

CARDIOLOGY

COMPARATIVE ANALYSIS OF MORPHOMETRIC DATA ON INTERNAL DIAMETERS OF SEGMENTS FORMING BIFURCATIONS IN CORROSION CASTS OF HUMAN CORONARY ARTERIES AND THEIR CALCULATION USING CONTEMPORARY METHODS

Zenin O.K.¹,
Kafarov E.S.²,
Miltiadis I.³

¹ Penza State University
(Krasnaya St., 40, 440026 Penza, Russian
Federation)

² A.A. Kadyrov Chechen State University
(A. Sheripov St., 32, 364024, Grozny,
Chechen Republic, Russian Federation)

³ University of Palermo (Piazza Marina, 61,
90133 Palermo, Italy)

Corresponding author:

Oleg K. Zenin,
e-mail: zen.olegz@gmail.com

RESUME

Background. The study of human coronary arteries (HCA) as a fractal system composed of arterial bifurcations (AB) has proven promising and effectiveness in the development of digital methods for diagnosing and treating vascular pathology. However, at present, there is no consensus among researchers regarding the theory of the optimal structure of HCA bifurcations and the methodology for calculating the internal diameters of arterial segments (AS) that form these bifurcations under normal conditions.

Objective. To conduct a comparative analysis of morphometric data from real normal HCA and contemporary numerical modeling methods for calculating diameters of segments forming AB.

Methods. A comparative study was carried out on the internal diameters of 2,072 AS comprising 1,078 AB from 60 corrosion casts of HCA obtained from hearts of both sexes, aged 36 to 74 years, without signs of pathology. Morphometric measurements were compared with values calculated using established equations, proposed by Mette S. Olufsen and G. Finet.

Results. It was found that the internal diameters of AS forming HCA bifurcations, obtained by morphometry of corrosion casts and by calculations using the equations of Mette S. Olufsen and G. Finet, differ significantly.

Conclusion. For numerical modeling of realistic HCA geometry as a fractal structure composed of heterogeneous AB, the use of the equations proposed Mette S. Olufsen and G. Finet would not be appropriate. At present, there is no universally accepted theory of the optimal structure of HCA bifurcations, and consequently, no established technology for numerical modeling of realistic vascular geometry.

Keywords: human heart, coronary arteries, fractal system, bifurcation

Received: 03.07.2025
Accepted: 14.10.2025
Published: 26.11.2025

For citation: Zenin O.K., Kafarov E.S., Miltiadis I. Comparative Analysis of Morphometric Data on Internal Diameters of Segments Forming Bifurcations in Corrosion Casts of Human Coronary Arteries and Their Calculation Using Contemporary Methods. *Acta bio-medica scientifica*. 2025; 10(5): 100-106. doi: 10.29413/ABS.2025-10.5.11

СРАВНИТЕЛЬНЫЙ АНАЛИЗ РЕЗУЛЬТАТОВ МОРФОМЕТРИИ ВНУТРЕННИХ ДИАМЕТРОВ СЕГМЕНТОВ, СОСТАВЛЯЮЩИХ БИФУРКАЦИЮ КОРРОЗИОННЫХ ПРЕПАРАТОВ РЕАЛЬНЫХ ВЕНЕЧНЫХ АРТЕРИЙ СЕРДЦА ЧЕЛОВЕКА И СОВРЕМЕННЫХ МЕТОДИК ИХ РАСЧЕТОВ

Зенин О.К.¹,
Кафаров Э.С.²,
Милтиадис И.³

¹ Пензенский государственный университет Минобрнауки России (440026, г. Пенза, ул. Красная, 40, Россия)

² Чеченский государственный университет имени А. А. Кадырова Минобрнауки России (364024, г. Грозный, ул. А. Шерипова, 32, Чеченская Республика, Россия)

³ Университет Палермо (Università degli Studi di Palermo) (90133, Пьяцца Марина, 61, Палермо, Италия)

Автор, ответственный за переписку:

Зенин Олег Константинович,
e-mail: zen.olegz@gmail.com

РЕЗЮМЕ

Обоснование. Исследование венечных артерий сердца человека (ВАСЧ) как фрактальной системы, состоящей из артериальных бифуркаций (АБ), доказали свою перспективность и эффективность при разработке цифровых методов диагностики и лечения сосудистой патологии. Однако в настоящее время среди исследователей нет единого мнения о теории оптимального строения АБ ВАСЧ и технологии расчета величин внутренних диаметров артериальных сегментов (АС), составляющих АБ ВАСЧ в норме.

Цель. Провести сравнительный анализ результатов морфометрии реальных ВАСЧ в норме и современных методик численного моделирования диаметров сегментов, входящих в состав АБ.

Методы. Проведено сравнительное исследование величин внутренних диаметров 2072 АС, составляющих 1078 АБ, 60-ти коррозионных препаратов ВАСЧ сердец лиц обоего пола в возрасте от 36 до 74 лет, без признаков патологии, полученных путем морфометрии и значений данных показателей, рассчитанных с использованием известных уравнений, предложенных Mette S. Olufsen и G. Finet.

Результаты. Установлено, что величины внутренних диаметров АС, входящих в состав АБ ВАСЧ, полученные путем морфометрии коррозионных препаратов и расчетным путем с использованием уравнений, предложенных Mette S. Olufsen и G. Finet, значительно отличаются.

Заключение. Для численного моделирования реалистичной геометрии ВАСЧ, как фрактальной структуры, состоящей из разнородных АБ, будет не правильным решением использование уравнений Mette S. Olufsen и G. Finet. Сегодня можно говорить об отсутствии общепризнанной теории оптимального строения АБ ВАСЧ и, соответственно, технологии численного моделирования реалистичной геометрии русла.

Ключевые слова: сердце человека, венечные артерии, фрактальная система, бифуркация

Статья поступила: 03.07.2025

Статья принята: 14.10.2025

Статья опубликована: 26.11.2025

Для цитирования: Зенин О.К., Кафаров Э.С., Милтиадис И. Сравнительный анализ результатов морфометрии внутренних диаметров сегментов, составляющих бифуркацию коррозионных препаратов реальных венечных артерий сердца человека и современных методик их расчетов. *Acta biomedica scientifica*. 2025; 10(5): 100-106. doi: 10.29413/ABS.2025-10.5.11

BACKGROUND

Following the paradigm of modern scientific research and the requirements of theoretical and clinical medicine, traditional morphology is increasingly undergoing digitalization [1]. In today's world, a simple verbal (qualitative) description of anatomical structures is no longer sufficient; medical theory and practice require a quantitative (digital) representation. This trend is directly reflected in the study of vascular beds in vital human organs, such as the heart, brain, kidneys, etc. The arterial beds of these organs can be considered as fractal (self-similar) systems, with the structural and functional unit (fractal) being a bifurcation. A bifurcation is a section of a vascular bed that consists of a parent vessel (D), two daughter (d_{max} , d_{min}) vessels, and the point where they join. Extensive research has been conducted on numerical modeling (a computer-based research method that performs calculations based on a specific mathematical model to simulate real-world physical objects or processes) of an arterial bifurcation (AB) [2-4]. From a theoretical perspective, this approach enables a quantitative description of the structure and function of the bed as a whole, as well as its individual components [5-7]. From a clinical perspective, the AB is a focus of attention for diagnosticians and interventional radiologists, as it is the most likely site for vascular damage [8, 9].

Such studies have already demonstrated their potential and efficacy in the development of digital diagnostic and therapeutic approaches for vascular pathology [8, 9]. However, there is currently a lack of consensus among researchers on the optimal design of the HCA bifurcation model and the corresponding technology for calculating the inner diameters of the arterial segments (AS) that comprise the HCA bifurcations in normal conditions. The theoretical data often diverge significantly from the morphometric findings of real-world objects. This has guided the direction of this study.

THE AIM OF THE STUDY

To conduct a comparative analysis of the results of morphometric data of actual normal HCA and modern numerical modeling techniques for the diameters of the segments included in AB.

METHODS

Study design

A comparative study was conducted on the internal diameters of the segments constituting the HCA bifurcations, which were previously obtained through the morphometry of actual anatomical specimens [10] and numerical modeling. This study adheres to the ethical standards set forth in 1964 Declaration of Helsinki and its subsequent revisions. Ethical approval was granted by the local ethics committee at the Medical

Institute of A.A. Kadyrov Chechen State University (Protocol No. 258/24-77, dated October 16, 2023).

Eligibility criteria

Inclusion criteria: Individuals of both sexes, aged 36–74 years, who died from non-vascular accidental causes; heart weight 250–350 g in women, and 300–400 g in men; and with no external organ damage.

Exclusion criteria: Age <36 years and >74 years; mechanical organ damage; history of diseases that may cause vascular injury; visually detectable vascular deformities and anomalies; heart weight <250 g and >350 g in women, and <300 g and >400 g in men.

The study involved 60 samples of HCA corrosion preparations, which were manufactured according to a standard method [10]. Following morphometric analysis, numerical characteristics of the internal diameters of the AS were obtained: D is the internal diameter of the maternal (proximal) AS (mm); d_{max} is the diameter of the larger daughter (distal) AS (mm); d_{min} is the diameter of the smaller daughter AS (mm), which constitute the AB of the corrosion preparations of actual HCA.

To obtain the calculated values of d_{max} and d_{min} , methods based on the previously described patterns were employed:

1) according to Mette S. Olufsen, et al., 2000 [11]:

$$d_{max(Olufsen)} = 0,9D; d_{min(Olufsen)} = 0,6D \quad (1)$$

2) according to G. Finet, et al., 2008 [12]:

$$d_{max(Finet)} = \frac{D}{0,678} - d_{min(Finet)}; d_{min(Finet)} = \frac{D}{0,678} - d_{max(Finet)} \quad (2)$$

A comparative analysis of the values of the studied parameters was conducted, using both morphometric measurements and equations (1) and (2). To assess the distribution of these values, the Kolmogorov – Smirnov test was applied, with a significance level of $p < 0.05$. Non-parametric methods of analysis were used (Wilcoxon signed-rank test). Median values, 95% confidence intervals (using asymptotic methods), interquartile ranges (25–75%), as well as minimum (min) and maximum (max) values of the studied parameter were calculated. Statistical analyses were conducted using the R programming language, employing the medianCI function provided by the MKinfer package: medianCI (x, method = "asymptotic").

RESULTS

The study included 1,078 AB, consisting of 2,072 AS, without signs of pathology. The findings are presented in Tables 1 and 2. It was found that the distributions of the studied parameters, including the internal diameters of AS (D – maternal (proximal), d_{max} – larger daughter (distal), and d_{min} – smaller daughter (distal)), which were obtained through morphometric analysis of the HCA and using equations (1) and (2), do not follow the normal distribution pattern (Table 1). This finding was taken

into consideration when selecting subsequent methods for statistical analysis.

The values of the parameters studied, obtained through morphometric analysis and using equations (1) and (2), are presented in Table 2.

The data in Table 2 clearly demonstrate that the values of the internal diameter of the larger and smaller daughter (distal) branches of the AB, obtained through morphometric analysis, significantly differ from the values of this parameter calculated using equations (1) and (2) ($p < 0.05$, where p represents the significance level for differences as determined by the Wilcoxon signed-rank test (here and further in the text).

A comparative analysis (Table 2) of the values of medians (Me) and 95% confidence intervals [CI 95%] of the internal diameters of the daughter (distal) AS (d_{max} and d_{min}), obtained from corrosion preparations of HCA from real anatomical specimens and using equations (1) and (2), convincingly demonstrates significant differences ($p < 0.05$) between the values of the studied parameters obtained through morphometric analysis and those calculated using these equations. It has been established that the measurements (Me [CI 95%], mm) of the larger and smaller daughter (distal) AS obtained through morphometric analysis ($d_{max} = 0.60$ [0.60; 0.70], mm and $d_{min} = 0.40$ [0.40; 0.50], mm, respectively) are significantly lower ($p < 0.001$ and $p < 0.001$, respectively) than the corresponding measurements (Me [CI 95%]) obtained using the equation (1) ($d_{max(Olufsen)} = 0.63$ [0.63; 0.72], mm and $d_{min(Olufsen)} = 0.42$ [0.42; 0.48], mm, respectively). The significance level for differences in the measurements (Me [CI 95%]) of the internal diameter of the larger daughter (distal) AS, obtained through morphometric analysis ($d_{max} = 0.60$ [0.60; 0.70] mm) and using the equation (2) ($d_{max(Finet)} = 0.60$ [0.60; 0.69], mm), is $p = 0.033$, although it can be visually observed that both measurements tend to converge. On the other hand, the measurement (Me

[CI 95%]) of the internal diameter of the smaller daughter (distal) branch of the AB, obtained through morphometric analysis ($d_{min} = 0.40$ [0.40; 0.50], mm), is noticeably and significantly higher ($p < 0.001$) than the value of the corresponding parameter ($d_{min(Finet)} = 0.34$ [0.34; 0.38], mm), obtained using equation (2).

It has been established (Table 2) that the interquartile range (IQR) of the internal diameter of the larger daughter (distal) AS, obtained through morphometric analysis ($d_{max} = 0.80$ mm) is significantly higher than the values of this parameter calculated using equation (1) ($d_{max(Olufsen)} = 0.72$ mm) and equation (2) ($d_{max(Finet)} = 0.72$ mm). Comparison of the interquartile range values of the internal diameters of the smaller daughter (distal) AS showed

TABLE 1
RESULTS OF TESTING THE DISTRIBUTION OF THE VALUES OF THE STUDIED INDICATORS FOR COMPLIANCE WITH THE NORMAL DISTRIBUTION LAW

Parameter	Kolmogorov – Smirnov test statistics	p
D	0.17	<0.001
d_{max}	0.18	<0.001
d_{min}	0.18	<0.001
$d_{max(Olufsen)}$	0.17	<0.001
$d_{min(Olufsen)}$	0.17	<0.001
$d_{max(Finet)}$	0.17	<0.001
$d_{min(Finet)}$	0.15	<0.001

Note. D – diameter of maternal (proximal) AS, morphometry; d_{max} – diameter of larger daughter (distal) AS, morphometry; d_{min} – diameter of smaller daughter (distal) AS, morphometry; $d_{max(Olufsen)}$ – diameter of larger daughter (distal) AS, equation (1); $d_{min(Olufsen)}$ – diameter of smaller daughter (distal) AS, equation (1); $d_{max(Finet)}$ – diameter of larger daughter (distal) AS, equation (2); $d_{min(Finet)}$ – diameter of smaller daughter (distal) AS, equation (2); p – significance level for differences.

TABLE 2
VALUES OF THE STUDIED PARAMETERS OBTAINED BY MORPHOMETRY AND USING EQUATIONS (1) AND (2) ($n = 2072$)

No.	Parameter	Values of the parameter			
		Me	CI 95%	Interquartile range (IQR) (25–75%)	Minimum and maximum (min; max)
1	D (mm)	0.70	0.70; 0.80	0.80	0.10; 7.50
2	d_{max} (mm)	0.60	0.60; 0.70	0.80	0.10; 5.10
3	d_{min} (mm)	0.40	0.40; 0.50	0.40	0.10; 3.50
4	$d_{max(Olufsen)}$ (mm)	0.63	0.63; 0.72	0.72	0.09; 6.75
5	$d_{min(Olufsen)}$ (mm)	0.42	0.42; 0.48	0.48	0.06; 4.50
6	$d_{max(Finet)}$ (mm)	0.60	0.60; 0.69	0.72	0.06; 6.69
7	$d_{min(Finet)}$ (mm)	0.34	0.34; 0.38	0.33	0.06; 2.64

Note. D – diameter of maternal (proximal) AS, morphometry; d_{max} – diameter of larger daughter (distal) AS, morphometry; d_{min} – diameter of smaller daughter (distal) AS, morphometry; $d_{max(Olufsen)}$ – diameter of larger daughter (distal) AS, equation (1); $d_{min(Olufsen)}$ – diameter of smaller daughter (distal) AS, equation (1); $d_{max(Finet)}$ – diameter of larger daughter (distal) AS, equation (2); $d_{min(Finet)}$ – diameter of smaller daughter (distal) AS, equation (2); Me, median; [CI 95%], 95% confidence interval; IQR – interquartile range (25–75%); min – minimum value of the parameter studied; max – maximum value of the parameter studied; n – number of AS studied.

that the morphometric value ($d_{min} = 0.40$ mm) is lower than that calculated using equation (1) ($d_{min(Olufsen)} = 0.48$ mm), but higher than the corresponding IQR value calculated using equation (2) ($d_{min(Finet)} = 0.33$ mm).

The minimum values (Table 2) of the internal diameters of the larger daughter (distal) AS $d_{max(Olufsen)}$ (min = 0.09 mm) and $d_{max(Finet)}$ (min = 0.06 mm), obtained by calculations, are significantly lower than the d_{max} (min = 0.10 mm) parameter obtained through morphometric analysis. On the other hand, the maximum value of the internal diameter of the larger daughter (distal) branch AB, obtained through morphometric analysis d_{max} (max = 5.10 mm), is significantly lower than $d_{max(Olufsen)}$ (max = 6.75 mm) and $d_{max(Finet)}$ (max = 6.69 mm). The opposite pattern is observed with respect to the minimum diameter of the smaller daughter (distal) branch AB. The minimum value of d_{min} (min = 0.10 mm), obtained through morphometric analysis, is significantly greater than those calculated using equation (1) $d_{min(Olufsen)}$ (min = 0.06 mm) and equation (2) $d_{min(Finet)}$ (min = 0.06 mm). With regard to the maximum value of the smaller daughter (distal) branch of AB, it is not entirely clear. The maximum value of the smaller daughter (distal) branch of AB d_{min} (max = 3.50 mm) is less than $d_{min(Olufsen)}$ (max = 4.50 mm) and greater than $d_{min(Finet)}$ (max = 2.64 mm).

DISCUSSION

Mette S. Olufsen et al., 2000 [11] determined the values of the internal diameters of AS that comprise the HCA bifurcations: the internal diameter of the proximal AS – D, the internal diameter of the larger distal AS – d_{max} , the internal diameter of the smaller distal AS – d_{min} , based on the power law:

$$D^\xi = d_{max}^\xi + d_{min}^\xi \tag{3}$$

This law is based on the principles outlined in the works of C.D. Murray, M. Zamir, and H.B.M. Uylings [13, 14], which are based on the concept of “minimum energy” in the arterial system. The equation is valid for laminar flow, where $\xi = 3.0$ [15], and for turbulent flow, where $\xi = 2.33$ [16]. In the study by [17], it was found that for the HCA bifurcations, the characteristic value of $\xi = 2.76$. According to data from a systematic review conducted by Taylor et al., the optimal index for the relationship between blood flow and vessel diameter in coronary arteries is 2.39 [18]. In combination with equations for calculating the area ratio (η)

$$\left(\eta = \frac{d_{max}^2 + d_{min}^2}{D^2} \right) \text{ and asymmetry ratio } (\gamma) \left(\gamma = \left(\frac{d_{min}}{d_{max}} \right)^2 \right),$$

$$d_{max} = \alpha D; d_{min} = \beta D; D_{k,n} = \alpha^k \beta^{n-k} D \tag{4}$$

arteries (d_{max} and d_{min}) relative to the diameter of the parent (proximal) artery (D)

where α and β are constants that characterize the asymmetry of the AB, n is the generation number (the division level of a newly formed set of AS), and $n = 0$ corresponds to an AS that is at the beginning of a channel. In each generation, up to 2^n vessels can exist. Within generation n , there can only be $n + 1$ AS of different sizes. This corresponds to k possible choices for the scale factor α , and $n - k$ choices for the scale factor β , where $0 \leq k \leq n$. The HCA continues to branch until any AS has a diame-

$$\eta = \frac{1 + \gamma}{(1 + \gamma^2)^{\frac{\xi}{2}}} \tag{5}$$

ter that is less than some specified minimum value (d_{min}). The asymmetry of the AB (γ) was determined using the following equation [19]:

$$\alpha = \left(1 + \gamma^{\frac{\xi}{2}} \right)^{-\frac{1}{\xi}} = 0,9 \ \& \ \beta = \alpha \sqrt{\gamma} = 0,6 \tag{6}$$

where η is the area coefficient and γ is the asymmetry coefficient. Using the values of $\eta = 1.16$ and $\gamma = 0.41$ as well as $\xi = 2.76$ [14], the values of α and β can be determined:

G. Finet et al., 2008 [12] derived the equation through a study on the fractal geometry of the HCA bifurcations. The researchers measured the diameter of the parent AS (D) as well as the two daughter AS (d_{max} and d_{min}), that comprise 173 AB in the HCA radiographs of 59 patients without cardiovascular pathology. They found that

the ratio $R = D / (d_{max} + d_{min})$ remains constant at 0.678

regardless of the observation scale. This finding confirms the fractal nature of the HCA bifurcations.

However, the results of this study suggest that it is not possible to obtain, through calculation using equations (1) and (2), values of the studied parameters that correspond to real morphometric data. This may indicate that the “minimum cost” principle [13, 14] is not suitable for numerical modeling of the structure of real HCA as fractal systems, at least for the section of the HCA studied in this research, which is the epicardial and transmural AS from the origin of the coronary artery to the level of the hemomicrocirculatory bed (up to 0.1 mm).

The majority of scientific studies on the HCA bifurcations are based on a fundamental biological principle described in 1926 by Murray’s law (C.D. Murray), which relates the form and function of these branched networks [13]. This law is founded on the principle of minimizing the work required to generate and maintain blood flow, as well as the energy needed to overcome viscous resistance [20]. This principle applies to both the epicardial and transmural systems of the HCA, which are composed of structural and functional units known as AB.

It is believed that the primary function of AB is blood transportation [21, 22]. However, this statement, which appears to be true for the proximal segments of the HCA, contrasts with the perfusing vessels of the distal segments, where a rapid increase in cross-sectional area (i.e., the increase in the total diameter of the vessels), contributes to a slower blood flow and less efficient substrate exchange [23, 24]. There is also compelling evidence that AB, in addition to transporting blood, also serve as the distribution and support system for an organ, acting as its soft skeleton. It should be noted that, in most studies, morphometric characteristics of AB focus on the ratio of internal diameters of the AS, rather than their lengths. However, it would be incorrect to assess hemodynamics and other functions of AB without considering the lengths of AS. In addition, the obtained results may be attributed to the fact that, as demonstrated by modern morphological studies, the AB population in all areas of the HCA (both distal and proximal sections), is heterogeneous. Previous studies have identified four types of AB: 1 – complete asymmetry, $D \neq d_{\max} \neq d_{\min}$; 2 – lateral asymmetry, $D = d_{\max}$ and $d_{\max} \neq d_{\min}$; 3 – one-sided symmetry – $D \neq d_{\max} \neq d_{\min}$ and $d_{\max} = d_{\min}$; 4 – complete symmetry, $D = d_{\max} = d_{\min}$ in the composition of the HCA [25]. This, to some extent, explains the significant differences between the values of the studied parameters calculated and those obtained through morphometric analysis.

For discussion purposes. In the absence of a widely accepted theory on the structure and function of the HCA, the use of machine learning models appears to be a valid approach for numerical modeling the realistic geometry of the HCA. These models can be based on both classical regression techniques and neural network architectures, which are trained on morphometric measurement data. The channel geometry can be modeled as a fractal or pseudo-fractal system composed of structurally diverse AB.

CONCLUSION

Considering the above, it can be stated that at present, there is no unified, universally accepted theory on the optimal design of the HCA bifurcations and the methodology for numerically modeling the realistic geometry of the HCA.

Funding

The authors declare that the study was not funded by any external sources.

Conflicts of interest

No potential conflict of interest relevant to this article reported.

REFERENCES

1. Kafarov ES, Milykh I, Dmitriev AV, Zenin OK. Anatomical variability of kidney arterial vasculature based on zonal and segmental topography. *Heliyon*. 2023; 9(4): e15315. doi: 10.1016/j.heliyon.2023.e15315
2. Blanco PJ, Watanabe SM, Passos MARF, Lemos PA, Feijóo RA. An anatomically detailed arterial network model for One-Dimensional Computational Hemodynamics. *IEEE Trans Biomed Eng*. 2015; 62(2): 736-753. doi: 10.1109/TBME.2014.2364522
3. Kopylova VS, Boronovskiy SE, Nartsissov YR. Tree topology analysis of the arterial system model. *J Phys Conf Ser*. 2018; 1141: 012027. doi: 10.1088/1742-6596/1141/1/012027
4. Roy Choudhury K, Skwerer S. Branch order regression for modeling brain vasculature. *Med Phys*. 2018; 45(3): 1123-1134. doi: 10.1002/mp.12751
5. Cuitino NS, Johannesson B, Pelegri AA. A Computational Model of Continuous Hollow Cerebrovascular Arterioles Using a Fractal L-System. In: *Volume 3: Biomedical and Biotechnology Engineering. American Society of Mechanical Engineers*. 2018; V003T04A060. doi: 10.1115/IMECE2018-88511
6. Zhang Z, Marin D, Drangova M, Boykov Y. Confluent Vessel Trees with Accurate Bifurcations. In: *2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*. IEEE. 2021: 9568-9577. doi: 10.1109/CVPR46437.2021.00945
7. Alberto OC, Alberto P M. The Geometry of Coronary Artery Bifurcations and its role in plaque formation. *Clin Cardiol Cardiovasc Med*. 2022; 4: 24-30. doi: 10.33805/2639.6807.131
8. Silva J, Nagato A, Reis R, Nardeli C, Abreu F, Bezerra F. Morphometric analysis of the coronary arteries: a study of the external diameters. *J Morphol Sci*. 2016; 33(03): 138-141. doi: 10.4322/jms.093115
9. Fandaros M, Kwok C, Wolf Z, Labropoulos N, Yin W. Patient-Specific Numerical Simulations of Coronary Artery Hemodynamics and Biomechanics: A Pathway to Clinical Use. *Cardiovasc Eng Technol*. 2024; 15(5): 503-521. doi: 10.1007/s13239-024-00731-4
10. Certificate of state registration of database No. 2021623049 Russian Federation. Quantitative anatomy of the intraorgan arterial channel of the human heart: No. 2021622956: submitted. 14.12.2021: publ. 20.12.2021 / O. Zenin, A.V. Dmitriev, I.S. Milykh; applicant Federal State Budgetary Educational Institution of Higher Education "Penza State University". (In Russ.). [Свидетельство о государственной регистрации базы данных № 2021623049 Российская Федерация. Количественная анатомия внутриоргана артериального русла сердца человека: № 2021622956: заявл. 14.12.2021: опублик. 20.12.2021 / О. Зенин, А.В. Дмитриев, И.С. Милых; заявитель Федеральное Государственное Бюджетное Образовательное Учреждение Высшего Образования «Пензенский Государственный Университет»].
11. Olufsen MS, Peskin CS, Kim WY, Pedersen EM, Nadim A, Larsen J. Numerical Simulation and Experimental Validation of Blood Flow in Arteries with Structured-Tree Outflow Conditions. *Ann Biomed Eng*. 2000; 28(11): 1281-1299. doi: 10.1114/1.1326031

12. Finet G, Gilard M, Perrenot B, et al. Fractal geometry of arterial coronary bifurcations: a quantitative coronary angiography and intravascular ultrasound analysis. *EuroIntervention*. 2008; 3(4): 490-498. doi: 10.4244/EIJV3I4A87
13. Murray CD. The physiological principle of minimum work applied to the angle of branching of arteries. *J Gen Physiol*. 1926; 9(6): 835-841. doi: 10/dq9qn9
14. Uylings HBM. Optimization of diameters and bifurcation angles in lung and vascular tree structures. *Bull Math Biol*. 1977; 39(5): 509-520. doi: 10/db7vdb
15. de la Torre Hernandez JM, Hernández Hernández F, Alfonso F, et al. Prospective Application of Pre-Defined Intravascular Ultrasound Criteria for Assessment of Intermediate Left Main Coronary Artery Lesions: Results From the Multicenter LITRO Study. *J Am Coll Cardiol*. 2011; 58(4): 351-358. doi: 10.1016/j.jacc.2011.02.064
16. Kassab GS, Rider CA, Tang NJ, Fung YC. Morphometry of pig coronary arterial trees. *Am J Physiol-Heart Circ Physiol*. 1993; 265(1 Pt 2): H350-65. doi: 10.1152/ajpheart.1993.265.1.H350
17. Pollanen MS. Dimensional optimization at different levels of the arterial hierarchy. *J Theor Biol*. 1992; 159(2): 267-270. doi: 10/b9898g
18. Taylor DJ, Saxton H, Halliday I, et al. Systematic review and meta-analysis of Murray's law in the coronary arterial circulation. *Am J Physiol-Heart Circ Physiol*. 2024; 327(1): H182-H190. doi: 10.1152/ajpheart.00142.2024
19. Zamir M. Nonsymmetrical bifurcations in arterial branching. *J Gen Physiol*. 1978; 72(6): 837-845. doi: 10.1085/jgp.72.6.837
20. Feynman RP, Leighton RB, Sands M. *The Feynman Lectures on Physics; New Millennium Ed*. Basic Books; 2010.
21. Drake R, Wayne Vogl A, Mitchell A. *Gray's Atlas of Anatomy*. 3rd ed. Churchill Livingstone; 2020.
22. Dhungana A, Buradi A, Dahal P, Bora BJ. Impact of Bifurcation and Bifurcation Angle on the Hemodynamics of Coronary Arteries. In: Bhattacharyya S, Verma S, Harikrishnan AR, eds. *Fluid Mechanics and Fluid Power (Vol. 3)*. Springer Nature. 2023: 31-36. doi: 10.1007/978-981-19-6270-7_6
23. Kassab GS. Functional hierarchy of coronary circulation: direct evidence of a structure-function relation. *Am J Physiol-Heart Circ Physiol*. 2005; 289(6): H2559-H2565. doi: 10.1152/ajpheart.00561.2005
24. Kassab GS, Molloy S. Cross-sectional area and volume compliance of porcine left coronary arteries. *Am J Physiol-Heart Circ Physiol*. 2001; 281(2): H623-H628. doi: 10.1152/ajpheart.2001.281.2.H623
25. Zenin OK, Overko VS, Dmitriev AV, Miltykh IS. Hemodynamic features in a structurally different arterial intraorganic bifurcations of the human heart by numerical modeling. *Sib J Life Sci Agric*. 2021; 13(2): 11-31. doi: 10.12731/2658-6649-2021-13-2-11-31

Information about the authors

Oleg K. Zenin – Dr. Sc. (Med.), Professor; Professor at the Department of Human Anatomy, Penza State University; e-mail: zen.olegz@gmail.com, <https://orcid.org/0000-0002-5447-1989>

Edgar S. Kafarov – Dr. Sc. (Med.), Associate Professor; Head of the Department of Normal and Topographical Anatomy with Operative Surgery, A.A. Kadyrov Chechen State University; e-mail: Edgar-kafarov@yandex.ru, <https://orcid.org/0000-0001-9735-9981>

Ilias Miltiadis – MSc student at University of Palermo; e-mail: ilia.miltykh@you.unipa.it, <https://orcid.org/0000-0002-9130-3255>