

Determinants and a Predictive Equation for the Aortic Length Estimation

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ABSTRACT: Aortic length is one of the important parameters in pulse wave analysis, which is widely used for arterial stiffness assessment. Accurate measurement of aortic length in routine medical practice is still not achieved. Non-invasive approximation to the distance between some sites on body surface is greatly affected by not allowed to correction factors. Invasive methods are more accurate, but not suitable for routine use. Other approaches are based on the estimation of aortic length by using either demographic or anthropometric parameters, or their different combinations. Our investigation was oriented towards the evaluation of the impact of demographic and anthropometric data to aortic length and the construction of a predictive equation for the aortic length estimation. Aortic length, measured on computed tomography (CT) images, was taken as actual aortic length and used in multiple linear regression analysis as a dependent variable for construction of the equation for aortic length estimation. It was demonstrated that about 65 per cent of the variations in aorta length could be explained by such determinants as height, weight and age. The equation-derived aortic length showed better accuracy than the aortic length estimated by approximation to jugulum-symphysis distance when compared with actual aortic length.

KEYWORDS: Aortic length, Pulse wave velocity, Jugulum-symphysis distance, Equation.

I. INTRODUCTION

The estimation of aortic length is a subject of scientific research interest mostly in the context of arterial stiffness investigation. Arterial stiffness (AS) is one of the earliest detectable manifestations of adverse structural and functional changes within the vessel wall [2] and the evaluation of AS was included in the ESH/ESC guidelines for the management of arterial hypertension.

The most validated methodology for arterial stiffness investigation is connected with the estimation of pulse wave velocity [2, 13]. Pulse wave velocity is estimated as the ratio between the distance travelled by pulse - aortic length and the pulse wave travelling time. The pulse wave travelling time can be recorded easily by most devices used in pulse wave analysis, but the determination of aortic length is the source of trouble.

Several studies have been oriented to the direct measurement of aortic length and different segments of aorta by using different imaging techniques, such as magnetic resonance imaging (MRI) [1, 3, 7, 8, 22, 26] or CT technique [9, 18, 20, 21, 28]. Although the direct investigation appears to be the most accurate, it cannot be widely used in routine medical practice because of the invasiveness of this approach.

Thus, there is a pressing necessity to estimate aortic length noninvasively, that means – indirectly, using the approximate assessment of aortic length through the appointed projection sites of aorta on body surface. The distance between the palpable upper edge of sternum (jugulum) and the recorded point on the femoral artery usually corresponds to the length of the carotid-femoral segment, whereas the distance between the jugulum and the upper edge of the symphysis pubica (Jug-Sy) corresponds to the length of the whole aorta. The distance measurement on body surface has both theoretical and practical reasons to be biased from actual aortic length. The most commonly used tape

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measurement method is greatly affected by the body surface curvature, like large bust and abdominal obesity [1, 11, and 25]; the morphology of the aorta is not also taken into account with this method [2]. A more accurate calliper measurement method is not affected by the body curvature, yet is not enough precise either as it fails to consider the morphology of the aorta [2]. There are also some additional limitations to the most commonly used carotid-femoral estimation, an admixture of data from two circulatory branches – aortic-carotid and aortic-femoral [6, 10, and 26]. In this case, the arterial segments are not straight [25] and can overestimate the aortic length by approximately 25% [23]. Taking into consideration that a direct, invasive determination of aortic length in routine medical practice cannot be achieved, and indirect, non-invasive measurements are biased from actual aortic length to a greater or lesser extent, some investigators have tried to find other approaches. They have calculated the aortic length, based on age [4] or other anthropometric data, such as height [5, 7, 22, 23, 24, 28] as well as body shape, size and weight [3, 9] of subjects. The results of these studies differ much in details.

The aim of the present investigation is to evaluate the impact of demographic and anthropometric determinants to aortic length, as well as to assess the possibility of the construction of a predictive equation for the aortic length estimation, based on the results of this evaluation. To achieve this goal direct, actual aortic length measurements on CT images and statistical assessment of the impact of demographic and anthropometric determinants to the actual aortic length with the final construction of the predictive equation for the aortic length estimation was carried out.

II. MATERIALS AND METHODS

Subject selection

44 subjects were selected retrospectively from the database of a previously carried out cross-sectional population based study of 1,026 people from Tallinn, Estonia [12]. The criteria for selection were the absence of aortic diseases and the availability of the images of CT scan covering at least thoracic, abdominal and pelvic regions. These scans had to be performed to some of the participants due to medical indications and within the time frame of the basic study.

The data on age, weight, height and body mass index (BMI) of the selected 44 subjects as well as Jug-Sy distance were previously collected during the above-mentioned study [12] and used in the current investigation.

CT studies

Estonian citizen identification code numbers of all the subjects from the above-mentioned cross-sectional population-based study were used to record CT scan data from the Estonian Picture Archiving and Communication System (PACS) database. Only the CT scans performed within the time frame of the basic study that cover at least thoracic, abdominal and pelvic regions were chosen from the recorded CT scans. Finally, CT images of 44 subjects were selected based on the above-mentioned criteria.

CT studies were performed using the GE Discovery 750HD scanner (General Electric, USA). Image processing workstation (Advanced Workstation, General Electric, USA) was used for the aortic length measurements on the CT images. To ensure accurate measurements contrast-enhanced axial CT images acquired with thin-collimation (slice thickness 0.625 mm) were used for analysis. The aortic length measurement on CT images was processed by the author as a specially trained investigator under the supervision of an experienced radiologist.

Aortic length measurement on CT images

The length of aorta was measured on the contrast-enhanced CT images from the level of the aortic valve to the aortic bifurcation along the aortic centreline. The levels of aortic valve and aortic bifurcation were carefully defined using both axial and coronal planes. The whole aorta was segmented on CT images by depositing at least ten points inside the aortic lumen. The quality of segmentation was checked to ensure that only the aorta without the surrounding tissues was included in the segmented volume and that the aortic luminal centreline was properly identified by the software. If necessary, additional points inside the aortic lumen were deposited to achieve aortic segmentation in the areas of the

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reduced contrast between contrast media in the aorta and the surrounding tissues. Subsequently the length of aorta was measured along the centreline of the segmented aorta. The measurement results were recorded in millimetres and rounded to the nearest 1.0 cm before the statistical evaluation.

Statistical analysis

Statistical analysis was performed with SPSS 17.0 statistical software (SPSS Inc., Chicago, IL, USA) [17, 27]. Normality of data distribution was assessed by complex criteria for normality. The distribution of variables was treated for skewness, kurtosis and outliers. Kolmogorov-Smirnov and Shapiro-Wilk normality test, as well as normality plots were investigated and assessed.

Multiple linear regression analysis with a stepwise approach was applied to treat the correlations between dependent and independent variables. Actual aortic length - length from the aortic valve to the bifurcation of the aorta measured on CT images, was taken as a dependent variable while age, height, weight, BMI and Jug-Sy distance were used as independent variables. The combination of variables with a significant correlation and maximum value for adjusted R-square was elicited and used for the construction of a prediction equation for aortic length.

Consequently aortic length was calculated by the constructed predictive equation. Then we evaluated the agreement between the equation-derived and the actual aortic length and compared it with the agreement between the estimated by approximation to Jug-Sy distance aortic length and actual aortic length.

The study was done in accordance with ethical standards of the responsible committee on human experimentation and with the Helsinki Declaration of 1983.

III. RESULTS

Descriptive Statistics of the study population

Table 1 Descriptive Statistics

Variable/units	N	Range	Minimum	Maximum	Mean	Standard Deviation (SD)	95% Confidence Interval (CI)
Age years	44	38	26	64	51.2	10.2	31-71
Height cm	44	34,0	150,0	184,0	168.8	8.9	150.8-185.8
Weight kg	44	69,6	48,0	117,6	79.7	14.7	50.2-107.8
BMI kg/m ²	44	21	19	40	27.9	4.9	18-38
Jug-Sy cm	44	14	44	58	50.3	3.7	43-58
Actual aortic length cm	44	19	39	58	47.5	4.4	39-56

Table 1 shows the descriptive statistics of the population under investigation. Since not all of the variance met ideally the criteria for the normality in distribution, the 95% CI is shown additionally to the mean and the SD.

The study included 44 subjects, of which 19 men and 25 women. Sex and age-defined subgroups were neither defined nor investigated separately because of the insufficient sample size in these subgroups.

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Analysis of variables for normality of distribution

Table 2 Summary of accordance to the criteria for normal distribution

Variable	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Overall decision
	Mean and median difference	Mean \pm 2 SD	SD <1/2 mean	Skewness and kurtosis	Critical values	Kolmogorov-Smirnov / Shapiro-Wilk tests	Plots	
Age	Yes	Yes	Yes	Yes	Slightly deviated	Yes/No	Probably normal	Slightly deviated
Height	Yes	Yes	Yes	Yes	Yes	Yes/Yes	Yes	Yes
Weight	Yes	Yes	Yes	Yes	Yes	Yes/Yes	Yes	Yes
BMI	Yes	Yes	Yes	Yes	Yes	Yes/Yes	Yes	Yes
Jug-Sy	Yes	Yes	Yes	Yes	Yes	No/No	Yes	Yes
Actual aortic length	Yes	Yes	Yes	Yes	Yes	No/Yes	Yes	Yes

Table 2 shows the summary of the estimation of the normality criteria results. "Yes" indicates the accordance to the normality criterion and "No"- not in accordance. Each of the criteria has its own identification by index number.

The detailed data on the investigation of the normality with the results for each variable across all criteria are presented below in Tables 3 – 6 according to its index numbers.

Table 3 Detailed summary of accordance to the criteria 1, 2 and 3 for normal distribution

Variable/ units	Range	95% CI	Mean and median difference	Median	Mean	1/2 of mean	SD	Mean \pm 2SD	Mean \pm 3SD
Age years	26 - 64	31-71	-1,8	53,0	51,2	25,6	10,2	31-72	20-82
Height cm	150,0 -184,0	150,8-185,8	0,8	168,0	168,8	84,4	8,9	150,9-186,6	142,0-195,6
Weight kg	48,0 – 117,6	50.2-107.8	0,6	79,1	79,7	39,8	14,7	50,3-109,1	35,5-123,8
BMI kg/m ²	19 - 39	18-38	0,9	27,0	27,9	14,0	4,9	18-38	13-43
Jug-Sy cm	44 - 58	43-58	0,3	50,0	50,3	25,1	3,7	43-58	39-61
Actual aortic length cm	39 - 58	39-56	0,5	47,0	47,5	23,7	4,4	39-56	34-61

Table 3 shows data for the assessment of normality by criteria 1, 2 and 3. All the investigated variables were complied with normality by these criteria.

Table 3 shows that the differences between the mean and the median (criterion1) were small for all of the variables, suggesting a normal distribution. One of the other features of normal distribution is that 95% of the data might lie

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within the interval of mean ± 2 SD (criterion 2). As shown in Table 3, the estimated 95% CI was within or close to the actual range of the mean ± 2 SD for all investigated variables. Criterion 3 expresses the rule of thumb regarding the ratio between the standard deviation and the one-half of the mean. All investigated variables were complied with normality due to their standard deviation being not larger than one-half of the mean. It is possible to assess additionally the outliers by data of Table 3. The outliers, neither univariate nor multivariate, do not exist because the complete data of all variables lie within 3 standard deviations above and below the means of corresponding variables.

Table 4 Detailed summary of accordance to the criteria 4 and 5 for normal distribution

Variable	Skewness			Kurtosis		
	Statistic	Std. Error	Critical value	Statistic	Std. Error	Critical value
Age	-,783	,357	-2,19031	-,076	,702	-0,10831
Height	-,017	,357	-0,04787	-1,037	,702	-1,47854
Weight	,201	,357	0,562529	,029	,702	0,041687
BMI	,091	,357	0,253333	-,475	,702	-0,6768
Jug-Sy	,196	,357	0,549336	-,815	,702	-1,16114
Actual aortic length	,436	,357	1,219611	-,201	,702	-0,28651

Table 4 shows data for the assessment of normality by criteria 4 and 5 with detailed results for skewness and kurtosis.

Skewness and kurtosis statistical values of almost all variables lie between (-1) and (+1), which indicates the normality. One kurtosis value slightly deviating from this range (-1.04) is observed for height, indicating that the distribution tends to be flat, but is still appropriate for normality.

Critical value is the other criterion for the assessment of normality. Being calculated by dividing skewness and kurtosis by their standard errors, it must be in the range of (-1.96) to (+1.96). All variables passed the test properly, only the critical value for age was slightly over the range (-2.19), that showed the tendency of age distribution to be slightly biased to the left.

Table 5 Detailed summary of accordance to the criterion 6 for normal distribution

Variable	Kolmogorov-Smirnov test			Shapiro-Wilk test			Kolmogorov-Smirnov / Shapiro-Wilk
	Statistic	df	Sig. (P-value)	Statistic	df	Sig. (P-value)	
Age	,115	44	,172	,928	44	,009	Yes/No
Height	,119	44	,132	,961	44	,145	Yes/Yes
Weight	,102	44	,200	,985	44	,833	Yes/Yes
BMI	,108	44	,200	,980	44	,616	Yes/Yes
Jug-Sy	,132	44	,052	,948	44	,048	No/No
Actual aortic length	,140	44	,030	,971	44	,333	No/Yes

Table 5 shows data for the assessment of normality by criterion 6 with detailed results of Kolmogorov-Smirnov and Shapiro-Wilk tests.

Table 5 shows that only height, weight and BMI are in accordance with the both criteria for normality. P-value for Jug-Sy is approximately 0.05 in both tests, which indicates that the distribution is significantly different from normal. Shapiro-Wilk test for aortic length is in accordance with normality, while Kolmogorov-Smirnov test is not. Normality test results for age are opposite to the results for actual aortic length.

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Table 6 Detailed summary of accordance to the criterion 7 for normal distribution

Variable	Histograms	Normal Q-Q plot	Detrended normal Q-Q plot	Box plot (no extreme values)	Box plot (median in centre)	Assessment of the normality plots
Age	Probably	Slight deviation	Probably	Yes	Slight deviation	Slight deviation
Height	Yes	Yes	Yes	Yes	Slight deviation	Yes
Weight	Yes	Yes	Yes	Yes	Yes	Yes
BMI	Yes	Yes	Yes	Yes	No	Yes
Jug-Sy	Probably	Yes	Yes	Yes	Yes	Yes
Actual aortic length	Yes	Yes	Yes	Yes	Yes	Yes

Table 6 consists of the summaries from normality tests of different plots assessment. The assessment of all plots is summarized in the last column.

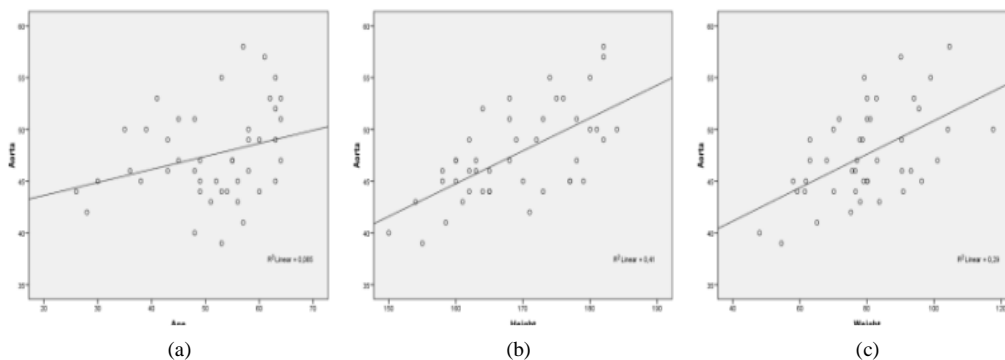
The histogram shape for height, weight, BMI and aortic length showed to be not ideal, but a satisfactory approximation to a bell-curve. Histograms curves for age and Jug-Sy were poorer than expected, but still acceptable. The normal and detrended Q-Q plots of all variable data showed slight deviations from the normal distribution. Normal Q-Q plot for age showed a slightly larger, albeit still acceptable deviation of data points from the linear progression. Detrended Q-Q plot for age showed the horizontal line biased to the top with approximately equal spread of points around it. The boxplot symmetry to the median line was acceptable for weight, Jug-Sy and actual aortic length. For BMI, height and age values the symmetry is slightly disturbed.

Final results of the assessment of variables by different normality criteria have been transferred from Tables 3,4,5,6 into Table 2 and the overall decision has been made based on all the observed results for the normality criteria. Table 2 shows that the results on height, weight and BMI variables are in good agreement with normality tests across all criteria. Jug-Sy and actual aortic length variables have passed almost all tests, except one. Age value distribution is characterized with slight deviation from normality, skewed with tail to the left and has not passed one of the tests. In spite of this bias at some skewness criteria, age is considered as approximately normally distributed because the mean value is a good estimate of the centre of data.

Thus, taking into consideration all the results together, all variables have been recognized as normally or approximately normally distributed and allowed to parametric statistic.

Assessment of an association between the actual aortic length and age, length, weight, BMI and Jug-Sy

Pearson`s correlation coefficients and scatter plots have been obtained for the assessment of associations between variables.



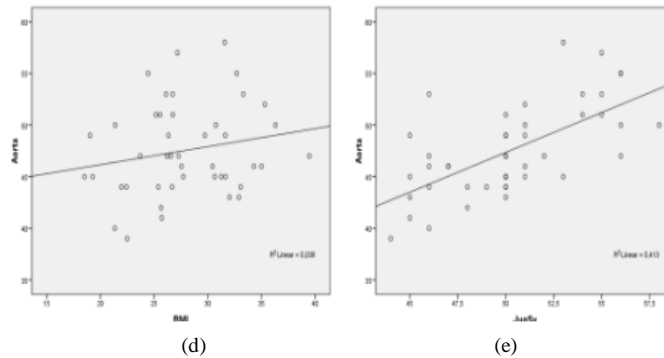


Fig. 1 shows scatter plots for the associations between investigated variables: actual aortic length and age (a), actual aortic length and height (b), actual aortic length and weight (c), actual aortic length and BMI (d), actual aortic length and Jug-Sy (e).

The scatter plots shown in Fig.1 indicate a positive linear association of the actual aortic length with all variables. Among them, the scatter around the plot is narrower for height (b) and Jug-Sy distance (e) and slightly wider for weight (c). Aorta association with age (a) is very weak and the weakest one is with BMI (d).

Table 7 Correlation coefficients

		Actual aortic length	Age	Height	Weight	BMI	Jug-Sy
Actual aortic length	Pearson Correlation	1	,292	,640	,538	,195	,642
	Sig. (2-tailed)		,027	,000	,000	,205	,000

Table 7 shows the correlation coefficients between actual aortic length and age, height, weight, BMI and Jug-Sy.

The comparison of the correlation coefficients in Table 7 shows the same tendency as the scatter plots: the best predictors of aortic length are height and Jug-Sy, the association with weight is slightly lower, but still highly significant at the $P < 0.0001$ level. The relation between aortic length and age is still significant ($P < 0.05$), but it is not significant for BMI.

Assessment of the impact of demographic and anthropometric data on the actual aortic length and the building of a predictive model for aortic length estimation

Although not all variables showed equally good correlation with actual aortic length, it was decided to include all the variables with significant correlation into the investigation of their impact on the changes in the aortic length. Thus, actual aortic length as a dependent variable and height, weight, age and Jug-Sy – as independent variables were treated by a standard linear regression approach with a stepwise method.

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Table 8 Summary of the stepwise analysis

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	R	R Square	Adjusted R Square
	B	Std. Error	Beta					
1 (Constant)	8,795	7,151		1,230	,226	0,642	0,413	0,399
Jug-Sy	,771	,142	,642	5,433	,000			
2 (Constant)	6,757	6,426		1,052	,299	0,736	0,541	0,519
Jug-Sy	,632	,133	,527	4,740	,000			
Weight	,113	,033	,377	3,388	,002			
3 (Constant)	-6,219	8,521		-,730	,470	0,769	0,591	0,560
Jug-Sy	,414	,162	,345	2,559	,014			
Weight	,099	,033	,328	3,023	,004			
Height	,149	,068	,301	2,198	,034			
4 (Constant)	-20,120	8,676		-2,319	,026	0,833	0,694	0,663
Jug-Sy	,140	,166	,117	,846	,403			
Weight	,082	,030	,274	2,789	,008			
Height	,273	,071	,551	3,843	,000			
Age	,157	,047	,363	3,337	,002			
5 (Constant)	-21,323	8,528		-2,500	,017	0,822	0,676	0,651
Weight	,083	,029	,275	2,813	,008			
Height	,316	,050	,637	6,372	,000			
Age	,176	,041	,408	4,331	,000			

Table 8 shows the summary of the stepwise analysis. The results of contribution of different combinations of independent variables to aortic length and R-square values are presented.

The first model of stepwise analysis with Jug-Sy distance as the only independent variable, has been recognized as not reliable because (as it is shown in Table 8) the constant in Jug-Sy predictable model is not significant ($P = 0.226$). The summary of stepwise analysis shows that despite good correlation ($R = 0.642$) between Jug-Sy and aortic length, the changes in Jug-Sy can describe only approximately 40% (adjusted R Square = 0.399) of changes in aortic length. The second, the third and the fourth models are also not reliable because either the constant or the coefficient of one of the variables in the models is not significant.

Thus, the model five, which includes weight, height and age for actual aortic length prediction, has been chosen as more appropriate. The model five represents significant correlations between the actual aortic length and age, height and weight and also demonstrates the relative importance of each independent variable through the standardized coefficients, or beta weights, that are independent from the units in which the measurement of variables is done. The model five demonstrates that height (beta=0.637, $p < 0.0005$) influences aorta length more than age (beta=0.408, $p < 0.0005$) and the influence of weight (beta=0.275, $p < 0.008$) is weak in the investigated population. The standardized Coefficient R (=Pearson's product moment correlation coefficient r) demonstrates strong ($R = 0.822$) relationship between actual aortic length and age, height and weight, taken all together. The coefficient of multiple determinations (adjusted R Square) shows that 65 per cent of variations in aorta length of the investigated population can be definitely explained by the combination of age, height and weight.

The distribution of the residuals was checked for normality of distribution by test for normality (Table 9) and different plots for a standardized predicted value (Fig. 2), a standardized residual (Fig. 3) and a regression standardised residual (Fig. 4).

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Table 9 Tests of Normality

	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Standardized Predicted Value	,118	44	,140	,966	44	,209
Standardized Residual	,053	44	,200	,993	44	,994

Table 9 shows the results of Kolmogorov-Smirnov and Shapiro-Wilk tests for a standardized predicted value and a standardized residual.

A standardized predicted value and a standardized residual showed a slight deviation from normality, as it is demonstrated by test of normality (Table 9).

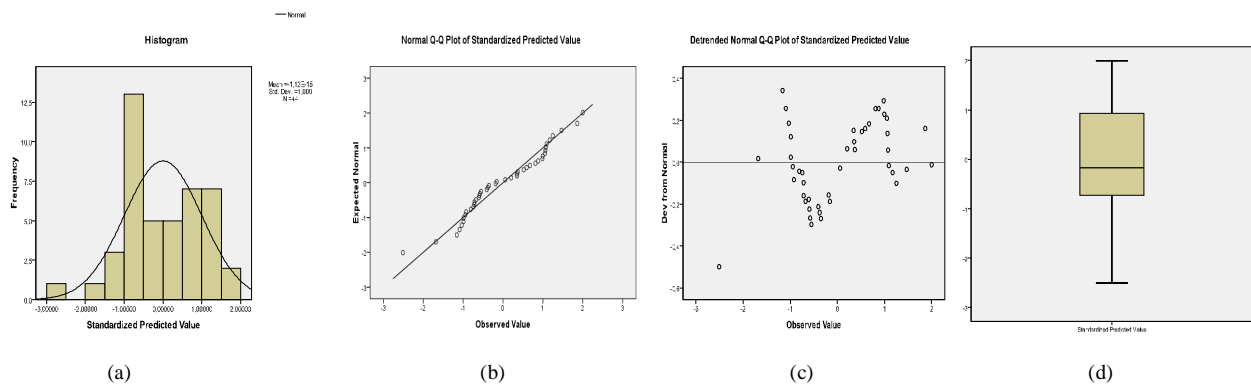


Fig.2 shows plots for a standardized predicted value: histogram (a), normal Q-Q plot (b), detrended Q-Q plot (c) and box plot (d).

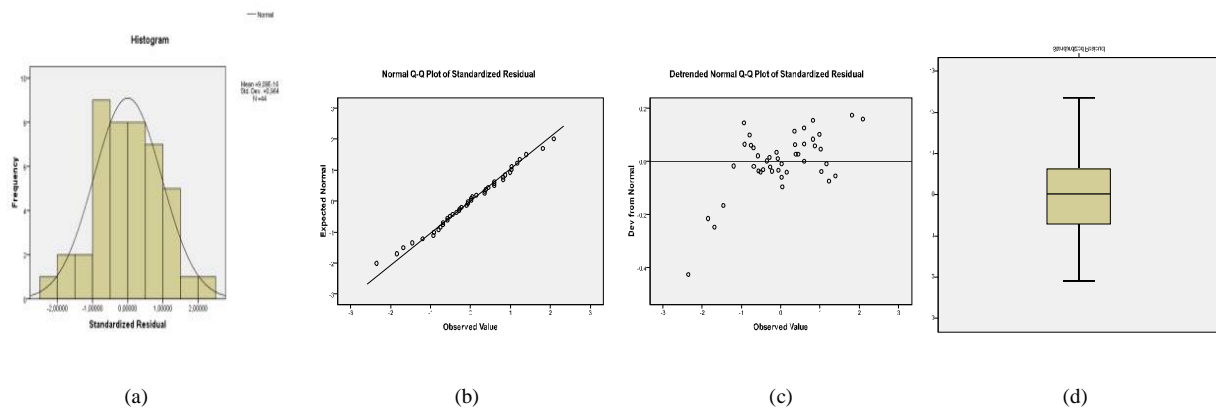


Fig. 3 shows plots for a standardized residual: histogram (a), normal Q-Q plot (b), detrended Q-Q plot (c) and box plot (d).

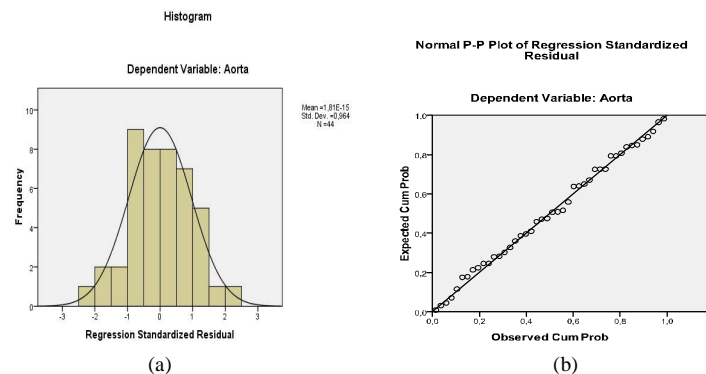


Fig. 4 shows plots for a regression standardised residual: histogram (a) and normal P-P plot (b).

The histogram shapes for a standardized residual and a regression standardised residual showed to be not an ideal, but a satisfactory approximation to a bell-curve. Histogram curve for a standardized predicted value was poorer, but still acceptable. The normal and detrended Q-Q plots showed slight deviations from the normal distribution for all parameters, with the poorer result for a standardized predicted value. The boxplot symmetry to the median line was acceptable for standardized residual and slightly disturbed in standardized predicted value distribution.

Predictive equation for the aortic length estimation

Data from all of 44 subjects was used for the construction of the predictive model for the aortic length estimation. The equation of the relationship between the dependent variable and three independent variables are generally expressed as:

$$Y = a + b_1x_1 + b_2x_2 + b_3x_3$$

The values of parameters for construction of the predictive equation for aortic length estimation were taken from the Table 8: $a = -21.323$ as Constant coefficient, the slopes of the regression line $b_1 = 0.176$ as coefficient for age (x_1 , in years), $b_2 = 0.316$ as coefficient for height (x_2 , in cm) and $b_3 = 0.083$ as coefficient for weight (x_3 , in kg).

Using these values, the equation was written the following way:

$$L = (-21.323) + 0.176 * (age) + 0.316 * (height) + 0.083 * (weight)$$

where L is the equation-derived aortic length.

Validation of the aortic length calculated by the constructed equation and aortic length estimated by approximation to the Jug-Sy distance against the actual aortic length

The aortic length of each subject was calculated according to the constructed equation. The means of actual aortic lengths and equation-derived were about equal: 47.6 (CI 40.5 – 54.8) cm and 47.5 (38.9 -56.2) cm, accordingly.

To assess whether there was a systematic bias [27] of the calculated length from actual aortic length, paired samples T-test for the mean differences between both measurement techniques was applied. The mean differences between the aortic length calculated by equation and the actual one approximated zero (0.09) and was not significant ($P=0.811$). This result indicates that there was no systematic bias of aortic length calculated by the equation from the actual one.

On the contrary, the mean of differences between Jug-Sy distance and the actual aortic length was far from zero (2.7) and $P<0.0005$ was significant. This result indicates that the Jug-Sy distance was systematically biased from the actual aortic length.

To visualize the bias of both techniques from actual aortic length, the graphic approach was used.

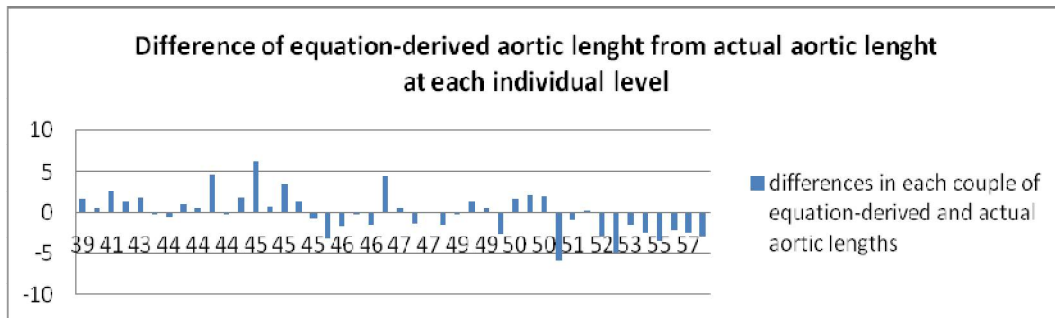


Fig. 5 shows the differences in couple of equation-derived aortic length and actual aortic length at each individual level.

The differences between each of 44 pairs of aortic length were calculated. In Fig.5 each pair of measurements is presented by an individual point. Actual aortic length value was plotted on X-axis as a zero line and a bias of each pair - on Y-axis. As it is shown in Fig.5, the aortic length calculated by the equation was about symmetrically distributed around zero at the values up to 51 cm, with only a slight prevalence of positively biased values. In the short interval of values above 51 cm there was the underestimation of calculated length in prevalence. To elucidate if the aortic length calculated by the equation is in better agreement with the actual aortic length than the Jug-Sy distance, the same graphic approach was applied to the comparison of the Jug-Sy distance with the actual aortic length (Fig. 6).

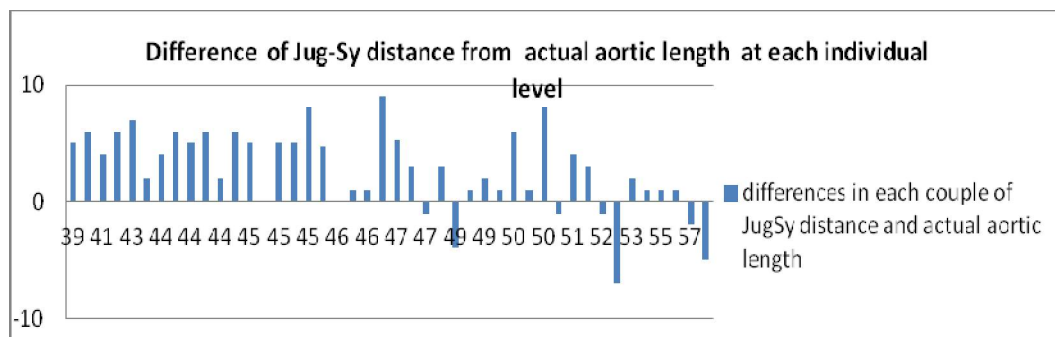


Fig. 6 shows the differences in couple of Jug-Sy distance and actual aortic length at each individual level.

As shown in Fig. 6, the Jug-Sy distance was systematically positively biased almost at all the aortic length levels, with negative bias at a few points. The bias at smaller aortic length values up to 51 cm was more prominent than at greater values of aortic length.

Thus, the observation of Fig.5 and Fig.6 showed that while the equation-derived aortic length was not biased in any systematic way in the range of measurement up to 51 cm, the Jug-Sy distance showed a systematic positive bias in the whole range of measurement.

Validation of the constructed equation on the other population against invasively measured aortic length

Weber et al [28] study has attracted our attention because the same part of aortic length was considered – i.e. from the ascending aorta to the aortic bifurcation. In contrast to our non-invasive investigation, the measurement technique for the estimation of aortic length [28] was invasive, that provided the most accurate measurement.

Weber et al [28] study was done during cardiac catheterization on 135 patients and aortic length was determined by catheter length. The mean values of age, height and weight of patients were slightly bigger than in our investigation: 60.3 vs. 51.2 years, 170.5 vs. 168.8 cm and 81.6 vs. 79.7 cm, respectively.

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We tried to predict the mean of aortic length for Weber et al [28] study population, applying mean values of age, height and weight of that population to our equation.

$$L = (-21.323) + 0.176 * (age) + 0.316 * (height) + 0.083 * (weight) = \\ = (-21.323) + 0.176 * (60.3) + 0.316 * (170.5) + 0.083 * (81.6) = 49.9$$

Thus calculated by our equation aortic length (49.9 cm) was found exactly the same as the invasively measured one reported in the Weber et al [28] study (49.9 cm).

IV. DISCUSSIONS

To the best of our knowledge, the present study is the first study oriented to the estimation of the length of the whole aorta from the aorta valve to the bifurcation that was performed on the CT images and resulted in the construction of the equation. Also it was statistically demonstrated that the equation describes 65% of the investigated population based on age, height and weight of subjects.

Our investigation showed that the estimation of aortic length by the constructed equation was more accurate than that based on the approximation to the Jug-Sy distance. Aortic length approximation to Jug-Sy distance corresponded to the actual aortic length only in about 40% of the investigated population and demonstrated a systematic positive bias from actual aortic length. The equation-derived aortic length showed no systematic bias, although indicated some tendency to overestimation at shorter and underestimation at longer actual aortic lengths.

Although in our previous work [18] we used the similar CT approach to the aortic length estimation, there are some fundamental distinctions. In the previous study we measured the longer aortic segment than in the present study, from aortic valve to the bifurcation of the left common femoral artery, the measurement technique on CT images was not described in detail, only four subjects were investigated and only the determinants in the form of age and Jug-Sy distance were treated. The measured range of Jug-Sy distance was 50 – 57 cm, while the ranges presented in this study are from a more extensive range of 44 - 58 cm, probably since more subjects were investigated. The correlation coefficients in the previous work were very similar to the finding in the present work: for Jug-Sy distance - 0.686 and 0.642, and for age - 0.248 and 0.292, accordingly. Despite the positive correlation of Jug-Sy distance with the aortic length, it was not applied to the predictive equation in the present study because of the results of statistical analysis.

Some investigators also compared Jug-Sy distance and actual aortic length. Although their methods differed from ours, the estimated distances were very similar, thus interesting for comparison. Rezai et al [20] investigation was done on MRI and a shorter aortic segment without the length of ascending aorta. Similarly to our study, they discovered that Jug-Sy distance was longer than the actual aortic length, although the mean difference was about 4 cm bigger than in our study. However, the discrepancy becomes minimal, if we take into account that they compared Jug-Sy distance with a shorter aortic segment. The omitted part of aorta was reported in their work as 4.7 cm. Weber et al [28] measured the aortic distance invasively by catheter length, extended from ascending aorta to bifurcation and compared it with Jug-Sy distance. According to their results, the mean of aortic length and Jug-Sy distance were slightly longer than in our study - 49.9 cm vs. 47.5cm and 54.1 cm vs. 50.3 cm, respectively. It can be logically explained by the positive bias in demographic data values of their investigated population in comparison with our investigated population, especially in the mean of age (60.3 vs. 51.2 years), height (170.5 vs. 168.8 cm) and weight (81.6 vs. 79.7 kg), respectively.

Some investigators estimated the aortic length by approximation to other distances on the body surface, such as the most usually used carotid-femoral length. Their results are not directly comparable with our results because the carotid-femoral distance is anatomically longer than Jug-Sy measured in our study. However, they also found that the distance measured on the body surface was longer than actual aortic distance. Thus Huybrechts et al [8] showed that the tape measurement from the body surface multiplied by 0.8, gives an acceptable correlation with a real aortic path length. Bossuyt et al [1] also applied the multiplication method and showed that it lacked equal accuracy for the right and left side measurements on the body surface. Nemeth et al [14] indicated that carotid-femoral distance on the body surface exceeds the catheter-derived aortic length by more than 5 cm.

Also the association between aortic length, demographic and anthropometric data was discussed in various publications before. They differ from our study and from each other either by the measurement technique, the estimated aorta segment or by the investigated determinants and established correlations.

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The height, weight, BMI and age are the most frequently used determinants among all the investigated. Unfortunately, correlation coefficients cannot be directly compared with our data because the investigated distances and study designs are very different from ours. Parissis and al [16] investigated the aortic segment length on cadavers during autopsy and the correlations with height, age, sex and distance from the jugular notch to trans-pyloric plane. They found that weight and BSA did not affect the investigated part of aortic length. Postulation about BSA is in accordance with our results, but it is not so for weight - the supplementation of weight gives the additional power to the prediction of aortic length in our investigation. Hallab et al [7] studied the correlation between the length of the aortic arch with height, age and weight. They found a correlation with height ($R=0.60$), but not with age and weight. On the contrary, we found a correlation with age and weight and this discrepancy is easily explained due to the completely different lengths of the investigated aortic segments. Igari et al [9] found a significant positive correlation of aortic segment length with height ($R=0.664$) and weight ($R=0.527$), the correlation with age ($R= -0.105$) was insignificant. Hallab et al [7] showed correlation with height ($R=0.60$), Weber et al [28] also found the aortic distance correlation with height ($R=0.46$). Sugawara et al [22] showed that aorta lengthens with age, mostly due to the elongation of the ascending aorta. Huybrechts et al [8] showed the moderate influence of age and minimal influence of BMI. We also found a moderate correlation for age and an insignificant for BMI. In contrast to our results, the study of Pierce et al [19] demonstrated the better impact of age and BMI to the estimation of aortic length.

Several authors have constructed the equations for aortic segment length prediction. Most of the equations were based only on height. Igari et al [9] equation was $L= (-26.253) + 1.507x$ (height), while Hallab et al [7] study presented another equation $L=1.8x$ (height) - 83.12. Weber et al [28] have constructed the equations on body height divided by 4, with addition of the empirical constant based on their data. Dotter et al [4] studied the influence of age and derived the predictive equation for thoracic aorta length on the basis of age; however it is incomparable with our data because the age variable in their equation was transformed into \log_{10} . Parissis and al [16] added height, age, sex and distance from the jugular notch to trans-pyloric plane to the equation. As a result, the predictive aortic length according to their study was proportional to the following variables: $0.37x$ (height), $0.35x$ (age), $0.21x$ (sex) and $0.61x$ (distance on the body surface). Pierce et al [19] derived the equation based on age and BMI: $0.173x(\text{age}) + 0.661x(\text{BMI}) + 34.548$. In our study, the value set of height, weight and age gives a more prominent impact to the aortic length estimation. This discrepancy may be explained by differences in the measurement techniques, the investigated parts of aorta and variables used in the predictive equations.

As mentioned above, we did not find any other studies for the determination of the whole aortic length by a similar methodology. Igari et al [9] estimated the length of the aortic segment from subclavian artery to the renal artery; Hallab et al [7] - the length of the aortic arch starting from the aortic valve and ending with the intersection of a point on a descending aorta adjacent to a horizontal plane passing through the aortic valve; Huybrechts et al [8] - from carotid to femoral artery, Rezai et al [20] - from aortic arch to the aortic bifurcation. However, the investigation of the whole aortic length, from ascending aorta to bifurcation is very important. As it is shown in the work of Sugawara et al [23], ascending aorta undergoes the elongation with age, almost 2-fold between 20 and 80 years of age [15]. Thus, the omitting of this part of aorta will influence the estimated aortic length accuracy dramatically.

As it was previously noted, the techniques used for the measurements of the aorta segment length were also different. Igari et al [9] and Hallab et al [7] used CT images, as in our work, but the estimated path length and measured methodology differed from ours. Some authors used MRI [1, 8, 20, and 23], others - catheters [28]. In their regression analysis Pierce et al [19] used aortic distance, which was computed by carotid-femoral pulse wave velocity, multiplied by travelling time.

Among these studies, the study of Weber et al is more comparable with ours. Similarly to our study, they measured the whole aortic length from the ascending aorta to the bifurcation and compared it with Jug-Sy distance. However, they used the invasive measurement method of the aortic length by the catheter, which differs from ours, but seems to be more precise. As it was mentioned above, their results were slightly different -- the mean of aortic length and Jug-Sy distance were slightly longer than in our study, which may be explained by slightly larger means of height, weight and age in the population investigated in their work. It is especially interesting that applying the means of age, height and weight reported in their work to our equation, we have predicted aortic length very closely to the reported in Weber study invasively measured ones.

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We demonstrated in a systematic manner that height, weight and age had the greatest impact on aortic length changes in the investigated population. But despite considerable contribution of these parameters to the aortic length, only about 65 per cent of the variations in aorta length could be explained by their values. We can probably explain this phenomenon not only by random influences of other, non-investigated determinants, but by the systematic opposite direction in the changes of main determinants - age and body height. While the aorta lengthens to some extent with age, the height diminishes and may provide false shortening of the aorta length evaluated by the equation. These opposite changes probably reduce the predictive power of the equation.

V. CONCLUSION

Our study demonstrated that age, height and weight were the main determinants of aortic length. The established predictive equation for aortic length estimation allowed to assess accurately aortic length in 65% of the investigated population. No doubt, the non-invasive approach to aortic length estimation can offer only an approximation to the actual aortic length due to the range of variation in aortic length, influenced by several individual factors. However, it remains increasingly important that the result of our investigation has demonstrated a better accuracy of the determination of the aortic length by the equation constructed in our work than the estimation of the aortic length by approximation to Jug-Sy distance. Finally, the accurate results of the validation of our equation against invasively measured aortic length on other (Weber et al) population, suggests that the equation can be reliably used in further investigations.

Study limitations

Relatively small amount of subjects imposed some limitations on the results of our study. Thus, a more precise analysis of the influence of the investigated determinants on the aortic length in subgroups of different sex and age was not possible.

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Conflict of interest

The authors declare that they have no conflict of interest.

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