RESEARCH PAPER

Anatomical Variations Of The Aortic Arch And Their Surgical Implications

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ABSTRACT
Background: Anatomical variations of the aortic arch are clinically important because they may alter vascular access, complicate catheter-based procedures, and influence cardiothoracic and vascular surgical planning.
Objective: To determine the prevalence of anatomical variations of the aortic arch and evaluate their potential surgical and endovascular implications.
Methodology: This descriptive cross-sectional study was conducted at Anatomy Department Dow Medical College Karachi from May 2024 to May 2025 and included 210 adult patients who underwent computed tomography angiography of the thoracic aorta. Demographic information including age, gender, body mass index (BMI), indication for CT angiography, and relevant medical history was recorded.
Results: The mean age of the participants was 54.8 ± 13.9 years, and 124 (59.0%) were male. A normal three-vessel branching pattern was observed in 156 (74.3%) patients, while 54 (25.7%) had an anatomical variation. The common origin of the brachiocephalic trunk and left common carotid artery was the most frequent variant, occurring in 29 (53.7%) patients with variations, followed by direct origin of the left vertebral artery from the aortic arch in 12 (22.2%), aberrant right subclavian artery in 8 (14.8%), right-sided aortic arch in 3 (5.6%), and other rare variants in 2 (3.7%). Patients with anatomical variations were older than those with normal anatomy (58.1 ± 14.2 vs. 53.7 ± 13.5 years; $p=0.046$), and anticipated procedural complexity was more frequent in the variant group (51.9% vs. 19.9%; $p<0.001$).
Conclusion: It is concluded that anatomical variations of the aortic arch are relatively common and are associated with increased surgical and endovascular complexity.....
Keywords: Aortic arch; anatomical variation; computed tomography angiography; vascular surgery; endovascular procedures..
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INTRODUCTION

The aortic arch is one of the key structures of the cardiovascular system, and is the passage between the ascending and descending aorta, and the source of the large vessels to the head and neck and upper extremities [1]. The normal branching has three branches, the brachiocephalic trunk, the left common carotid artery and the left subclavian artery. This is the typical anatomical pattern, but many congenital abnormalities have been reported as a result of abnormalities in the embryologic development of the pharyngeal arch arteries [2]. It is important to recognize these differences as they can affect the diagnosis and surgical planning. Aortic arch variations are relatively common and have been reported in 10–35% of the general population, but the prevalence varies between different ethnic groups and geographical regions [3]. The most

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common variation is the common origin of the brachiocephalic trunk and left common carotid artery (the 'bovine arch') followed by the presence of an aberrant right subclavian artery, isolated (single) vertebral artery origin and right-sided aortic arch [4]. The majority of these variants are asymptomatic and are only identified on computed tomography angiography (CTA), magnetic resonance angiography (MRA) or digital subtraction angiography (DSA) when not being performed for the diagnosis of the patient's condition [5]. The development and regression of the paired pharyngeal arch arteries of early fetal development is complicated, and the embryological basis of aortic arch variations is based on this [6]. Abnormal regression or persistence of embryonic vascular segments can lead to abnormal branching, vascular rings or abnormal origins of major arteries [7]. While these variations are asymptomatic in most cases, some abnormalities can cause compression of neighboring structures, resulting in dysphagia, respiratory abnormalities and vascular insufficiency [8].

The knowledge of the aortic arch anatomy has gained in significance, as a result of the widespread use of endovascular and minimally invasive cardiovascular procedures [9]. The complexity of the arteries, with varying branching patterns, can hinder the procedure, increase procedural time, length of fluoroscopy, and risk of vascular damage during catheterization, carotid artery stenting, thoracic endovascular aortic repair (TEVAR), coronary angiography and cerebral angiography [10]. Unrecognized anatomical variations can also contribute to bleeding, nerve injury, cerebral ischemia or technical difficulties during vascular reconstruction in open cardiothoracic, vascular and neck surgeries [11]. Multidetector computed tomography angiography (MCTA) is now the imaging modality of choice for assessing aortic arch anatomy prior to surgical or endovascular treatment and is characterized by good spatial resolution [12]. Proper identification of vascular variants prior to surgery, allows surgeons to tailor an operative plan, choose a vascular access, limit operative time and reduce peri-operative complications, [13]. As a result, many centers have adopted the routine evaluation of aortic arch branching patterns as an important part of vascular imaging prior to surgery [14]. There is considerable variability in the prevalence and distribution of aortic arch branching pattern across ethnic and geographical groups in previous studies, highlighting the effect of ethnic and geographical factors [15].

Objective

To determine the prevalence of anatomical variations of the aortic arch and evaluate their potential surgical and endovascular implications.

Methodology

This descriptive cross-sectional study was conducted at Anatomy Department Dow Medical College Karachi from May 2024 to May 2025 and included 210 patients who underwent computed tomography angiography (CTA) of the thoracic aorta for various clinical indications. Patients between 18 years of age and older, both male and female, with adequate image quality for evaluation of aortic arch anatomy on contrast-enhanced computed tomography angiography imaging were included. Patients who gave their informed consent for imaging data being used in research studies were recruited. Patients who had previously undergone surgery on the aortic arch, traumatic aortic injury, congenital cyanotic heart disease, poor quality or incomplete CT angiographic images, obstruction of the aortic arch by previous mediastinal surgery or extensive mediastinal pathology to prevent visualization of the aortic arch, and those who refused to participate were not included.

Data Collection

After obtaining approval from the Institutional Ethical Review Committee, eligible patients were enrolled using a non-probability consecutive sampling technique. Demographic data such as age, gender, body mass index (BMI), indication for CT angiography, and pertinent medical history were collected. All images were independently analyzed by two experienced radiologists who knew nothing of the clinical findings and used contrast-enhanced multidetector computed tomography angiography (MDCTA). The branching pattern of the aortic arch was categorized as normal (three-vessel configuration) and as anomalies such as common origin of the brachiocephalic trunk and left common carotid artery (common or bovine arch), aberrant right subclavian artery, left vertebral artery from the aortic arch, right-sided aortic arch and others. The route, direction and branching of each vessel was recorded. Each anatomical variation was evaluated for possible surgical consequences in relation to cardiothoracic surgery, vascular surgery, carotid artery surgery, thoracic endovascular aortic repair (TEVAR), coronary angiography, cerebral angiography, and catheter-based surgery. The variants were classified as low-, moderate- and high-procedural complexity based on fixed anatomic criteria. The main finding was the incidence of aortic arch anatomical variations. Secondary outcomes were the frequency of each branching pattern, anatomical variant distribution among the patients, and expected surgical and endovascular implications.

Statistical Analysis

The data analyzed were SPSS version 26.0. The mean ± SD was used for continuous variables and frequencies and percentages were used for categorical variables. The association with anatomical variation and demographic variables were evaluated by independent t-test, one-way ANOVA, Chi-square test or Fisher's exact test. Multivariable logistic regression was used to determine factors independently associated with complex aortic arch anatomy. A p-value ≤ 0.05 was considered statistically significant.

Results

The study included 210 patients with a mean age of 54.8 ± 13.9 years and a mean BMI of 27.1 ± 4.3 kg/m². Most participants were aged 40–59 years, comprising 89 (42.4%), followed by 83 (39.5%) aged 60 years or older and 38 (18.1%) aged 18–39 years. There were 124 (59.0%) males and 86 (41.0%) females. Hypertension was present in 118 (56.2%) patients, while 92 (43.8%) were normotensive. Diabetes mellitus was reported in 69 (32.9%) patients and was absent in 141 (67.1%).

Table 1. Demographic and baseline characteristics of the study participants (n=210)

Characteristic	Category	n (%) / Mean ± SD
Age (years)	Mean ± SD	54.8 ± 13.9
Age group	18–39 years	38 (18.1)
	40–59 years	89 (42.4)
	≥60 years	83 (39.5)
Gender	Male	124 (59.0)
	Female	86 (41.0)
BMI (kg/m²)	Mean ± SD	27.1 ± 4.3
Hypertension	Yes	118 (56.2)
	No	92 (43.8)
Diabetes mellitus	Yes	69 (32.9)
	No	141 (67.1)

A normal three-vessel branching pattern of the aortic arch was observed in 156 (74.3%) patients, whereas 54 (25.7%) had an anatomical variation. Among the 54 variants, the common origin of the brachiocephalic trunk and left common carotid artery was the most frequent, occurring in 29 (53.7%), followed by direct origin of the left vertebral artery from the aortic arch in 12 (22.2%), aberrant right subclavian artery in 8 (14.8%), right-sided aortic arch in 3 (5.6%), and other rare variants in 2 (3.7%).

Table 2. Prevalence and distribution of anatomical variations of the aortic arch (n=210)

Variable	Category	n (%)
Aortic arch anatomy	Normal branching pattern	156 (74.3)
	Anatomical variation	54 (25.7)
Type of variation (n=54)	Common origin of brachiocephalic trunk and left common carotid artery (Bovine arch)	29 (53.7)
	Left vertebral artery arising directly from the aortic arch	12 (22.2)
	Aberrant right subclavian artery	8 (14.8)
	Right-sided aortic arch	3 (5.6)
	Other rare variants	2 (3.7)

Patients with an anatomical variation were older than those with normal arch anatomy, with mean ages of 58.1 ± 14.2 and 53.7 ± 13.5 years, respectively (p=0.046). Their mean BMI was also slightly higher at 27.8 ± 4.5 kg/m² compared with 26.9 ± 4.2 kg/m², although the difference was not significant (p=0.211). Male gender was observed in 35 (64.8%) patients with variations and 89 (57.1%) with normal anatomy (p=0.324). Hypertension was significantly more common in the variant group than the normal group (36 [66.7%] vs. 82 [52.6%]; p=0.048), while diabetes mellitus showed no significant difference (22 [40.7%] vs. 47 [30.1%]; p=0.163).

Table 3. Comparison between patients with normal and variant aortic arch anatomy

Variable	Normal Anatomy (n=156)	Anatomical Variation (n=54)	p-value
Age (years), Mean ± SD	53.7 ± 13.5	58.1 ± 14.2	0.046
BMI (kg/m²), Mean ± SD	26.9 ± 4.2	27.8 ± 4.5	0.211
Male gender	89 (57.1%)	35 (64.8%)	0.324
Hypertension	82 (52.6%)	36 (66.7%)	0.048
Diabetes mellitus	47 (30.1%)	22 (40.7%)	0.163
Anticipated complex surgical/endovascular procedure	31 (19.9%)	28 (51.9%)	<0.001

Multivariable analysis showed that an aberrant right subclavian artery had the strongest association with complex surgical or endovascular anatomy, increasing the odds by 4.65 times (95% CI: 1.31–16.49; p=0.017). A bovine arch configuration increased the odds by 3.82 times (95% CI: 1.74–8.37; p=0.001), while direct origin of the left vertebral artery from the arch increased the odds by 2.73 times (95% CI: 1.08–6.91; p=0.034). Age 60 years or older was associated with 2.48-fold higher odds (95% CI: 1.21–5.08; p=0.013), and hypertension with 2.14-fold higher odds (95% CI: 1.05–4.35; p=0.036).

Table 4. Multivariable logistic regression analysis of factors associated with anatomically complex aortic arch variations

Variable	Adjusted Odds Ratio (95% CI)	p-value
Age ≥60 years	2.48 (1.21–5.08)	0.013
Hypertension	2.14 (1.05–4.35)	0.036
Bovine arch configuration	3.82 (1.74–8.37)	0.001
Aberrant right subclavian artery	4.65 (1.31–16.49)	0.017
Left vertebral artery arising directly from the aortic arch	2.73 (1.08–6.91)	0.034

Discussion

In the present study 210 patients were assessed for the presence of anatomical variations of the aortic arch and their surgical significance. The mean age of the participants was 54.8 ± 13.9 years and 59.0% were males. The prevalence of hypertension in the patients was 56.2% and of diabetes mellitus 32.9%. The results of this study suggest that imaging of the aortic arch is frequent endoluminal imaging procedure in middle-aged and elderly people with cardiovascular risk factors. Other studies have also shown that the majority of patients who underwent TCTA were male, and hypertension was a common comorbidity [16][17]. In 74.3% of patients, the three-vessel branching pattern was found and in 25.7% of patients, an anatomical variation was detected. The common origin of the brachiocephalic trunk and left common carotid artery was the most frequent variant, accounting for 53.7% of all variations. The direct origin of the left vertebral artery from the aortic arch (22.2%), aberrant right subclavian artery (14.8%), right-sided aortic arch (5.6%) and other rare patterns (3.7%) followed. Past studies have also found that the classic branching pattern occurs in about 2/3 - 3/4 of patients and the most common variation is a common origin of the brachiocephalic and left common carotid arteries [18].

The frequency of the different types of aortic arch variations seen in this study should emphasize the need for meticulous preoperative imaging. These variants can be asymptomatic, but can affect the course and origin of major arteries, making catheterization and other procedures more difficult, and making the thoracic endovascular aortic repair and open vascular procedures more difficult. A previous study has also shown that the abnormal arch branching patterns can cause the procedure to be technically challenging, extend fluoroscopy and procedural time and may impair advancement of the catheter or cause vascular injury, cerebral embolization or a failure [19]. Patients with anatomical variations were significantly older than those with normal arch anatomy with mean ages of 58.1 ± 14.2 years versus 53.7 ± 13.5 years respectively. Patients with variants were also more likely to have hypertension (66.7% vs. 52.6% of patients with normal anatomy). However, BMI, male gender, and diabetes mellitus were not significant differences between the groups. Similar results have been reported previously, and although the distribution of the arches is congenital, perhaps some variants will be more clinically relevant with ageing due to vascular elongation, atherosclerosis, vascular calcifications and decreased arterial compliance [20]. Patients with anatomical variants were significantly more likely to have complex surgical or endovascular procedures than patients with normal arch anatomy (51.9% vs. 19.9%, respectively). This discovery directly paves the way for the clinical relevance of identifying such variants prior to intervention. Previous studies have also shown that the variant aortic arch anatomy was related to the difficulty of selective cannulation of a vessel, variations in vascular landing zones for endovascular grafts, and requires modifications to surgical exposure or vascular reconstruction [21]. The limitations of this study include the cross sectional design and a single center approach, which may not be generalizable to other centers. Rare anatomical variants might have been underrepresented due to the relatively low number of subjects. Furthermore, in the absence of real-world experience and without the benefit of real-world surgical complexity, the implications of the surgery were determined by the imaging results prior to the operation.

Conclusion

It is concluded that anatomical variations of the aortic arch are relatively common, with the common origin of the brachiocephalic trunk and left common carotid artery being the most frequent variant. These anatomical differences have important implications for cardiothoracic, vascular, and endovascular procedures by increasing procedural complexity and influencing surgical planning. Routine preoperative evaluation with multidetector computed tomography angiography is essential for accurate identification of vascular variants, facilitating safer operative strategies and reducing the risk of perioperative complications..

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