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# DEVELOPMENT OF MULTISCALE HEMODYNAMICS MODEL FOR RESEARCH OF BASILAR ARTERY CIRCULATION

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**Key words and phrases:** cardiovascular system; hemodynamics; mathematical model.

**Abstract**: One of the major diseases of cerebral circulation is an aneurysm of the basilar artery. Particular interests for medical practices are prediction methods of emergence and development of the aneurysm. One of the most promising methods used in medicine, is mathematical modeling. The paper presents the concept of developing a multiscale hemodynamic mathematical model of the cardiovascular system, including a model of global hemodynamics, arterial tree model and the model of basilar artery bifurcation. This model allows calculating the hemodynamic parameters at the bifurcation of the basilar artery. Using mathematical modeling results we can conclude the probability of a basilar artery aneurysm.

**Introduction.** Cerebral circulation is a complex system of blood vessels responsible for the transportation of blood and nutrients to the brain cells. One of the most common disorders of cerebral circulation is an aneurysm of the basilar artery [15]. The basilar artery is the main artery of the brain; it is formed where the two vertebral arteries join together at the base of the skull (Fig. 1).

Aneurysm is bulge in the vessel wall that is caused by its thinning or stretching. An aneurysm occurs in the places where vessel wall is damaged (typically at the arteries bifurcation). Fig. 2 shows an example of the basilar artery aneurysm.

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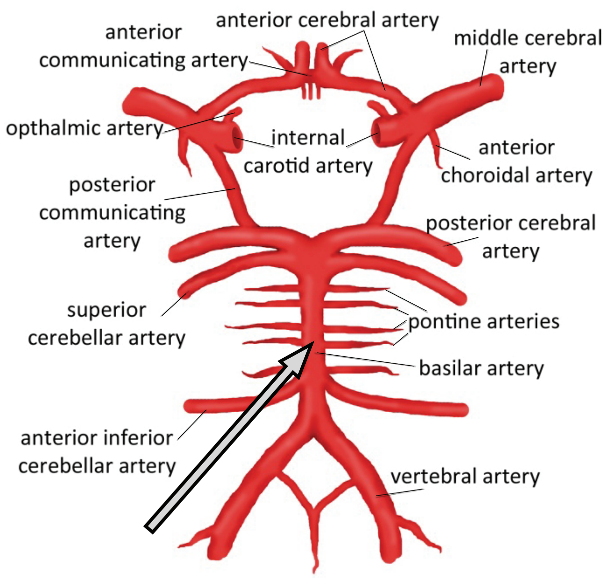
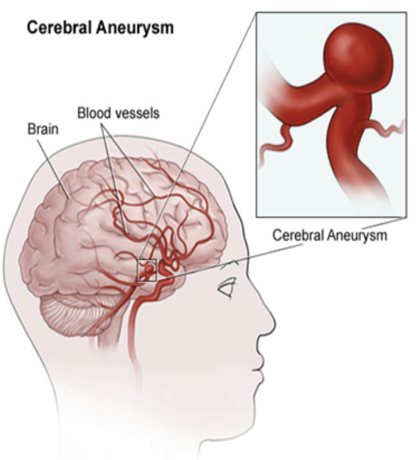
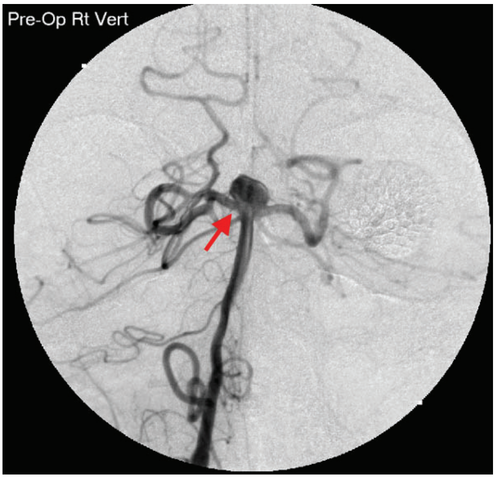



**Fig. 1. Schematic representation of the circle of Willis**
(the arrow shows the basilar artery) [7]




*a*) *b*)

**Fig. 2. Basilar artery aneurysm:**
*a* – schematic representation [11]; *b* – two-dimensional angiogram [16]

Damage of the vessel wall is caused by local hemodynamics disorders [10, 13]; therefore, the study of basilar artery hemodynamics plays a key role in identifying the causes of the emergence and development of the aneurysm. Particular interest is the bifurcation of the basilar artery into two posterior cerebral arteries (PCA).

**Methods.** For the investigation of basilar artery circulation it is proposed to use a multiscale mathematical model of hemodynamics [8], which is a set of mathematical models of circulation with different levels of detail.

Consider model of each level in more detail.

0D model is used to describe the hemodynamics of the cardiovascular system in general. According to this method the whole cardiovascular system is divided into a group of individual elements (compartments) [1–5, 9]. Each of the compartments described as lumped parameter model. The advantages of this approach are the computational efficiency, a relatively small number of experimentally determined parameters of the model. However, using such models pulse wave propagation cannot be investigated [8].

It is proposed to develop a 0D model, its structure is shown in Fig. 3.

In this model, it's planned to describe all major compartments of cardiovascular system and to describe heart in terms of physiology. In most models of the heart developed to date [8], heart, for ease of description, is modeled as an element with variable elasticity that prevents the use of such a model for the study of cardiac disorders, which is extremely important in intensive care. 0D model developed in future will be the basis for a multiscale model of hemodynamics.

Developing the one-dimensional hemodynamics (1D model) model of arterial tree it is planned to describe upper body arteries as a set of quasi-one-dimensional vessels. It is assumed that the velocity of blood in the artery and the pressure changes only in one spatial coordinate (along the length of the vessel) and in the vessel cross-section remain constant [8]. Sectional area of the vessel under the influence of blood pressure varies along the length of the vessel. This model allows studying the phenomenon of pulse wave propagation through the arterial tree, and to identify and predict the possible disorder in the functioning of the arteries.

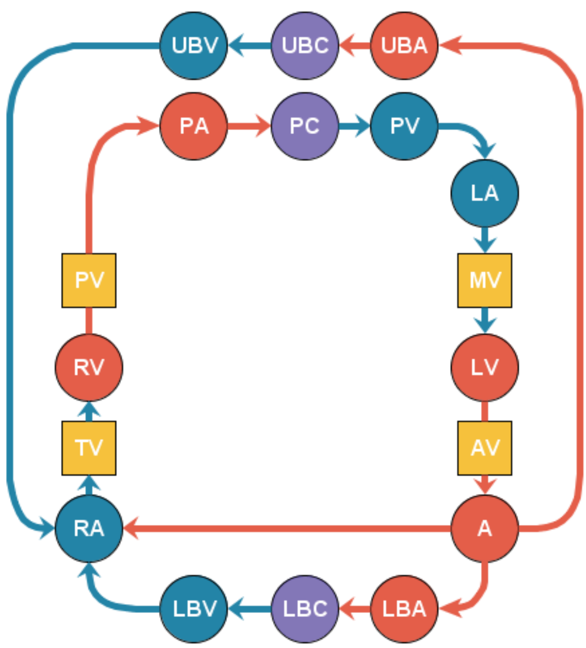



**Fig. 3. 0D cardiovascular system model scheme:**
LV – left ventricle; AV – aortic valve; A – aorta; UBA – upper body arteries; UBC – upper body capillaries; UBV – upper body veins; LBA – lower body arteries; LBC – lower body capillaries; LBV – lower body veins; RA – right atrium; TV – tricuspid valve; RV – right ventricle; PV – pulmonary valve; PA – pulmonary arteries; PC – pulmonary capillaries; PV – pulmonary veins; LA – left atrium; MV – mitral valve

The proposed structure of 1D model, consisting of 48 arteries is shown in Fig. 4. Arteries list is shown in Table (each artery number in Table corresponds to artery number in Fig. 4). This model describes upper body arteries and cerebral circulation which is described in detail. For proper functioning of the model 1D it is required appropriate boundary con ditions at the terminal edges of the arterial tree. Such boundary conditions can be obtained by using 0D model. In this approach, blood flow and pressure which is calculated by 0D model converted in accordance with a particular algorithm, and set as the boundary conditions for the model 1D.

Using 3D model it is planned to describe the basilar artery local hemodynamics. The researcher will receive information about a blood flow rate of change and blood pressure at any point of the basilar artery. According to results risk of developing an aneurysm of the basilar artery can be predicted.

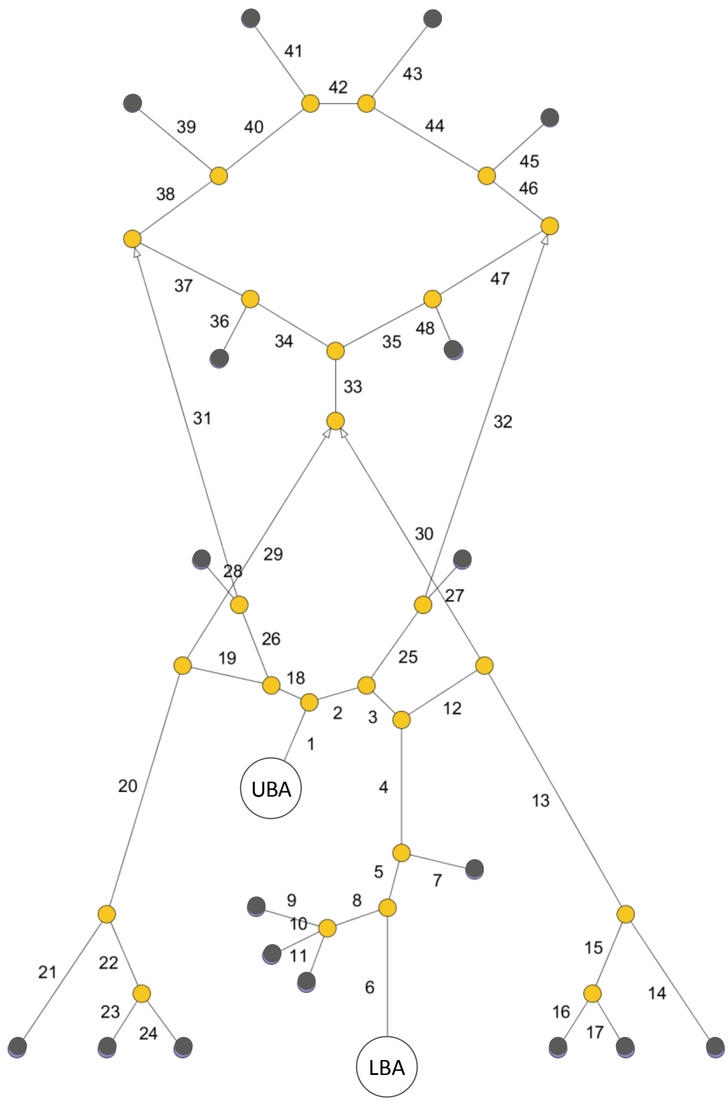



**Fig. 4. The structure of one-dimensional mathematical model of the upper body arteries and brain:**
UBA, LBA – compartments of 0D model; ○ – bifurcations; ● – terminal elements

**Arteries list**

| № | Artery | № | Artery |
|---|---|---|---|
| 1 | Ascending aorta | 25 | Left carotid |
| 2 | Aortic arch 1 | 26 | Right carotid |
| 3 | Aortic arch 2 | 27 | Left external carotid |
| 4 | Thoracic aorta 1 | 28 | Right external carotid |
| 5 | Thoracic aorta 2 | 29 | Right vertebral |
| 6 | Abdominal aorta A | 30 | Left vertebral |
| 7 | Intercostals | 31 | Right internal carotid 1 |
| 8 | Coelic | 32 | Left internal carotid |
| 9 | Gastric | 33 | Basilar |
| 10 | Splenic | 34 | Right posterior cerebral artery1 |
| 11 | Hepatic | 35 | Left posterior cerebral artery 1 |
| 12 | Left subclavian 1 | 36 | Right posterior cerebral artery 2 |
| 13 | Left subclavian 2 | 37 | Right posterior communicating artery |
| 14 | Left radius 1 | 38 | Right internal carotid 2 |
| 15 | Left ulnar 1 | 39 | Right middle cerebral artery |
| 16 | Left ulnar 2 | 40 | Right anterior cerebral artery 1 |
| 17 | Left interosseous | 41 | Right anterior cerebral artery 2 |
| 18 | Brachiocephalicus | 42 | Anterior communicating artery |
| 19 | Right subclavian 1 | 43 | Right brachial |
| 20 | Right subclavian 2 | 44 | Left anterior cerebral artery 1 |
| 21 | Right radius | 45 | Left middle cerebral artery |
| 22 | Right ulnar 1 | 46 | Left internal carotid 2 |
| 23 | Right interosseous | 47 | Left posterior communicating artery |
| 24 | Right ulnar 2 | 48 | Left posterior cerebral artery 2 |

Also, with this model it is possible to conduct numerical experiments to determine the optimal stent position in basilar artery stenting.

3D model is developed using the Navier-Stokes equations [8]. Blood flow rate and pressure are studied functions. Unlike 1D model studied functions vary in three spatial directions, causing a significant increase in simulation time for this type of models. To solve this problem, as a rule, use parallel computing [15] (both using computing clusters, and with the use of powerful graphics processors, designed for non-graphical computing (such as accelerators NVIDIA Tesla). Besides computational cost, using 3D models there are certain difficulties in obtaining reliable form of the computational domain. For obtaining the corresponding geometry form it is used magnetic resonance and computed tomography [8].

For 3D model, as well as for 1D model, remains a major problem with the definition of appropriate boundary conditions. To solve this problem the boundary conditions are applied from the results of 1D model converting according to appropriate algorithm.

Thus, a correct modeling of the investigated arterial segment (basilar artery) requires development a set of interrelated models 0D, 1D and 3D, which together form a multiscale mathematical model of the hemodynamics of the cardiovascular system (Fig. 5).

This model allows you to combine models of the global hemodynamics, hemodynamic blood stream and local hemodynamics that takes advantage

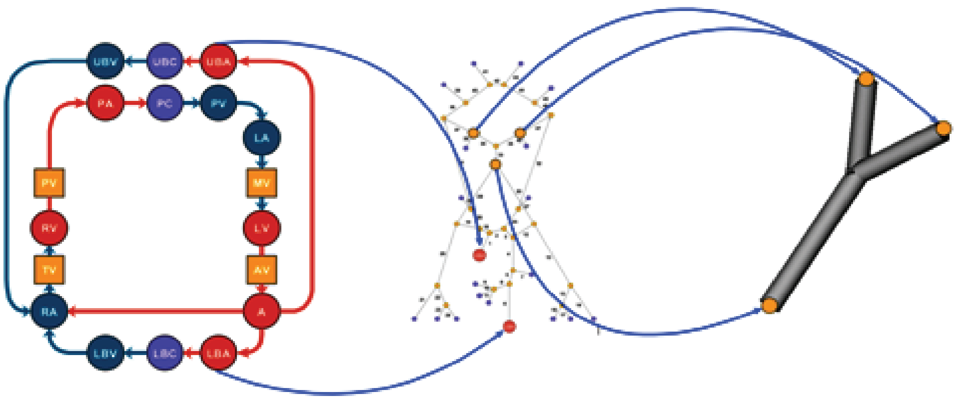


**Fig. 5. Structure of multiscale mathematical model of hemodynamics for basilar artery circulation research**

of each type of models and minimize their weaknesses. For example, a multiscale model of hemodynamics has an opportunity to study the impact of regulation (0D model) at the local segment of cardiovascular system (3D model).

**Experimental set-up.** The experimental set-up is shown in Fig. 6. With laser-Doppler-anemometry it is possible to measure the velocity distribution of a flow with high spatial (70 µm) and temporal (1 ms) resolution in transparent models of human vessels without disturbing the flow [6, 12, 14]. The flow velocity is measured with a 5 mW He-Ne laser-Doppler-anemometer (BBC Goerz. Spectraphysics, Munich, Germany, *5* in Fig. 6) with a wavelength of $\lambda = 632.8$ nm.

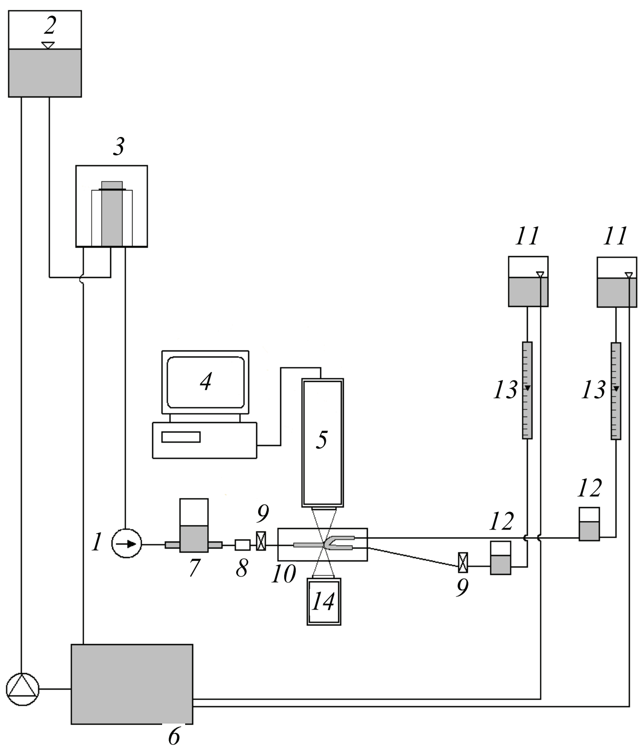


**Fig. 6. Experimental set-up**

The vessel's model is mounted on an *x*-*y*-*z*-moving table so that velocities can be measured and recorded very precisely at each point of interest. In order to obtain a representative picture of the flow, velocity is measured at each point for seven pulse cycles and then averaged.

To simulate the physiological human flow conditions we use a blood-like fluid developed in our laboratory. The perfusion fluid is a transparent glycerol-water mixture to which is added a small amount of Separan AP-302 and Separan AP-45 (Dow Chemical). This fluid exhibits a non-Newtonian flow behavior similar to that of blood.

The perfusion fluid is pumped from a collecting tank (*6* in Fig. 6) through an elevated tank (*2* in Fig. 6) into an overflow tank (*3* in Fig. 6). It maintains a constant static pressure in the model. A computer driven piston pump (*1* in Fig. 6) superimposes an oscillatory pulse on the stationary flow creating a pulsatile flow. Buffer tanks (*7*, *12* in Fig. 6) are installed in front and behind of the model to simulate the compliance of a human aorta. The fluid streams through the model (*10* in Fig. 6) back into the collecting tank (*6* in Fig. 6). Regulation tanks (*11* in Fig. 6) allow an adjustment of the flow rate. Pressure is measured with inductive pressure transducers (*9* in Fig. 6). Systolic and diastolic pressure can be set in the range between 150 and 70 mmHg.

Velocity, pressure and flow rate data obtained with the above described experimental set-up allow to correlate with the mathematical simulation in order to evaluate its reliability.

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## Разработка многоуровневой модели гемодинамики сердечно-сосудистой системы для исследования кровообращения базилярной артерии

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**Ключевые слова и фразы:** гемодинамика; математическая модель; сердечно-сосудистая система.

**Аннотация:** Одним из основных нарушений церебрального кровообращения является аневризма базилярной артерии. Для медицинской практики особый интерес представляют методы прогнозирования появления и развития аневризмы. Одним из наиболее перспективных методов, применяемых в медицине, является математическое моделирование. Предложена концепция построения многоуровневой математической модели гемодинамики сердечно-сосудистой системы, включающей модели глобальной гемодинамики, артериального русла и бифуркации базилярной артерии. Данная модель позволит рассчитать гемодинамические параметры в области бифуркации базилярной артерии. На основе анализа результатов расчета математической модели возможно прогнозирование возникновения аневризмы базилярной артерии.

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