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Original Research Article

Numerical simulations of the pulsatile blood flow in the different types of arterial fenestrations: Comparable analysis of multiple vascular geometries

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ABSTRACT

In medical terms, *fenestration* stands for an anomaly within the circulatory system in which the blood vessel lumen is divided into two separate channels that rejoin in the distal part of this vessel. The primary objective of this research was to analyze the impact of the left vertebral artery (LVA) and basilar artery (BA) fenestrations on the blood flow characteristics in their regions and downstream, in the cerebral circulation. The geometrical data, obtained from the angio-Computed Tomography, were the basis for the generation of a 3D model in SolidWorks 2015. In order to observe the flow characteristics within the whole spatial domain, computational fluid dynamics was involved in performing simulations of the blood flow in the patient-specific arterial system (beginning with the aortic arch and finishing with the Circle of Willis). To examine the flow distribution changes resulting from altered fenestration geometries, additional models were built. The blood flow velocity, volume flow rate and shear stress distribution were analyzed within this study. It was proven that the length/size/position of the fenestration altered the flow characteristics in different manners. The investigations showed that the patient-specific LVA, at the V3 section (extracranial part of the artery located between the spine and the skull), is not a reason of aneurysm formation. However, BA fenestration at the proximal segment might be a possible reason of future aneurysm formation. It was proven that the computational fluid dynamics tool could support medical diagnostic procedures and multivessel brain vascular disease treatment planning.

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1. Introduction

Currently, in the era of vast availability of computational fluid dynamics (CFD) tools and machines with high computational efficiency, there is a possibility to perform numerical simulations of the complex physical phenomena occurring inside the human organism, e.g. blood flow in the cardiovascular system. Several fields of this science have been already intensely explored, hence, tremendous amount of publications appeared. General blood flow and its hydrodynamics (rheology, viscosity, governing equations) and flow inside major arteries have been broadly discussed [1–3]. Nowadays, numerous publications devoted to simulations in more complex anatomical structures are being created – they include investigations of the blood flow through coronary arteries with stenoses [4,5] or blood flow inside cerebral artery circle, known as Circle of Willis [6,7]. Moreover, scientists are also investigating phenomena connected with the aneurysms presence [8,9] and their impact on the flow hemodynamics. Nevertheless, some fields have not been explored yet and one of them is an application of CFD on the blood flow in the vascular developmental anomalies – fenestrations. Since fenestrations are relatively rare anomalies, a limited number of publications devoted to the numerical analysis of the blood flow in the vascular system encompassing fenestrations was found in the literature [10]. Therefore, the following research aims at investigation of the influence of fenestrations presence on the blood flow hydrodynamics.

Fenestration is an anomaly within the circulatory system characterized by a duplication of the vessel part – the blood vessel lumen is divided into two separate channels that rejoin in the distal part [11,12]. Such an additional vessel leads to an alternation in the flow characteristics, mainly the blood velocity, volume flow rate and shear stress distribution. It is believed that it does not exert any significant impact on the overall patient's health, however, aneurysms could originate from the proximal fenestration part [11,12] as a result of the increased turbulent flow and elevated hemodynamic stress [13]. The blood flow within the fenestration region might be affected by various factors, including fenestration location, its diameter and length. The authors are familiar with a hypothesis that fenestrations are clinically irrelevant, although numerous studies claim that there exists a correlation between fenestration presence and aneurysm formation [11,12]. Thus, it negates the aforementioned hypothesis – if there is even an inconsiderable risk of aneurysm occurrence, it means that this case is clinically relevant.

Patients investigated in the present study were 50-year old male and 51-year old female. Performed medical examination, angio-Computed Tomography, revealed that the first patient's left vertebral artery (LVA) was fenestrated at V3 section (extracranial part of the artery located between the spine and the skull). The second patient had a fenestration in the area of the basilar artery (BA), at the proximal segment. Concerning the prevalence of those types of the fenestrations among population, different referential statistics can be found in literature, see Table 1.

The paramount objective of this study included an investigation of the impact of the fenestration location and its geometry on the blood flow hydrodynamics, so as to obtain a biomechanical insight into phenomena occurring in the region of this anomaly. Such an analysis required a reconstruction of the patient-specific arterial system (from the aorta up to the Circle of Willis) and a vascular system in which a patient-specific basilar artery fenestration replaced particular part of the former geometry. It was decided not to reconstruct the second entirely new, patient-specific arterial system, since it would not lead to a solid comparison between LVA and BA fenestrations impact on the blood flow. Additionally, various models with slightly altered fenestration geometries were built to observe influence of the fenestration diameter/length/location on the flow hydrodynamics. The numerical simulations performed with the ANSYS CFX code helped in visualizing flow structures, such as the maximal blood velocity, area averaged volume flow rate and maximal shear stress distribution. They were conducted as transient simulations – cardiac cycle boundary conditions were implemented.

Currently, in the era of endovascular techniques for treatment of brain vascular diseases, there is a fundamental dilemma, i.e. a proper choice of endovascular access. It is extremely crucial to decide whether an artery with a duplication should be chosen as a way of endovascular access or a contralateral vessel, especially when cerebral aneurysms are present. One of the additional purposes of the presented study is to show that computational fluid dynamics tools could support medical diagnostic procedures in patients and multivessel brain vascular disease treatment planning.

Table 1 – Reported statistical prevalence of the vertebral and basilar artery fenestrations.

Fenestration location		Prevalence among all fenestrations
Vertebral artery (VA)	Intracranial	0.54%[a]
	Extracranial	0.90%[a]
	At V3 section	0.16%[d]
	Total occurrence	1.44%[a]
		0.23–1.95%[b]
		0.3–2.0%[c]
Basilar Artery (BA)	total occurrence	2.07%[a]
		0.6–5%[c]

[a] Uchino, Saito, Okada, Kozawa, Nishi, Mizukoshi, Inoue, Nakajima & Takahashi (2012) [14].
[b] Ples, Loukas, Jacob, Andall, Miclaus, Tubbs & Matusz (2015) [15].
[c] Dimmick & Faulder (2009) [13].
[d] Fortuniak, Bobeff, Polguj, Kośla, Stefańczyk & Jaskólski (2016) [16].