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Digital-image analysis of the aortic arch's development and its variations

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The study was performed on 103 human foetuses (58 female, 45 male) spontaneously aborted at between 14 and 30 weeks of gestation. The arteries were filled with latex, preserved in formalin and then dissected under the microscope and digitalised using a camera system. The following measurements were taken with the use of special computer software: the external diameter, the length and the volume of the arch of the aorta. The increase in diameter and length in relation to age corresponded to a linear function with values ranging from 1.77 mm to 4.09 mm for the diameter and from 4.94 mm to 13.31 mm for the length. The increase in volume corresponded to a square root function with values ranging from 13.42 mm^3 to 173.96 mm^3. Analysis of arch of the aorta variations revealed 11 cases of a common trunk for the brachiocephalic trunk and the left common carotid artery and 7 cases with the left vertebral artery arising directly from the arch of the aorta. In 2 cases the brachiocephalic trunk was absent, the right subclavian artery branching directly from the arch of the aorta at the level of the left subclavian artery or from the descending aorta just below the arterial duct ostium.

Key words: human foetus, morphometric measurements, variability, aortic arch

INTRODUCTION

The primary arterial system undergoes many complicated changes during development. Between the first 6 and 8 weeks of foetal life primary arterial arches arise from the arterial sac to evolve into the final pattern of great arterial vessels. The left 4th arch builds the aortic arch, which grows intensively and joins the dorsal aorta [15].

The aortic arch is short and its limits are difficult to define. As the upper limit we assumed the level of the 2nd right sternocostal joint and as the lower the narrowing (often termed the isthmus) lying above the arterial duct ostium to the descending aorta. Arterial variations of the aortic arch appear as an increase or decrease in number of certain of its branches [2, 14, 16]. The differences may also concern the location and relationships of the arteries [10]. In some cases these anomalies do not influence the organism, but in others they can cause clinical symptoms such as dysphagia [4, 6]. The variability of branching sites of the aortic arch has been studied by various authors on the basis of adult autopsy specimens. In the present work morphometric studies were performed of the aortic arch in human foetuses in relation to developmental age. Furthermore analysis was made of the variability of the foetal aortic arch branching sites.

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MATERIAL AND METHODS

The study was performed on 103 human foetuses obtained from spontaneous abortions (58 female, 45 male) aged from 14 to 30 weeks of gestation. The foetal age (in weeks) was established by measuring the length of their humeral and femoral bones using USG equipment (Table 1). The foetal arteries were filled with latex and preserved in 4% formalin and then dissected under a surgical microscope. The dissected arteries were digitalised in 24 bit BMP. For approximation and scaling of the microscopic pictures (2272 × 1704 pix) the Olympus AnalySIS computer program was used. In order to make measurements of the vessels under examination, a special computer program, MORPHO04, was developed. The program's operation is based on B-splines modelled with Bezier's Curves generated over textured graphic (pictures) of the vessels examined (Fig. 1). Moreover, on the assumption that the vessel cross-section is circular, it was possible to calculate its volume [8].

The measurements were taken as follows: the external diameter, the length, and the volume of the aortic arch. The results were correlated to foetal age so as to establish the growth dynamics of the arteries.

To make the statistical analysis, the foetuses were split into 5 groups as follows: 14–16 weeks, 17–20 weeks, 21–24 weeks, 25–28 weeks and 29–30 weeks. These groups correspond to the 4th, 5th, 6th, 7th and 8th months of gestation.

Table 1. Distribution of foetal age and sex

Foetal age [weeks]	Number	Sex	
		Female	Male
14	1	0	1
16	5	3	2
17	10	4	6
18	3	2	1
19	14	10	4
20	9	6	3
21	19	11	8
22	17	9	8
23	12	8	4
24	3	1	2
26	3	0	3
27	5	4	1
29	1	0	1
30	1	0	1

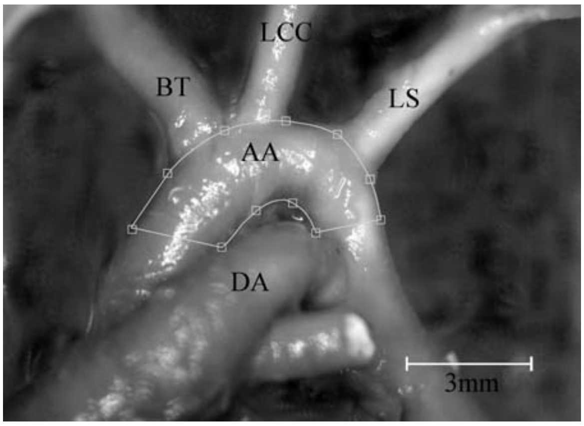


Figure 1. Foetal aortic arch with matched vector curves. AA — arch of aorta, DA — *ductus arteriosus*, BT — brachiocephalic trunk, LCC — left common carotid artery, LS — left subclavian artery.

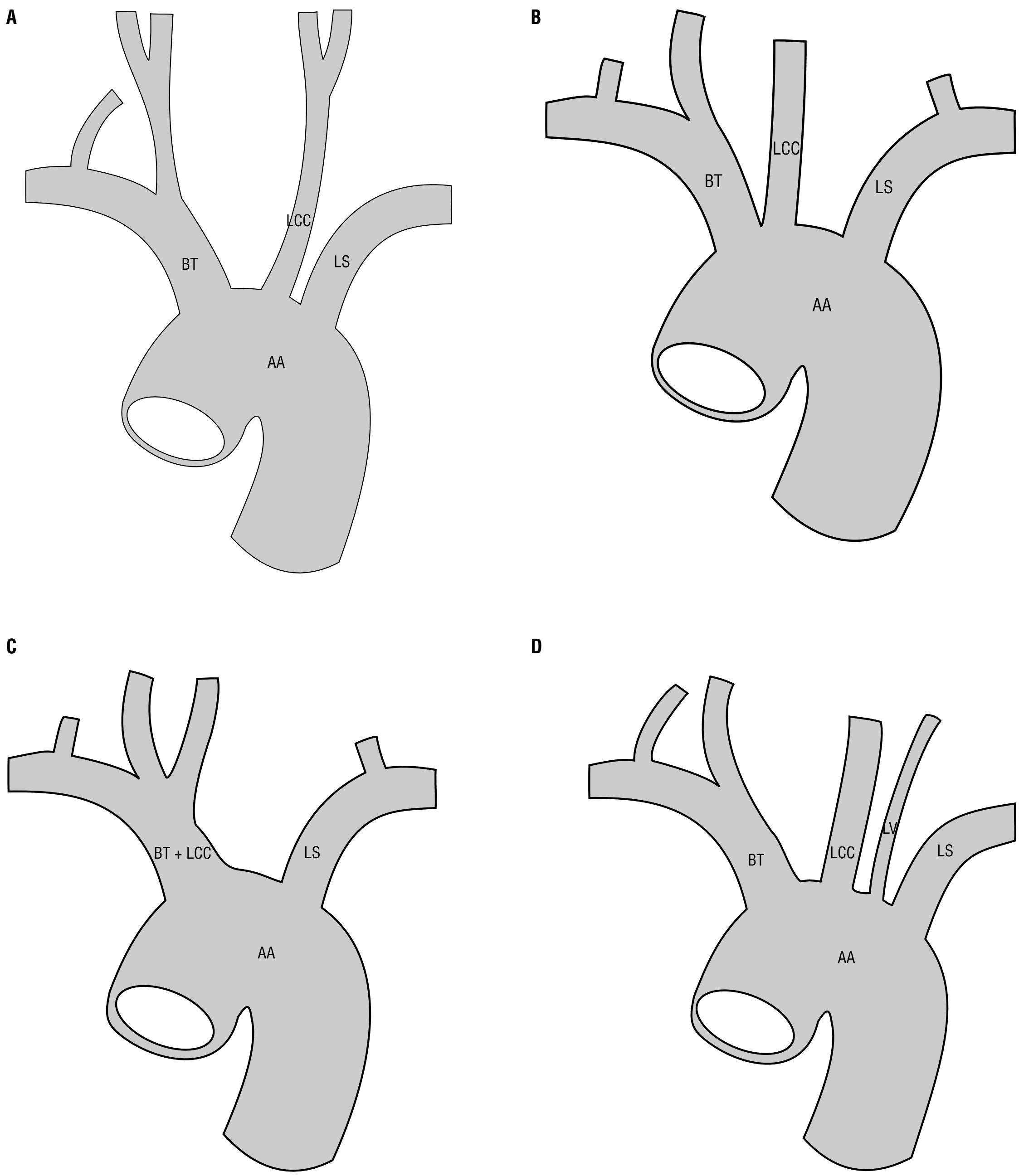
The results were analysed using statistical tests (ANOVA, NIR, and RIR) for equal and unequal amounts. The Pearson test, based on the method of the smallest squares, was used to establish the linear correlation for each parameter against gestational age. The results obtained were presented in tables and figures.

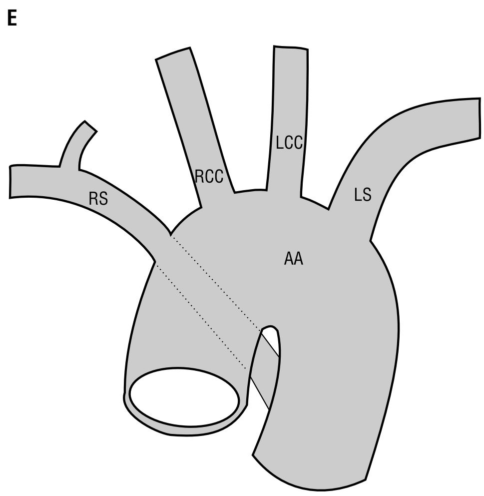
The aortic arch variations were analysed and different types of abnormalities in the origin and position of the aortic arch branches were distinguished based on Niżankowski's classification [13].

RESULTS

Variation analysis

Usually 3 main arterial trunks emerge from the aortic arch (Fig. 2A). The distances between their origins are the same, although the arteries can change their position, arising from a single arterial trunk or very close together. This usual pattern of 3 branches was found in 83 specimens (80.6%). In the remaining specimens (28 specimens — 27.2%) it was possible to distinguish aortic arches where the left common carotid artery branched very close to the brachiocephalic trunk (Fig. 2B). In 11 cases (10.7%), only a single arterial trunk was found for the brachiocephalic trunk and the left common carotid artery (Fig. 2C, 3). In 7 cases (6.8%) the left vertebral artery sprang directly from the aortic arch between the left common carotid and left subclavian arteries (Fig. 2D, 4). In one case the right subclavian artery originated from the posterior surface of the aorta at the level of the left subclavian artery, while in another case the right subclavian ar-





Figures 2A–E. Diagrams illustrating variations in the arch of the aorta. AA — arch of the aorta, BT — brachiocephalic trunk, LCC — left common carotid artery, LS — left subclavian artery, RCC — right common carotid artery, LV — left vertebral artery.

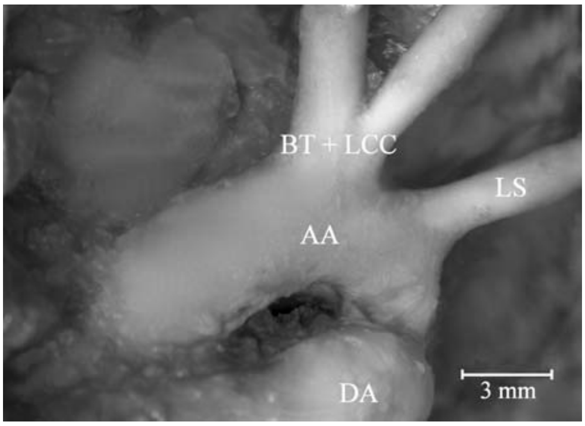


Figure 3. Single trunk for common carotid artery and brachiocephalic trunk. AA — arch of the aorta, DA — *ductus arteriosus*, BT + LCC — single trunk for the common carotid artery and brachiocephalic trunk, LS — left subclavian artery.

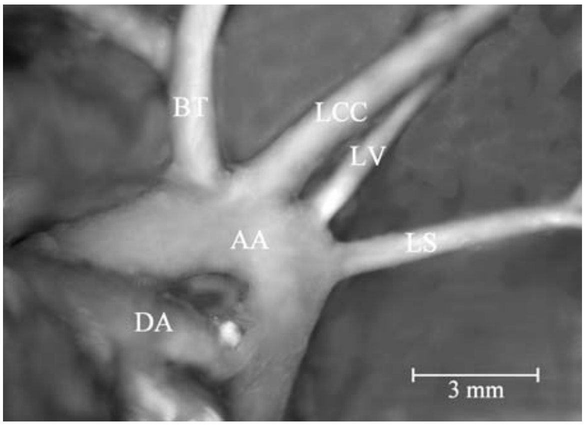


Figure 4. Left vertebral artery spreading out directly from the aortic arch. AA — arch of the aorta, DA — *ductus arteriosus*, BT — brachiocephalic trunk, LCC — left common carotid artery, LV — left vertebral artery, LS — left subclavian artery.

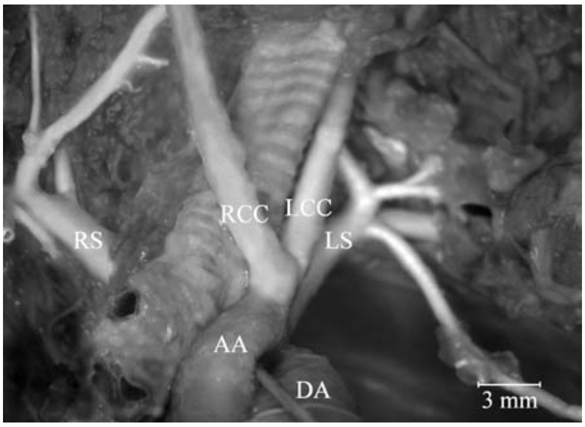


Figure 5. Right subclavian artery originating from the posterior surface of the aorta just below the arterial duct ostium, passing posteriorly to the trachea and oesophagus. AA — arch of the aorta, DA — *ductus arteriosus*, RCC — right common carotid artery, LCC — left common carotid artery, LV — left vertebral artery, LS — left subclavian artery.

tery originated from the descending aorta just below the arterial duct ostium (Fig. 2E, 5). In both cases the arteries were directed towards the right upper extremity, crossing the anterior surface of the vertebral column and passing posterior to the trachea and oesophagus, reaching the posterior cleft of the scalenus muscles.

Morphometric analysis

The values for all foetal age groups have been presented in Table 2.

The mean values of the aortic arch diameter ranged from 1.77 mm for the 14–16 week gestational group to 4.09 mm for the 29–30 week age group. With regard to foetal age, the diameter of the arteries increased according to the linear function $y = a + b * x$ with a correlation coefficient of 0.82. The results obtained were statistically significant ($p < 0.05$) (Fig. 6A) for each age group.

The length of the aortic arch ranged from 4.94 mm to 13.31 for the 14–16 and 29–30 week gestational groups respectively. With regard to the aortic arch diameter, the increase in the artery length was dependent on foetal age in accordance with the linear function $y = a + b * x$ with a correlation coefficient of 0.79 and the results obtained showed statistical significance ($p < 0.05$) (Fig. 6B).

The volume of the aortic arch ranged from 13.42 mm^3 to 173.96 mm^3 for groups of 14–16 weeks and 29–30 weeks of gestation respectively. The volume increase runs according to the square root model $y = (a + b * x)^2$ with a correlation coefficient of 0.86 and the results obtained were of statistical significance ($p < 0.05$) (Fig. 6C).

DISCUSSION

The aortic arch variations observed in the material under examination have been described earlier. Czerwiński et al. [6] reported on the basis of autopsy specimens (118 cadavers) one case in which the left vertebral artery sprang directly from the aortic arch and one case in which the right subclavian artery originated from the posterior wall of the descending aorta below the level of the left subclavian artery. Both the above-mentioned variations with respect to the position and number of the arteries were present in the material under examination. Czerwiński also analysed the clinical signs associated with aortic arch variations. In the first case no clinical symptoms were observed in connection with the variation. In second case difficulties in swallowing and in breathing were noted, especially during

Table 2. The diameter, length and volume values of the arch of the aorta (SD — standard deviation)

Foetal age group [weeks]	Diameter [mm]	SD	Length [mm]	SD	Volume [mm^3]	SD
14–16	1.77	0.42	4.94	0.73	13.42	8.08
17–20	2.52	0.40	6.62	1.15	35.05	16.32
21–24	2.91	0.38	8.09	1.33	55.52	18.61
25–28	4.07	0.27	10.19	1.22	132.61	27.33
29–30	4.09	0.26	13.31	1.10	173.96	7.88

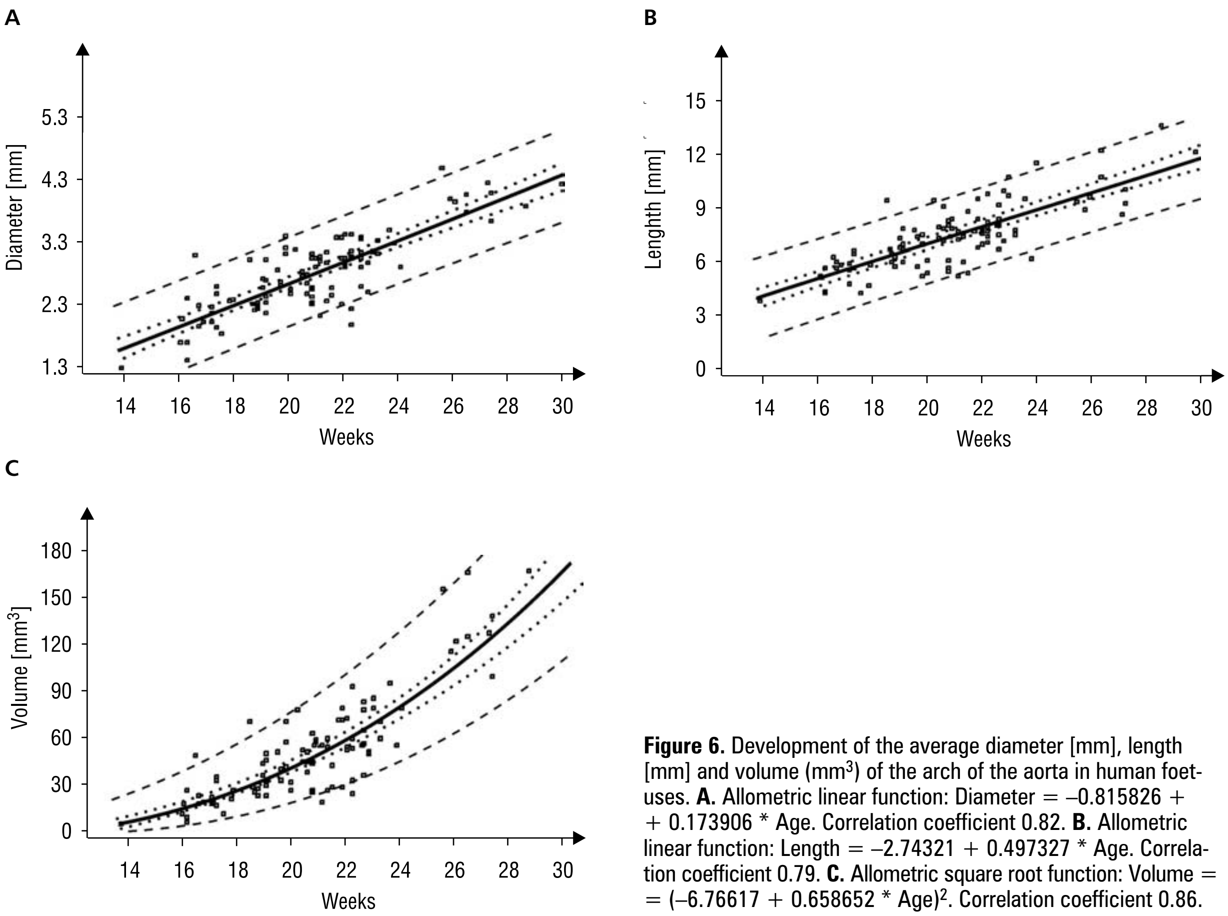


Figure 6. Development of the average diameter [mm], length [mm] and volume (mm^3) of the arch of the aorta in human foetuses. **A.** Allometric linear function: Diameter = –0.815826 + + 0.173906 * Age. Correlation coefficient 0.82. **B.** Allometric linear function: Length = –2.74321 + 0.497327 * Age. Correlation coefficient 0.79. **C.** Allometric square root function: Volume = = (–6.76617 + 0.658652 * Age)^2. Correlation coefficient 0.86.

upper limb abduction. Similar variations were described by Aleksandrowicz [2] and Lize [11], also on the basis of autopsy specimens. In Sora's et al. [16] investigation a case of a single arterial trunk for the brachiocephalic trunk and left common carotid artery was analysed. In Niżankowski's work [13] the variation was described as present in 0.9% of the specimens examined, while we noted it in 7 specimens (8%). Roguin et al. [14] analysed the case of a 6-day-old infant with a single arterial trunk arising from the aortic arch, from which emerged the right subclavian, both carotid arteries and the left subclavian artery. The single trunk presence was associated with coarctation of the aorta and patent *ductus arteriosus*. Białowąs et al. [4] noted 3 cases of a right-sided aortic arch which passed beyond or in front of the oesophagus and trachea. The variations in great arterial trunks in association with pathological changes to the heart, such as interventricular septal defects in human foetuses, were described by Moulaert et al. [12]. Kozielec [10] described the case of a left subclavian artery arising from the *ductus arteriosus*. These anomalies were absent in the material under examination.

In the morphometric studies, it was found that the increase in the aortic arch external diameter was in accordance with a linear function in relation to foetal age. Hyett et al. [9] obtained similar results from a study of human foetuses of between 9 and 18 weeks of gestation. Ursell et al. [17] also noted linear growth of this parameter in relation to age when analysing the internal diameters of the great vessels in human foetuses from 10 to 26 weeks of gestation. Alvarez et al. [3] observed correlations between foetal weight and length and aortic arch diameter.

The results obtained from autopsy specimens have been confirmed by clinical examinations using echocardiography or ultrasonography. According to many authors [1, 3, 5, 7] the increase in the diameter of the aortic arch has a close linear correlation to foetal age.

The present studies on autopsy material have confirmed the linear growth of the diameter and length according to foetal age and, furthermore, provide data on the type of volume increase. It was found that volume growth is in accordance with a square root function.

The method used has a high degree of accuracy in view of the introduction of the main principles of vectorial computer graphics. The high sensitivity of this method allows precise evaluation of the morphometric parameters of the vessels. As a result, the digital measurements made in accordance with Bezier's Curves, are more precise than those solely made with a raster image visible on the computer screen.

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