2.0 mm was observed in 11 (3.1%) of 353 right VAs and 15 (4.3%) of 351 left VAs. At the primary hypoplasia threshold of < 2.5 mm, hypoplasia was identified in 41 (11.6%) of 353 right VAs and 37 (10.5%) of 351 left VAs. Aplasia was analyzed separately and was present in seven (1.9%) right VAs and nine (2.5%) left VAs among all patients (Table 1). Analysis of VA dominance demonstrated left-sided dominance in 193 (53.6%) individuals, right-sided dominance in 166 (46.1%) individuals, and codominance in one (0.3%) individual (Table 1).

All right VAs originated from the right subclavian artery. Because VA origin cannot be determined in aplastic arteries, subjects with left VA aplasia (n = 9) were excluded from all origin-based analyses. Accordingly, VA origin was evaluated in 351 individuals. The left VA originated from the left subclavian artery in 333 (94.9%) and directly from the aortic arch in 18 (5.1%) individuals (Figure 1). No statistically significant differences were observed between the two origin groups in terms of age (subclavian origin: median, 72 years [IQR, 62 to 78 years] *vs.* aortic arch origin: median, 74 years [IQR, 62 to 80 years]; Wilcoxon rank-sum test, p = 0.480) or sex (male: 206/333 [61.9%] *vs.* 14/18 [77.8%]; Fisher's exact test, p = 0.214; Table 2).

Subjects with direct aortic arch origin exhibited significantly smaller left VA diameters than those with conventional subclavian origin. The median left VA diameter was 3.15 mm in the aortic arch group and 3.76 mm in the subclavian group (Wilcoxon rank-sum test p = 0.006). Mean diameters were 3.07 ± 0.98 mm and 3.70 ± 0.85 mm, respectively (Figure 2). In contrast, right VA diameters did not differ significantly according to left VA origin. Median right VA diameters were 3.80 mm in the aortic arch group and 3.53 mm in the subclavian group (p = 0.177). Although right VA diameters were numerically larger among subjects with direct aortic arch origin (3.75 ± 0.77 mm *vs.* 3.45 ± 0.95 mm), this difference did not reach statistical significance.

Left VA hypoplasia was more frequent in the aortic arch-origin group at both evaluated diameter thresholds (Figure 3). At < 2.5 mm,

TABLE 1
Study population and vertebral artery characteristics (n = 360)

Characteristic	n	%	Mean ± SD	Median	p
Age (year)				72	
Sex					
Male	220	61.1			
Female	140	38.9			
VA diameter (mm)					
Right (aplasia excluded)	353		3.48 ± 0.95		
Left (aplasia excluded)	351		3.67 ± 0.87		
Right *vs.* left VA diameter					0.061
VA aplasia					
Right	7	1.9			
Left	9	2.5			
VA hypoplasia (< 2.0 mm)					
Right	11	3.1			
Left	15	4.3			
VA hypoplasia (< 2.5 mm)					
Right	41	11.6			
Left	37	10.5			
Right-sided dominance					
Right	166	46.1			
Left	193	53.6			
Codominance	1	0.3			

SD, standard deviation, VA, vertebral artery. Percentages for hypoplasia were calculated among nonaplastic arteries (right VA, n = 353; left VA, n = 351); aplasia percentages were calculated using the full cohort (n = 360). Hypoplasia was defined using diameter thresholds of < 2.0 mm and < 2.5 mm, excluding aplastic arteries. Right-versus-left diameter comparison was performed using the Wilcoxon signed-rank test in subjects with bilateral measurable VAs.

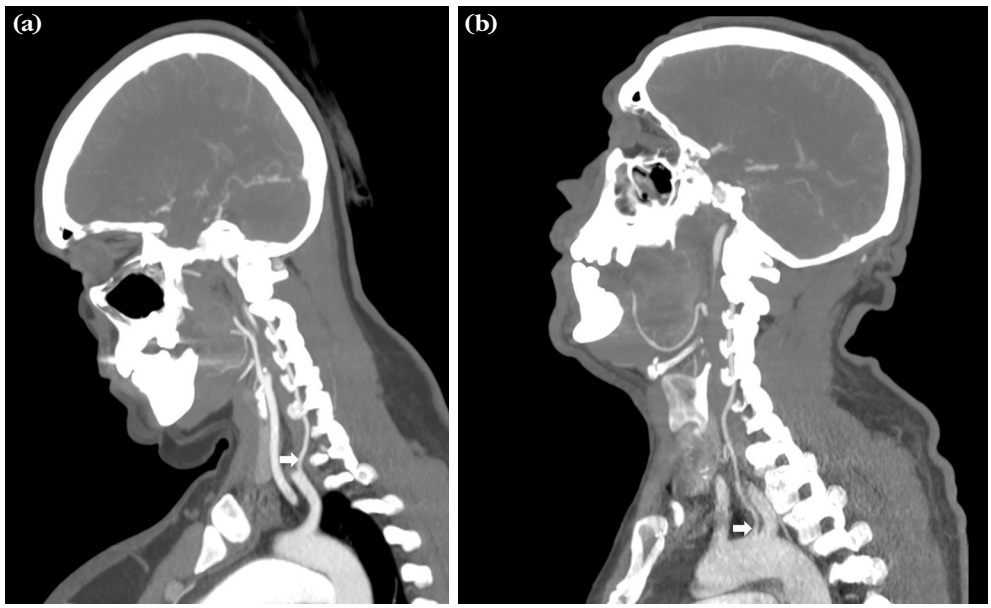


Figure 1. Representative CTA images of VA origin. **(a)** Conventional origin of the left VA from the left subclavian artery; **(b)** Direct origin of the left VA from the aortic arch. Sagittal maximum-intensity-projection CTA images are shown.
CTA, computed tomography angiography; VA, vertebral artery.

hypoplasia occurred in 31 of 333 subclavian-origin arteries (9.3%; 95% Wilson confidence interval [CI]: 6.6-12.9%) and six of 18 aortic arch-origin arteries (33.3%; 95% Wilson CI, 16.3-56.3%; Fisher's exact test, p = 0.007). At the stricter < 2.0-mm threshold, hypoplasia occurred in 12 of 333 (3.6%; 95% Wilson CI, 2.1-6.2%) versus three of 18 (16.7%; 95% CI: 5.8-39.2%), respectively (Fisher's exact test, p = 0.035). Both unadjusted comparisons were statistically significant. These findings were obtained using threshold-specific analyses of left VA diameter; the two hypoplasia definitions overlap and should not be interpreted as independent cohorts.

Intraobserver reproducibility was assessed in 30 randomly selected CTA examinations. The intraclass correlation coefficient was 0.827 (95% CI: 0.670-0.913) for right VA diameter measurements and 0.855 (95% CI: 0.718-0.929) for left VA diameter measurements. Bland-Altman analysis showed a mean repeat-measurement difference of −0.107 mm (95% limits of agreement −0.942 to +0.727 mm) for the right VA and −0.148 mm (−1.103 to +0.807 mm) for the

TABLE 2
Vertebral artery characteristics according to left VA origin (n = 351)

	Subclavian origin (n = 333)					Aortic arch origin (n = 18)					
Characteristic	n	%	Mean ± SD	Median	IQR	n	%	Mean ± SD	Median	IQR	p
Age (year)				72	62-78				74	62-80	0.480
Sex											0.214
Male	206	61.9				14	77.8				
VA diameter (mm)											
Right			3.45 ± 0.95	3.54				3.75 ± 0.77	3.80		0.177
Left			3.70 ± 0.85	3.71				3.07 ± 0.98	3.15		0.006
Left VA hypoplasia (< 2.5 mm)	31	9.3				6	33.3				0.007

VA, vertebral artery; SD, standard deviation; IQR: interquartile range. Groups were defined exclusively by left VA origin; all right VAs originated from the right subclavian artery. Aplastic left VAs were excluded (n = 351). Right VA diameter represents an exploratory contralateral measurement stratified by left VA origin, not right VA origin. Continuous variables were compared using the Wilcoxon rank-sum test and categorical variables using Fisher's exact test. Hypoplasia was defined as left VA diameter < 2.5 mm.

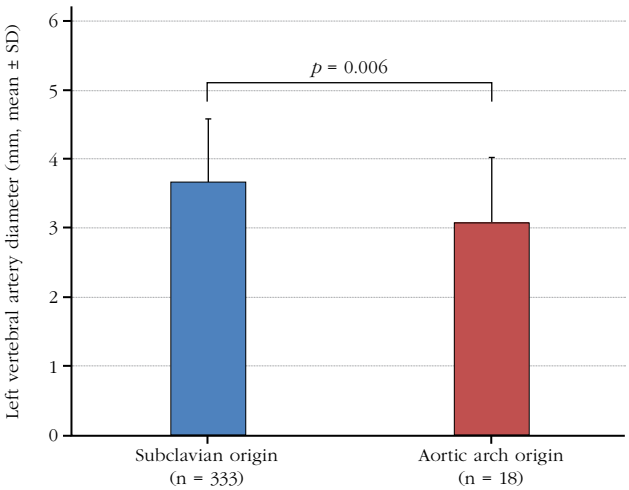


Figure 2. Left VA diameter according to arterial origin.

The mean left VA diameter was 3.70 ± 0.85 mm in those with subclavian origin (n = 333) and 3.07 ± 0.98 mm in those with direct aortic arch origin (n = 18; Wilcoxon rank-sum test, $p = 0.0061$). Bars show means; error bars indicate standard deviations (SD). VA, vertebral artery.

left VA. These findings indicate good intraobserver reliability, while the limits of agreement warrant consideration when interpreting small individual diameter differences.

In primary multivariable linear regression analysis excluding patients with VA aplasia (n = 351), direct aortic arch origin was independently associated with a 0.705-mm reduction in left VA diameter (β = −0.705, 95% CI: −1.107 to −0.302, $p < 0.001$). Female sex was also independently associated with smaller vessel caliber (β = −0.261, 95% CI: −0.447 to −0.075, $p = 0.006$). Increasing age demonstrated a modest positive association with left VA diameter (β = +0.011 per year, 95% CI: 0.004 to 0.017, $p = 0.002$). The overall model explained 6.5% of the variance in left VA diameter ($R^2 = 0.065$; Table 3).

In multivariable logistic regression (aplastic arteries excluded) with hypoplasia (< 2.5 mm) as the outcome, direct aortic arch origin emerged as the strongest independent predictor. Subjects with direct aortic arch origin demonstrated 5.78-fold increased odds of left VA hypoplasia compared to those with subclavian origin (OR = 5.78, 95% CI: 1.85 to 16.74, $p = 0.002$). Female sex was not independently associated with hypoplasia (OR = 1.59, 95% CI: 0.77 to 3.29, $p = 0.2073$). Increasing age demonstrated a weak inverse association with hypoplasia risk (OR = 0.975, 95% CI: 0.952 to 1.000, $p = 0.041$).

Sensitivity analyses

Because of the relatively small number of subjects with direct aortic arch origin, Firth penalized logistic regression was additionally performed. The association between direct aortic arch origin and VA hypoplasia remained essentially unchanged (OR = 5.81, 95% CI:

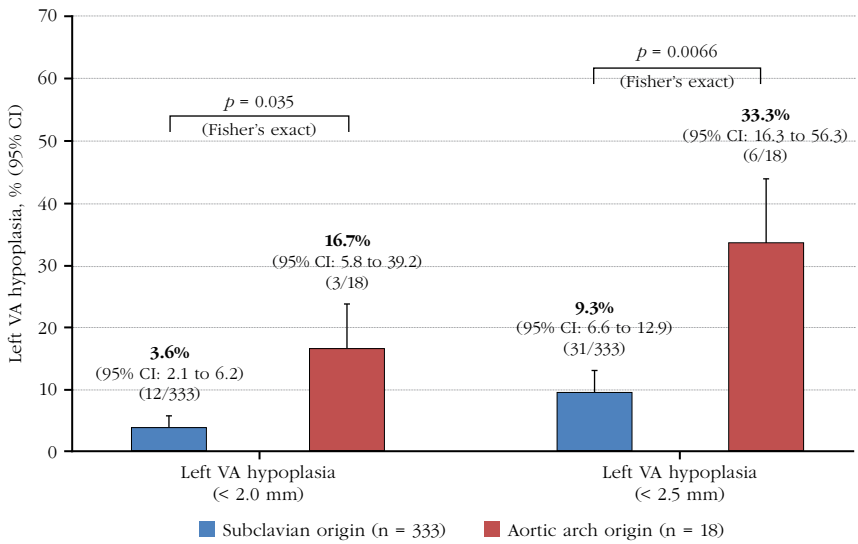


Figure 3. Prevalence of left VA hypoplasia by arterial origin at two diameter thresholds.

For < 2.0 mm, hypoplasia was observed in 12 of 333 (3.6%; 95% Wilson CI, 2.1-6.2%) individuals with subclavian origin and three of 18 (16.7%; 95% CI: 5.8-39.2%) with aortic arch origin (Fisher's exact test, $p = 0.035$). For < 2.5 mm, the corresponding proportions were 31 of 333 (9.3%; 95% CI: 6.6-12.9%) and six of 18 (33.3%; 95% CI: 16.3-56.3%), respectively ($p = 0.007$). Bars represent proportions; error bars represent 95% Wilson confidence intervals. Aplastic vessels were excluded. VA, vertebral artery.

TABLE 3
Multivariable regression models for determinants of left VA diameter and hypoplasia (primary models; aplastic arteries excluded, n = 351)

	Linear regression			Logistic regression		
Predictor	β	95% CI	*p*	OR	95% CI	*p*
Direct aortic arch origin	−0.705	−1.107 to −0.302	< 0.001	5.78	1.85 to 16.74	0.002
Sex						
Female	−0.261	−0.447 to −0.075	0.006	1.59	0.77 to 3.29	0.207
Age (per year)	+0.011	0.004 to 0.017	0.002	0.975	0.952 to 1.000	0.041

CI, confidence interval; VA, vertebral artery; OR, odds ratio; Both models were adjusted for age, sex, and left VA origin (reference categories: subclavian origin and male sex; logistic outcome: left VA hypoplasia < 2.5 mm). Aplastic left VAs were excluded (n = 351). Linear model R^2 = 0.065 (adjusted R^2 = 0.057); logistic model area under the ROC curve = 0.642 (95% CI, 0.540-0.744). Vertebral arteries with aortic arch origin were identified in 18 individuals; estimates should be interpreted considering its small sample size. β, linear regression coefficient (mm);

1.94-16.28, p = 0.003), confirming the robustness of the primary findings (Figure 4).

In an exploratory sensitivity analysis using the stricter < 2.0-mm hypoplasia definition (12 of 333 patients with subclavian origin versus three of 18 patients with aortic arch origin; Fisher exact test, p = 0.035), direct aortic arch origin remained associated with hypoplasia after adjustment for age and sex (OR = 7.23, 95% CI: 1.46 to 28.65, p = 0.007). Firth penalized regression produced similar results (OR = 7.47, 95% CI: 1.71 to 27.46, p = 0.010), further supporting the stability of the observed association.

DISCUSSION

The present study demonstrated a consistent, independent association between direct aortic arch origin of the left VA and both reduced vessel diameter and VA hypoplasia in a clinical CTA cohort. The findings remained consistent after adjustment for age and sex and across multiple sensitivity analyses, including Firth penalized regression and alternative hypoplasia definitions.

Direct aortic arch origin is the most frequently encountered VA branching variation, with previous angiographic, cadaveric, and CTA studies reporting prevalence rates of 2 to 8% depending on population characteristics and imaging methodology. The 5.1% prevalence observed here falls within this range, although the single-center clinical cohort cannot be assumed to represent the general population. Embryologically, direct aortic arch origin is believed to result from persistence of the sixth cervical intersegmental artery with regression

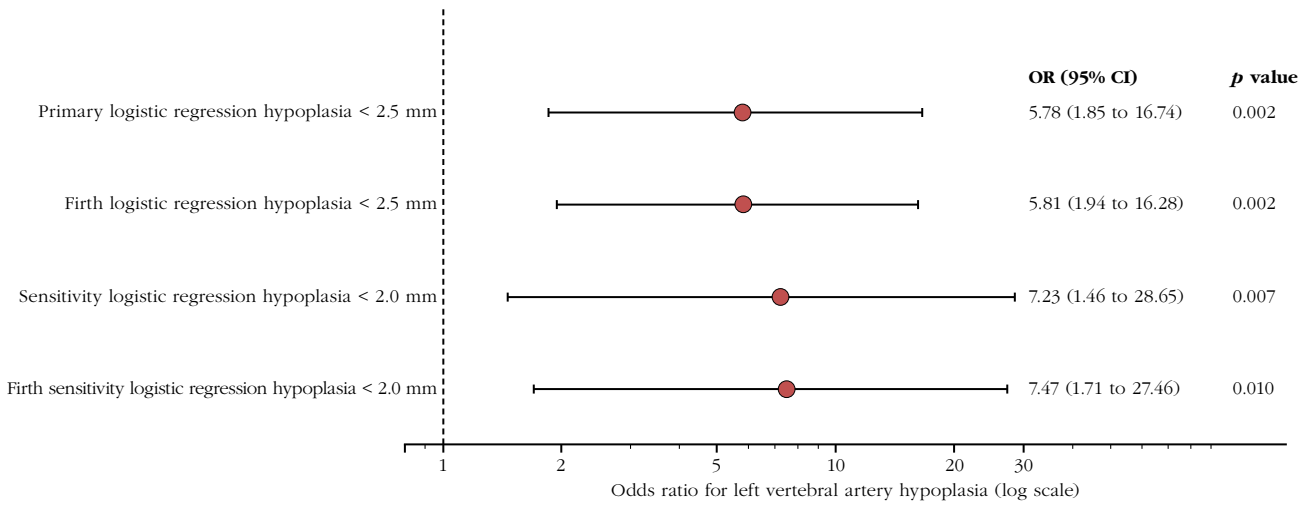


Figure 4. Robustness of the association between direct aortic arch origin and left VA hypoplasia across logistic model specifications. Odds ratios (points) with 95% confidence intervals (lines) are shown on a logarithmic scale for the primary model (hypoplasia < 2.5 mm), the Firth penalized model (< 2.5 mm), and both under a stricter threshold (< 2.0 mm). The dashed line indicates an odds ratio of 1. All models were adjusted for age and sex (reference category: subclavian origin).
OR, odds ratio; CI, confidence interval.

of the normal proximal VA segment, producing a more proximal origin and a longer extracranial course before entry into the cervical transverse foramina.

The most important morphometric finding was the independent association between direct aortic arch origin and reduced left VA diameter, evident in both univariable and multivariable analyses. Given that adult VA diameter typically ranges between approximately 3 and 4 mm, the 0.705-mm reduction represents a substantial anatomical difference rather than a trivial statistical finding.

Previous studies have largely focused on the prevalence and anatomical description of VA origin variations. While Uchino et al.,[2] Lin et al.,[18] and Wang et al.[19] extensively characterized branching patterns and anatomical variants, relatively few studies have quantitatively examined whether anomalous VA origin is independently associated with vessel caliber. A notable exception is the study by Kim et al.,[15] which suggested that anomalous VAs may be more frequently hypoplastic. The present findings extend this observation by demonstrating an independent association between aortic arch origin and reduced vessel diameter within a multivariable framework.

Several mechanisms may explain this relationship. Embryological factors may simultaneously influence both VA origin and subsequent vessel development, and the altered geometry of VAs originating directly from the aortic arch, with a longer extracranial course and different takeoff angles, may modify local hemodynamics during vascular maturation. Because the study was observational, however, causality cannot be established and these mechanisms remain speculative.

The association of direct aortic arch origin of the left VA with hypoplasia was the most clinically relevant finding: one-third of VAs with aortic arch origin met hypoplasia criteria versus 9.3% of VAs with subclavian origin, and aortic arch origin remained associated with a nearly sixfold increase in the odds of hypoplasia after adjustment for age and sex. To our knowledge, few studies have specifically evaluated hypoplasia risk according to VA origin, most previous reports having focused on anatomical prevalence, embryology, or procedural implications. Therefore, the present study adds quantitative evidence that VA origin variation is associated with vessel caliber and hypoplasia. The stability of these findings across sensitivity analyses further supports this conclusion: Firth penalized regression produced virtually identical estimates, and a stricter hypoplasia threshold (< 2.0 mm) yielded an even larger effect, indicating robustness across analytical approaches.

Importantly, the present findings should be interpreted as evidence of association rather than causation. While VA origin and vessel caliber may share common developmental determinants, the current data do not establish a direct developmental mechanism.

Right VA caliber was evaluated only as an exploratory, contralateral measurement stratified by left VA origin; no right VA originated directly from the aortic arch. The numerically larger right VA diameter in the those with left aortic arch origin (3.75 ± 0.77 *vs.* 3.45 ± 0.95 mm; Wilcoxon rank-sum test, $p = 0.177$) did not demonstrate compensatory remodeling. The mean difference was approximately +0.300 mm (95% CI: −0.094 to +0.695 mm). With only 18 subjects in the anomalous-origin group, this secondary comparison may have been underpowered and a type II error cannot be excluded. Accordingly, no claim of contralateral compensation is made.

Consistent with reports of larger extracranial arterial dimensions in males, female sex was independently associated with smaller VA diameter but not with VA hypoplasia, indicating that sex-related differences in vessel size do not necessarily translate into a higher prevalence of hypoplasia. Age showed only a weak positive association with diameter in the multivariable model, substantially smaller than the effect of vessel origin.

The findings of the present study may have several practical implications. First, recognition of direct aortic arch origin is relevant during diagnostic angiography and neuroendovascular procedures in the posterior circulation, including VA catheterization, thrombectomy, and stenting, where anomalous origin and smaller vessel caliber can complicate catheter navigation, influence device selection, prolong procedure times, and occasionally necessitate alternative access. Anticipating a smaller VA in these patients may aid procedural planning. Second, because aortic arch origin is strongly associated with hypoplasia, its identification on CTA should prompt careful assessment of vertebrobasilar anatomy; although VA hypoplasia is often asymptomatic, it has been linked to altered hemodynamics, impaired

collateral capacity, and susceptibility to posterior circulation ischemia. The hemodynamic relevance of proximal VA anatomy is further illustrated by reports in which the anatomical relationship between a subclavian arterial lesion and the VA origin determined the direction of VA flow and the pattern of collateral recruitment in the posterior circulation.[20,21] Third, VA origin variation may serve as an imaging marker of VA morphology; although its clinical significance remains to be established, awareness of this relationship may assist radiologists, vascular surgeons, and neurointerventionalists in anatomical assessment and procedural planning.

The present study offers several methodological strengths that lend consistency and credibility to its findings. The inclusion of 360 consecutive patients allowed a comprehensive CTA-based characterization of VA origin, caliber, hypoplasia, aplasia, and dominance. By employing standardized diameter measurements at the V2 segment, the study established a uniform anatomical framework for comparing VA morphology across origin patterns. The reliability of these measurements was further supported by good intraobserver agreement, with intraclass correlation coefficients of 0.827 and 0.855 for the right and left VAs, respectively, alongside Bland-Altman assessment of measurement agreement. Furthermore, multivariable analyses were adjusted for age and sex, while sensitivity analyses employing Firth penalized logistic regression and an alternative hypoplasia threshold yielded consistent findings. This convergence of anatomical measurements and complementary statistical approaches reinforces the stability of the observed associations, while leaving their underlying biological and clinical significance open to further investigation.

Notwithstanding these strengths, several limitations deserve careful consideration. A central challenge lies in distinguishing congenital VA hypoplasia from acquired reductions in luminal caliber. Although diameter measurements were obtained from representative, nonstenotic portions of the V2 segment, the relatively advanced age of the study population (median age: 72 years) raises the possibility that atherosclerotic changes, diffuse vascular remodeling, or other acquired vascular processes contributed to the observed differences. This uncertainty is compounded by the absence of detailed vascular risk-factor data, including hypertension, diabetes mellitus, dyslipidemia, and smoking status, which could not be incorporated into the multivariable models. Consequently, adjustment for age and sex does not eliminate the possibility of residual confounding, and a small VA diameter on CTA cannot, in isolation, be regarded as definitive evidence of congenital hypoplasia. An equally important consideration concerns the distinction between anatomical association and clinical consequence. Although VA origin and caliber may influence vertebrobasilar hemodynamics, posterior circulation ischemic stroke, transient ischemic attack, and vertebrobasilar insufficiency were not systematically assessed as clinical outcomes in this cohort. The present findings therefore cannot establish whether the observed anatomical differences translate into an increased risk of cerebrovascular events. Their potential clinical relevance, particularly in the context of posterior circulation ischemia and neuroendovascular intervention, remains biologically plausible but unconfirmed. Further limitations arise from the imaging methodology and sample distribution. Diameter assessment was confined to the V2 segment and may not fully capture variations along the entire VA. Although repeated measurements in 30 examinations demonstrated good intraobserver reproducibility, the absence of an independent second reader precluded evaluation of interobserver agreement. In addition, the small number of patients with direct aortic arch origin (n = 18) limited statistical precision, particularly for exploratory comparisons involving contralateral VA caliber, for which a type II error cannot be excluded. The retrospective, single-center, cross-sectional design further restricts generalizability and prevents causal inference. Taken together, these considerations underscore the importance of interpreting the findings within their anatomical and methodological boundaries. The observed associations are supported by consistent morphometric and statistical evidence, but their developmental origins, hemodynamic implications, and clinical consequences remain unresolved. Future multicenter investigations integrating comprehensive vascular risk-factor profiles, independent imaging assessments, quantitative hemodynamic measurements, and systematically adjudicated posterior circulation outcomes will be essential to bridge the gap between anatomical observation and clinical significance.

In conclusion, direct aortic arch origin of the left VA was independently associated with smaller vessel caliber and a markedly higher likelihood of hypoplasia, with consistent findings across conventional and sensitivity analyses.

These results identify a meaningful relationship between VA origin and morphology, suggesting that arterial branching patterns may provide information beyond anatomical variation alone. Recognition of direct aortic arch origin on CTA may therefore enhance the assessment of VA anatomy and inform procedural planning, particularly during VA catheterization and posterior circulation neuroendovascular interventions. Although the developmental mechanisms and clinical consequences of this association remain uncertain, the present findings highlight the value of considering arterial origin and vessel caliber together in cerebrovascular imaging.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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