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Anatomy and radiology of the variations of aortic arch branches in 1,266 patients

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Background: The most reliable data about arterial variations, which are very important in surgery and radiology, can be obtained from a large series of patients.
Materials and methods: We examined angiographic and multislice computerised tomography (MSCT) images in a group of 1,265 patients and in 1 dissected specimen.
Results: While in 946 (74.72%) of the patients a normal vascular pattern (type I) was noticed, in the remaining 320 (25.28%) patients variations of the branches of the aortic arch were found, which were classified into types II through VIII and a few subtypes. Type II (2.84%) comprised a common origin of the left common carotid and subclavian arteries. Type III (15.56%) was related to an origin of the left subclavian artery from the brachiocephalic trunk. Type IV (0.55%) included the aortic origin of both common carotid and subclavian arteries, with the right subclavian artery having a retroesophageal course. Type V (0.24%) included the same 4 supra-aortic branches, which, however, arose from a double or a right-sided aortic arch. Type VI (3.63%) comprised the aortic origin of the left vertebral artery, type VII (0.24%) the same origin of the right vertebral artery, and type VIII (2.22%) the aortic origin of the thyroidea ima artery. A corresponding embryological background and clinical implications of the described aberrant vessels were presented.
Conclusions: In more than one quarter of the cases, the branching pattern of the examined arteries did not follow the classical pattern. Detailed knowledge of aortic branch variations is of great significance in anatomy, embryology, and clinical medicine, especially in radiology and thoracic surgery. (Folia Morphol 2013; 72, 2:113–122)

Key words: anatomical variations, aortic arch, neck arteries, radiology, thoracic arteries, thoracic surgery

INTRODUCTION

Variations of the thoracic arteries, including branches of the aortic arch, are interesting from an anatomical and embryological aspect [4, 8, 27, 32]. They are, however, more important for thoracic operations, especially in vascular, cardiac, oesophageal, and mediastinal surgery [1, 9, 12, 14, 34]. Modern radiological techniques, especially computerised tomographic angiography (CTA), magnetic resonance angiography (MRA), multislice CT (MSCT), and MSCT angiography, have enabled an elegant insight into the thoracic blood vessels [21, 27]. Obviously, the mentio-

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ned variations are also very important in radiological diagnostics and interventional radiology.

The aim of this study was, firstly, to present the anatomical variations of the aortic arch and the supra-aortic arteries in a very large group of patients following transfemoral angiography, MSCT imaging, or MSCT angiographic examination. Secondly, to present the embryological background of those variations. And thirdly, to stress the radiological and surgical significance of the variations based on the obtained anatomical and radiological data.

MATERIALS AND METHODS

A group of 1,265 patients were examined following approval by the Ethics Committee of the University Clinical Centre. The group consisted of 751 males and 514 females, with mean ages of 68 and 65 years, respectively. The angiography was performed by a transfemoral approach after Seldinger in all individuals in order to identify the arterial variations and their possible vascular diseases, as well as for certain measurements of the relevant vessels, especially their diameter. Selected patients underwent CT, MSCT, or MSCT angiography. One case of aberrant origin of the vertebral artery, obtained during a routine dissection for students' practice, was included into the patient group. Thus, the total number of patients was 1,266.

In addition to angiography and other radiological procedures, all patients underwent the relevant biochemical analysis, cardiovascular and neurologic examination. Statistical methods comprised counting of the percentages related to the whole series of patients (1,266), as well as to a group with the arterial variations (320).

RESULTS

The normal (left) arch of the aorta (Fig. 1) typically gives rise to 3 large vessels: the brachiocephalic trunk (BCT), or the innominate artery, which divides into the right common carotid (RCCA) and subclavian arteries (RSCA), as well as the left common carotid (LCCA) and subclavian arteries (LSCA). The common carotid arteries divide into the right internal (RICA) and external carotid arteries (RECA), and into the same vessels on the opposite side (the LICA and LECA). Direct branches of the aortic arch are also known as the primary or the supra-aortic arteries. We examined both the primary and secondary arteries, as well as the variations of the aortic arch itself.

Our study was carried out in 1,266 patients. Among them, 946 (74.72%) showed a normal vascular pattern,

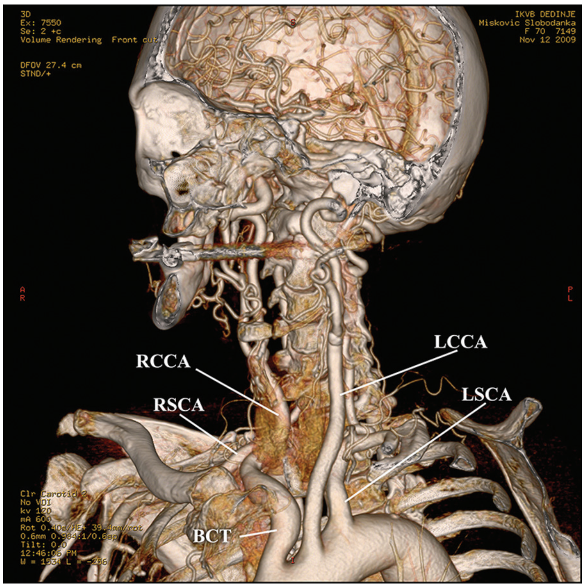

Figure 1. A multislice computed tomographic image to show a normal branching pattern (type I) of the arch of the aorta. BCT — brachiocephalic trunk; RCCA and LCCA — right and left common carotid arteries; RSCA and LSCA — right and left subclavian arteries.

whereas 320 (25.28%) presented with variations of the supra-aortic vessels and the aortic arch.

Aortic arch variations

Examination of the aortic arch itself revealed a double arch and several right-sided arches. A double aortic arch, which was found in a male patient (0.08%), encircled and compressed the trachea and oesophagus, and showed a separate origin of the main arteries: the RCCA and RSCA, and the LCCA and LSCA, respectively.

A right-sided aortic arch was found in 4 male patients (0.32%). In 2 of them it compressed the trachea or oesophagus. The descending aorta in 3 patients continued along the right side, but in the remaining person it was found to return to the left side of the mediastinum. Branches of the right-sided arch were arranged in a 4-vessel pattern. Namely, the BCT was absent, so that the RCCA and RSCA arose directly from the aortic arch, in addition to a normal aortic origin of the LSCA and LCCA (see later).

Patterns of the aortic arch branches

The branches of the aortic arch were classified into 8 types (Table 1). In some of these groups we made a combination of the variations of both the aortic arch and its branches. In addition to the classical vascular pattern (type I), the remaining 7 types showed

Table 1. Normal origin and variations of the aortic arch branches

Types of variants	No. of patients	Frequency (%): all patients	No. of patients	Frequency (%): patients with variants
I*	946*	74.72*	0	0.00
II	36	2.84	36	11.25
IIIa	86	6.79	86	26.88
IIIb	84	6.64	84	26.25
IIIc	27	2.13	27	8.44
IV**	7	0.55	7	2.19
Va***	1	0.08	1	0.31
Vb**	1	0.08	1	0.31
Vc**	1	0.08	1	0.31
VIa	37	2.92	37	11.56
VIb	8	0.63	8	2.50
VIc	1	0.08	1	0.31
VII	3	0.24	3	0.93
VIII	28	2.22	28	8.76
Total	1,266	100.00	320	100.00

*patients lacking arterial variations; **some variations associated with a right-sided aortic arch; ***a variation associated with a double aortic arch

a specific origin, arrangement, and relationship of the mentioned branches.

Type I. This type, which was found in 946 patients (74.72%), refers to the usual branching pattern: the BCT, LCCA, and LSCA (Fig. 1). These vessels arose from a normal (left) aortic arch in all the patients, except in the 5 individuals mentioned with a double or a right-sided aortic arch. We measured diameters of the supra-aortic branches and their divisions, i.e. the RICA and RECA, and LICA and LECA (Table 2).

The BCT, which averaged 0.6 cm in diameter (Table 2) and between 2.2 and 7.1 cm (mean, 4.6 cm) in length, divided into the RCCA and RSCA above (94.71%), below (1.97%), or at the level (3.32%) of the sternoclavicular joint. The RCCA gave rise to the superior thyroid artery in 11 patients (0.87%) before dividing into the RICA and RECA, most often at the level of the 4^{th}–5^{th} cervical vertebrae. The RCCA was usually smaller than the RSCA (Table 2).

The LCCA was similar to the RCCA, except for its longer course (Fig. 1). It gave off the superior thyroid artery in 143 patients (11.29%). Its terminal branches, i.e. the LICA and LECA, also arose most frequently at the mentioned level. The former artery was seen to give rise to the ascending pharyngeal artery in 32 patients (2.53%). The LECA was similar to the RECA. It gave off a linguofacial trunk in

Table 2. Measurements of the relevant arteries in type I (946 patients)

Artery: type (side)		Diameter: mean [cm]
Brachiocephalic trunk	(BCT right)	2.1
Common carotid artery	(RCCA)	0.7
	(LCCA)	0.6
Internal carotid artery	(RICA)	0.3
	(LICA)	0.4
External carotid artery	(RECA)	0.4
	(LECA)	0.4
Subclavian artery	(RSCA)	0.8
	(LSCA)	0.7
Vertebral artery	(RVA)	0.2
	(LVA)	0.3

BCT — brachiocephalic trunk; RCCA and LCCA — right and left common carotid arteries; RECA and LECA — right and left external carotid arteries; RSCA and LSCA — right and left subclavian arteries; RVA and LVA — right and left vertebral artery

0.39% of the patients. The LCCA also was smaller than the LSCA.

Types II through VIII of the supra-aortic branches were distinguished within a group of 320 patients (25.28%). Each type is presented separately (Table 1).

Type II. Type II contained, in fact, only 2 branches of the aortic arch, i.e. the BCT, as well as the same origin

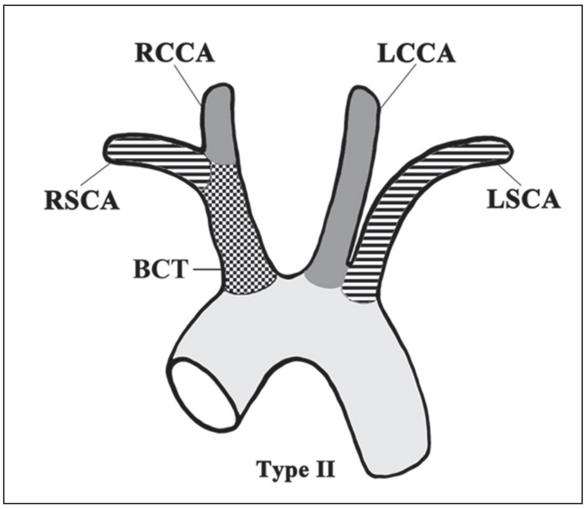

Figure 2. A drawing presenting a typical brachiocephalic trunk (BCT) and a common origin of the left carotid (LCCA) and subclavian artery (LSCA); RCCA — right common carotid artery; RSCA — right subclavian artery.

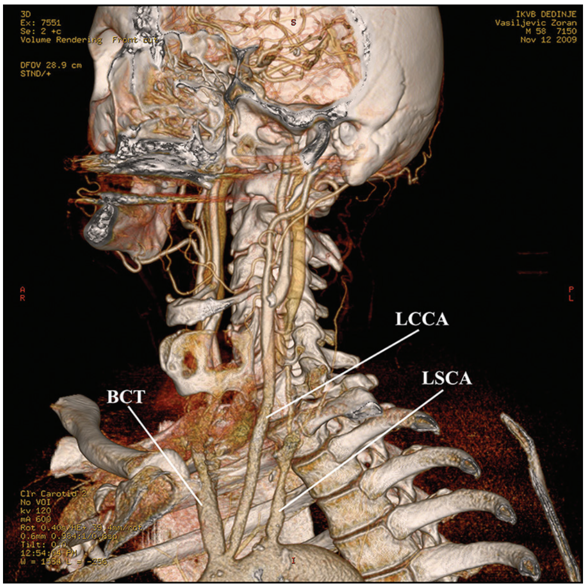

Figure 3. A multislice computed tomographic image of type IIIa. The left common carotid artery (LCCA) shares a origin site with the brachiocephalic trunk (BCT). Note the left subclavian artery (LSCA).

site of the LCCA and LSCA (Fig. 2). This double BCT pattern was present in 36 patients (2.84%) (Table 1).

Type III. This type, which was observed in 15.56% of the patients, was presented with 3 variants (Table 1). In the first variant, or subtype IIIa, the LCCA and BCT shared the same site of origin in 86 patients (Fig. 3). In the IIIb subtype, observed in 84 patients, the LCCA originated from a typical BCT (Figs. 4A, B). In the IIIc variant, the LCCA arose from a shorter BCT in

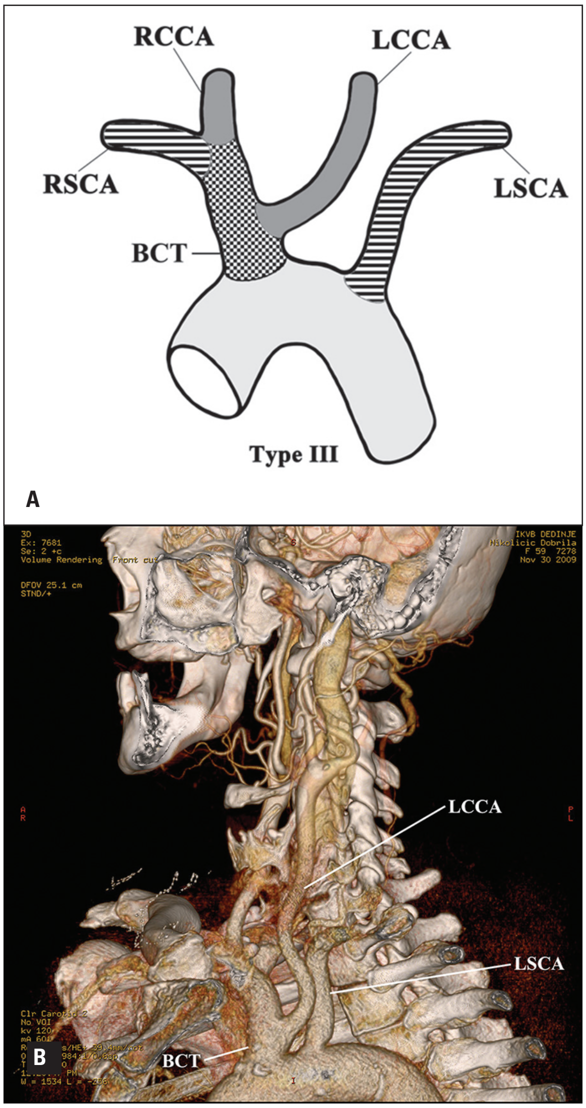

Figure 4. A drawing (**A**) and a multislice computed tomographic image (**B**) of type IIIb. The left common carotid artery (LCCA) originates from the brachiocephalic trunk (BCT), close to the left subclavian artery (LSCA); RCCA — right common carotid artery; RSCA — right subclavian artery.

27 patients. The LSCA in all the subgroups originated from the aortic arch as the most distal branch.

Type IV. Type IV comprised the aortic origin of both carotid arteries (the RCCA and LCCA) and the subclavian arteries (RSCA and LSCA). This 4-vessel pattern was present in 7 patients, i.e. in 5 with a left aortic arch (Fig. 5A) and in the remaining 2 with a right-sided arch (Fig. 5B). All of them had the RSCA as a distal aortic branch. This so-called arteria lusoria extended posterior to the esophagus. The initial segment of the arteria lusoria was enlarged, i.e. the LSCA originated from a Kommerell diverticulum.

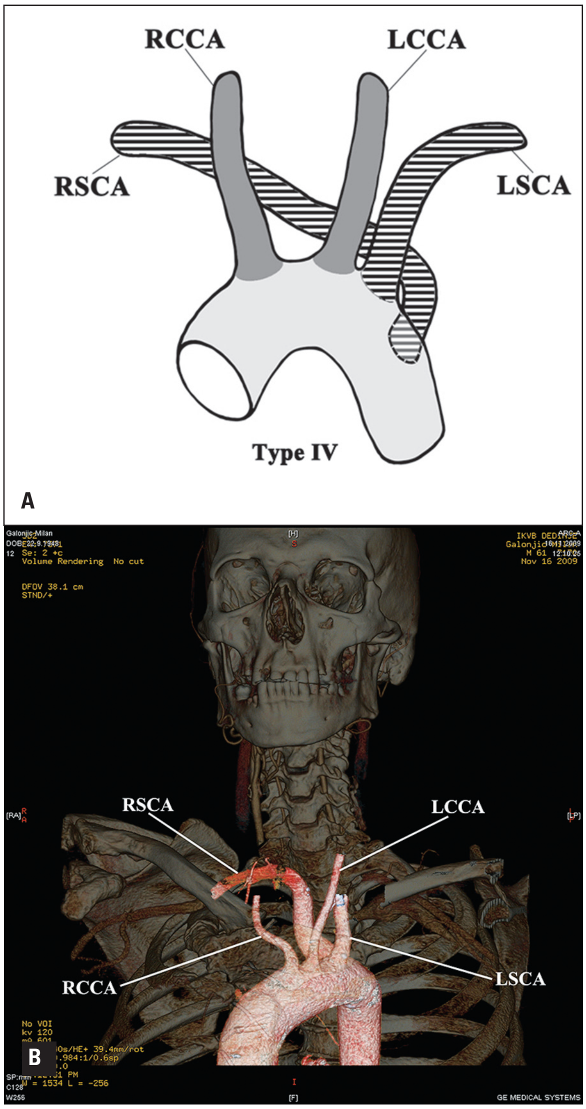

Figure 5. A drawing (**A**) and a multislice computed tomographic image (**B**) of type IV with the right subclavian artery (RSCA) arising as an arteria lusoria in patients with a left-sided (**A**) and a right--sided arch of the aorta (**B**); LSCA — left subclavian artery; LCCA and RCCA — left and right common carotid arteries.

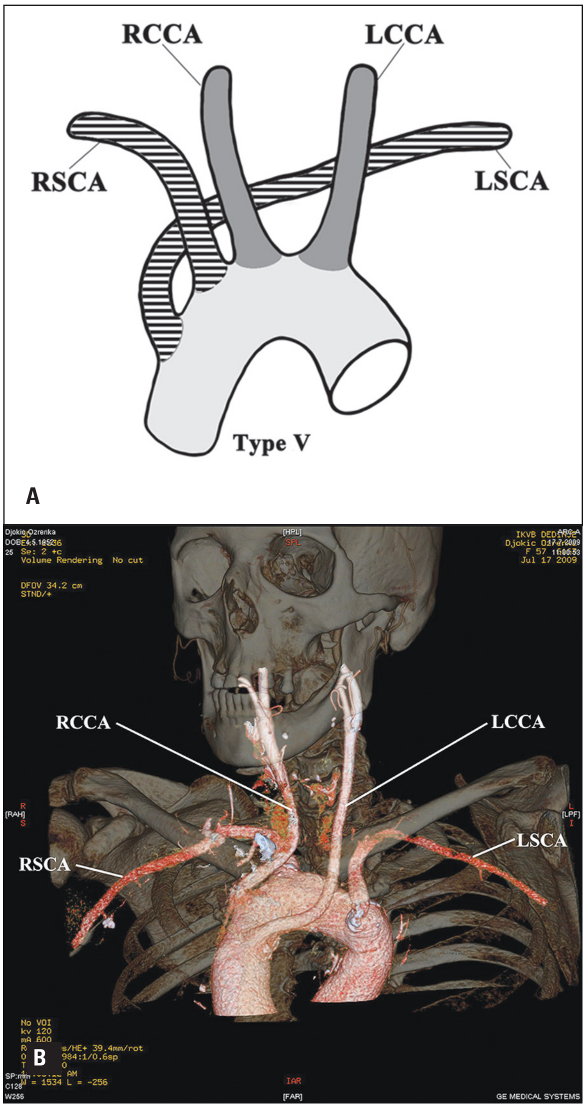

Figure 6. A drawing (**A**) and a multislice computed tomographic image (**B**) of type Vb. A separate origin of the right and left subclavian arteries (RSCA and LSCA), and the right and left common carotid arteries (RCCA and LCCA) in patients with a right-sided aortic arch.

Type V. This was also a 4-vessel pattern (the RCCA, LCCA, RSCA and LSCA), which, however, comprised 3 subtypes in 3 patients (Table 1). In 1 with a double aortic arch (type Va), the RCCA and RSCA arose on the right side, and the LCCA and LSCA on the left side. Another patient, with a right-sided arch, showed the LSCA and RSCA as the most distal aortic branches (type Vb) (Fig. 6A), while in the remaining patient with a right arch the LSCA and RSCA were the most proximal branches (type Vc) (Fig. 6B). All the 4 vessels in the latter case had longer initial parts than usual.

Type VI. Type VI is characterised by an aberrant origin of the left vertebral artery (LVA) in 3.63% of the patients. It also presented with 3 subtypes (Table 1). The most frequent 1 was the VIa subtype, which showed a typical vessel arrangement (the BCT, LCCA, LSCA) with the LVA origin between the LCCA and LSCA (Figs. 7A, B). The LVA in the VIb subtype was a component of a 5-vessel pattern: the RSCA, RCCA, LCCA, LVA, and LSCA. The VIc subtype is referred to the LVA as the most distal branch, as was seen in our anatomical specimen (Fig. 8), which was included into the patient group.

Type VII. Type VII showed the aortic origin of the right vertebral artery (RVA) in 3 patients (Table 1). In all the subjects the RVA was the most distal branch (Fig. 9). The RVA continued to the right side by coursing be-

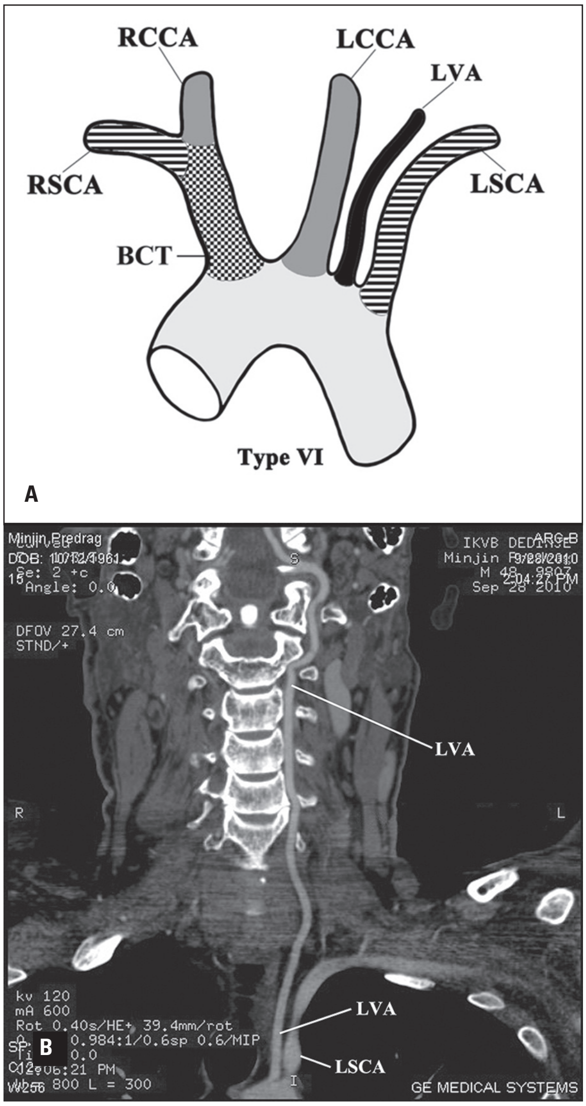

Figure 7. A drawing (**A**) and an anterior multislice computed tomographic angiogram (**B**) presenting type VIa, i.e. the left vertebral artery (LVA) arising from the aortic arch just proximal to the left subclavian artery (LSCA); rest abbreviations as in Table 2.

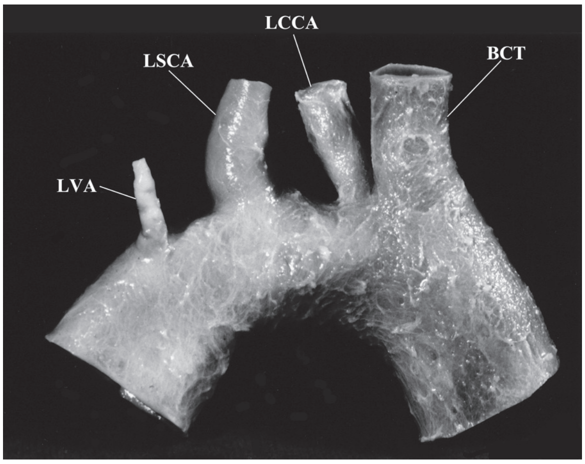

Figure 8. An anatomical specimen in a posterior view showing type VIb, i.e. the aortic origin of the left vertebral artery (LVA) distal to the left subclavian artery (LSCA), the left common carotid artery (LCCA), and the brachiocephalic trunk (BCT).

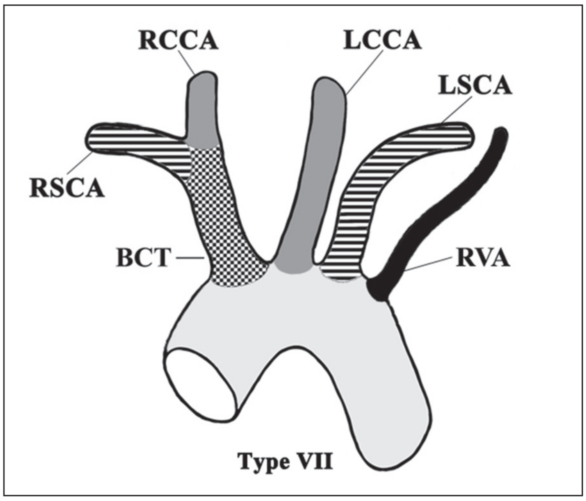

Figure 9. A drawing presenting the aortic origin of the right vertebral artery (RVA); rest abbreviations as in Table 2.

tween the trachea and oesophagus. This type in our study belongs to the 4-vessel pattern.

Type VIII. Type VIII comprised a typical vascular pattern (BCT, LCCA, LSCA) (Fig. 10), but also the aortic origin of the thyroidea ima artery (ThIA). The latter vessel arose between the BCT and LCCA in 2.22% of our patients (Table 1).

Some subjects from both groups, i.e. from 320 patients with variations and from 946 of the remaining individuals, presented with certain clinical signs due to a corresponding vascular pathology of the supra-aortic arteries or their branches: compression to the adjacent organs, arterial dissection, stenosis, occlusion, aneurysm, elongation, kinking, or coiling.

DISCUSSION

Among the 1,265 patients examined, plus one anatomical specimen, the variations of the branches of the aortic arch were revealed in 320 individuals (25.28%) These variations have been presented by some other authors but in much smaller groups of patients or anatomical specimens [4, 27, 28]. The anomalies of the aortic arch and its branches arise as a result of altered development of primitive aortic arches (Figs. 11A, B), or may occur as a consequence of irregular and imperfect development of the aorticopulmonary septum of the truncus arteriosus [4, 23, 32].

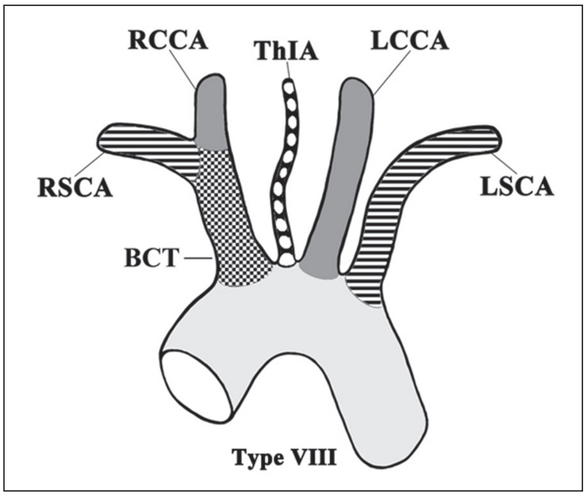

Figure 10. A drawing showing the aortic origin of the thyroidea ima artery (ThIA); rest abbreviations as in Table 2.

Variation types

The variations from our study were classified into 7 types, taking into account both the branches and the aortic arch itself.

Type I. The common vascular pattern was present in 74.72% of our patients, while it was observed in a range between 64.9% and 94.3% in other series [27, 28]. This 3-vessel pattern of the aortic arch branches understands the presence of the BCT, LCCA, and LSCA. The BCT is localised on the right, and extremely rarely on the left side. In the latter case, the BCT normally divides into the RCCA and RSCA, which soon return to the right side of the neck [31]. Nevertheless, type I develops embryologically in a typical manner (Fig. 11B).

The mentioned aortic arch vessels usually do not give off the side branches in the mediastinum, but occasionally the BCT may give rise to the internal thoracic, inferior thyroid, or right vertebral artery [31]. On the other hand, the LCCA may give off the superior thyroid artery (in 11.29% of our patients), and very rarely the inferior thyroid, thyroidea ima, laryngeal, or left vertebral arteries [27, 32].

Type II. This pattern comprises a left BCA, in addition to the present right BCA [26, 28]. It is a result of an involution of part of the left 4th embryonic arch (Fig. 11B) [9]. Consequently, the LCCA arises in common with the LSCA. Since such a double BCT pattern is seen in birds, it is also known as the avian type [32]

Type III. This type, consisting of the LCCA arising from the BCT, occurs when the left horn of the aortic sack fails to develop (Fig. 11B) [28, 32]. Being similar to the vascular pattern of the cattle, this type is known as the bovine aortic arch variant [13, 27]. In these cases, the RCCA, as one of the two BCT divisions, may give rise to the right vertebral artery [6, 8, 12, 21]. Type III in our study was observed in 15.56%, as compared to 11–27% found by other authors [27, 29].

Type IV. It comprises the aortic origin of all the main branches, among which the right subclavian artery is the most distal vessel (the RCCA, LCCA, LSCA, and RSCA). The latter vessel is known as the arteria lusoria [12, 25, 27, 28]. It courses posterior to the trachea and oesophagus, and hence its name: the retroesophageal RSCA. However, it may also extend between the trachea and oesophagus, or in front of the trachea [10, 11, 27]. We found it in 0.55% of the cases, which is within the reported range of 0.13% through 25% [6, 11].

This anomalous vessel is caused by an obliteration of the right 4th aortic arch and a portion of the dorsal aorta proximal to the right 7th intersegmental artery, along with persistence of the Z segment of the right dorsal aorta [30, 32]. In this way, the right 7th intersegmental artery and the Z segment continues as the RSCA to the left dorsal aorta [28, 32]. The RSCA is obviously the most distal branch. In addition, the RVA in these instances may arise from the RCCA [30].

Type V. This type, which is also a 4-vessel pattern, is sometimes a mirror image of the previous type. The RSCA and LSCA arise either as the most distal branches (Figs. 5A, 6A) or the most proximal vessels (Fig. 6B) of a right-sided aortic arch [3, 9, 27, 28]. The aberrant LSCA in the former cases is the result of involution of the left dorsal aorta between the left subclavian and common carotid arteries, in association with persistence of the right dorsal aorta and the left dorsal aorta between the 7th intersegmental artery and the junction with part Z (Fig. 11B). Due to that, the first aortic branch is the LCCA, followed by the RCCA, RSCA, and LSCA.

Type VI. This 4-vessel pattern (BCT, LCCA, LVA, LSCA) comprises the LVA, which has such a position in the majority of patients [4, 19]. Type VI may also be a 5-vessel pattern (RSCA, RCCA, LCCA, LSCA, LVA). Nevertheless, the LVA is very rarely localised distal to the LSCA [8], as was the case in our anatomical specimen. Type VI was found in 3.63% of subjects in the present study, which is in accordance with other reports (2.5–8.0%) [4, 25, 27].

The aberrant origin of the LVA is due to persistence of the 6th or 8th left intersegmental artery, respectively,

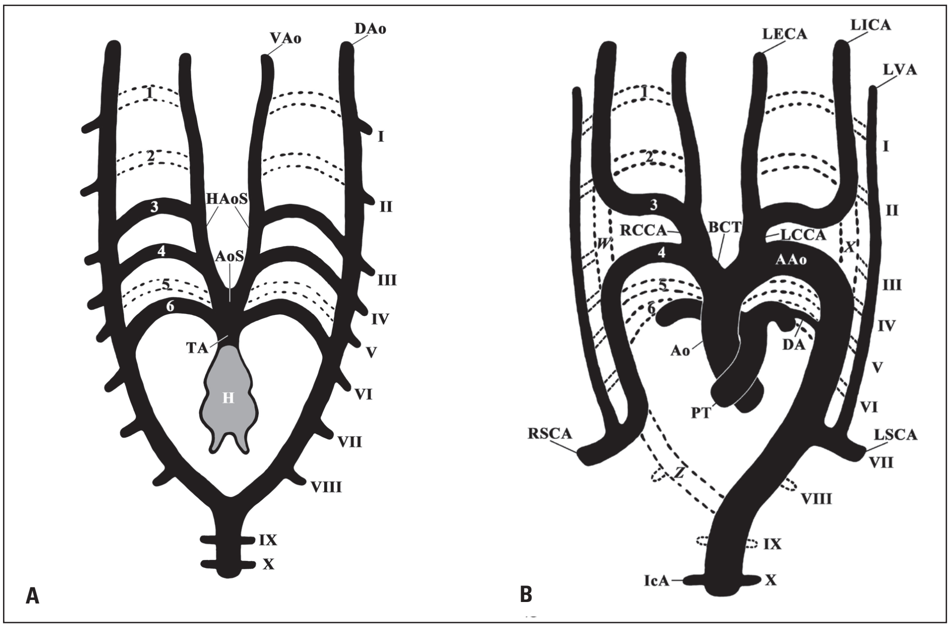

Figure 11. Embryonic development of the arterial system. **A**. Truncus arteriosus (TA), which leaves the heart (H), is continuous with the aortic sack (AoS) whose horns (HAoS) form the right and left ventral aortae (VAo). The aortic arches (1 through 6) interconnect the ventral and dorsal aortae (DAo). Note the cranial and thoracic intersegmental arteries (I through X); **B**. Development of the main arteries, i.e. the pulmonary trunk (PT) and aorta (Ao) with its arch (AAo), interconnected by the ductus arteriosus (DA), as well as the brachiocephalic trunk (BCT), the right and left common carotid arteries (RCCA and LCCA), the right and left external carotid (LECA), and internal carotid arteries (LICA), as well as the right and left subclavian arteries (RSCA and LSCA). The left vertebral artery (LVA), like its counterpart on the right, interconnects the cranial intersegmental arteries (I through VI). Some of the remaining intersegmental vessels become the intercostal arteries (IcA). The aortic arches are labelled by numerals 1 through 6. Note the regressed segments (X, W, Z) of the dorsal aortae.

one of which becomes the initial part of the LVA [16, 28]. If the LVA develops from the 6th artery, it will be located between the LCCA and LSCA in adults. If, however, the LVA originates from the 8th artery, it will be situated distal to the LSCA (Fig. 11B). Finally, there is a common stem of the LSCA and LVA in some people [5, 15, 29].

Type VII. This type showed the aortic origin of the RVA, which was found in 0.24% of our patients. In general, the RVA may arise between the RSCA and RCCA, the LCCA and LSCA, or distal to the LSCA [16, 22]. Such types of origin could be due to a separate development of the RVA from the right 6th or 8th embryonic intersegmental artery [16].

The RVA in our patients was the most distal aortic branch. It arose from the right 8th intersegmental artery, i.e. distal to the RSCA, after losing a connection with the latter vessel. The RVA was continuous with the persistent Z part of the right dorsal aorta [17]. They both became continuous with the distal part of the left dorsal aorta (Fig. 11B). Due to that, the RVA originated distal to the LSCA in those patients.

Finally, an origin of both the LVA and RVA from the aortic arch is an extremely rare event [16, 22, 33]. One or both of the aberrant vertebral arteries may arise distal to or among the other branches of the aortic arch. The RVA in some patients originates directly from the aortic arch, whereas the LVA forms a common stem with the LSCA [15].

Type VIII. This type is characterised by the aortic origin of the ThIA, which was located between the BCT and the LCCA. This variant was present in 2.22% of our patients, as compared to the range 0.16–10.0% in other reports. The ThIA, which ascends in front of the trachea and the thyroid gland, may also arise from the BCT, RCCA, or RICA or, very rarely, from the vertebral artery [22, 27, 30].

GENERAL DISCUSSION

Several kinds of vessel variations were noticed by the present authors and the mentioned investigators, i.e. the alterations in their size or number, the absence of some vessels, their aberrant origin or position, or both. There are often various combinations of 2 or more aberrant arteries in the same patient

[3, 6, 10, 11]. Similarly, a combination of aberrations of both branches and the aortic arch variations can be observed, especially in patients with a double or a right-sided aortic arch [1, 9, 18, 35].

By comparing the frequencies in our study, it is clear that type III, i.e. the origin of the LCCA from the BCT, is the most frequent variation, which occurred in 15.56% of patients (Table 1). On the other hand, types IV, V, and VII are the rarest ones, with a frequency less than 1%.

In general, we noticed the majority of the supra-aortic variations described thus far. We did not find, however, a common stem of the RCCA and LCCA or of the RSCA and LSCA, some other origin types of the RVA, LVA, or both, nor the aortic origin of some other aberrant vessels, e.g. the internal thoracic, thymic, or left coronary arteries [6, 27]. On the other hand, we revealed some rare patterns, e.g. those presented in Figures 6B and 8. The mentioned differences can be explained, among others, by some national and racial features or environmental circumstances [4, 27].

The observed variations are of great clinical significance. Thus, a double or a right-sided aortic arch, then a common stem of the RCCA and LCCA, a left BCT, a double BCT, or a retroesophageal RSCA, may cause a compression of the trachea and the oesophagus and hence dyspnoea, cough, recurrent respiratory infections, and dysphagia [1, 3, 9, 11, 27, 34]. In the latter case, an arterioesophageal fistula may develop, which is usually a fatal event [11].

An anomalous origin of a common carotid artery and, especially, a common trunk of the RCCA and LCCA, distal origin of the latter, or an aberrant vertebral artery, seem to be associated with a higher incidence of cerebrovascular disorders [16, 20, 28, 29]. Thrombosis of a retroesophageal subclavian artery may cause acute ischaemia of the upper limb [11]. The aortic origin of some aberrant vessels, such as the internal thoracic, thyroid, or coronary arteries, may also have certain clinical implications.

Similarly, a left BCT or a longer BCT that also inclines to the left, as well as the RCCA or the LCCA, thyroidea ima artery, and similar aberrant vessels, may extend in front of the trachea above the sternum, which can cause their injury during tracheostomy, thyroid resection, laryngeal transplantation, mediastinoscopy, etc. [28, 31]. The RVA arising from the common carotid artery can be lacerated during thyroid or anterior cervical spine surgery [28, 30]. The arteria lusoria is important in oesophageal surgery. The RCCA or LCCA may bifurcate into the internal and external carotid arteries very low, i.e. in the thorax, or very high — at the level of the hyoid bone or even the styloid process, which is important in thoracic, neck, and head surgery [1, 34]. Non-recognition of certain aberrant aortic arch branches at surgery may have fatal consequences [27].

As regards vascular surgery in symptomatic patients, various techniques can be used: division of a vascular aortic ring, transposition and reimplantation of certain arteries, angioplasty, endovascular grafts, stent placement, bypass grafting, etc. [1, 2, 7, 9, 10, 14, 34]. Radiologists usually apply various types of angiography, MSCT, catheterisation, and trans-catheter coil occlusion, either for examination and identification of the aberrant arteries or for the treatment of their pathology [24, 27].

CONCLUSIONS

Three kinds of the aortic arches and 8 main types of their branching patterns were revealed in this study. Left aortic arch and I and III branching patterns were the most frequent. The common and the rare variations can be accompanied by certain clinical symptoms, especially when associated with a corresponding vascular pathology. Patients with these variants are at risk of iatrogenic injury during surgical or radiological intervention. Accordingly, all the variants are very important in radiology and vascular surgery, as well as in planning operations in cardiothoracic, neck, and head surgery.

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