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NUMERICAL ANALYSIS OF THE INFLUENCE OF A CHANGE IN THE VERTEBRAL ARTERIES JOINT ANGLE ON THE BLOOD FLOW

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Abstract

Cerebral circulation can be regarded as the most important element of blood circulation. Total ischaemia of neurotic cells, lasting longer than a few minutes, is irreversible in its consequences and results in their death. Due to that fact, blood must be constantly delivered to this region of human body. The primary system of brain blood supply consists of independent systems of two carotid and vertebral arteries. Vertebral arteries join into a basilar artery. This joint has a specific character as only 2% of all nodes are vessel joints. Moreover, due to its spatial shape, various diameters of inner vessels, various lengths, as well as various joint angles become an area of interesting research. Because of a lack of opportunity in direct diagnosis of this area, numerical experiments on average combinations of geometric models have been carried out. To conduct these investigations, two 3D models of the artery system differing in the value of the joint angle of vertebral arteries and the basilar artery, starting with the aortic ostium and finishing with the basilar artery have been generated. At the inlet to the system, three different velocities of the liquid modelling blood have been applied one by one. The results of the simulation indicate the way the joint angle and velocity change at the inlet influences the character and velocity of the flow in the area under analysis. Also, they clearly show which angle would be better from the view point of the flow hemodynamics.

Key words: vertebral arteries, blood flow, computational fluid dynamics, human vascular system

1. INTRODUCTION

Brain plays a key role in the life maintenance, thus blood has to be supplied constantly without any disturbances to this region of human body (in particular). Thus, the system of blood supply consists of two independent pair of arteries – carotid and vertebral. Vertebral arteries join to form a basilar artery. Such a connection is unique, especially when relatively large arteries are concerned. Only 2% of all arteries joint together to create a larger one [3,5].

Vertebral arteries and the basilar artery are not independent. They are connected to the cerebral arterial circulation (called also Circle of Willis CoW), together with a pair of carotid arteries, which in many cases lets to equilibrate the flow disturbance or insufficiency caused by atherosclerosis occurring in one of the arteries in the system. When a significant narrowing occurs in one of the arteries, a series of different equalizing actions are taken by the organism itself. The most important among them are locally acting regulations of the cerebral flow, an increase of systolic pressure, and in case of long lasting reduction of blood supply, creation of collateral circulation [3,4,6].

Despite of continuous development of diagnosis tools and therapy, Temporary Ischaemic Attacks are recognized too rarely. Especially those caused by changes occurring in vertebral and basilar arteries. The reason for that is a problem with direct examination of this region of the arterial system. Disturbances in blood supply through vertebral and basilar arteries cause ischemia of the neck part of the spinal cord, the brain stem, the cerebellum and the inner ear [2,4,6,13].

2. NUMERICAL EXPERIMENT

Two 3D models of the system of arteries were generated in order to examine an influence of changes of the vertebral arteries joint angle on the blood flow in the basilar artery. Models that differ in the joint angle, starting from the aortic ostium and finishing with the basilar artery, were created. The model of arteries does not correspond to any individual. It is assumed to create a geometry independent of individual, personal differences in artery shape, lengths, diameters and bifurcation angles. Averaged values of the above mentioned were used.

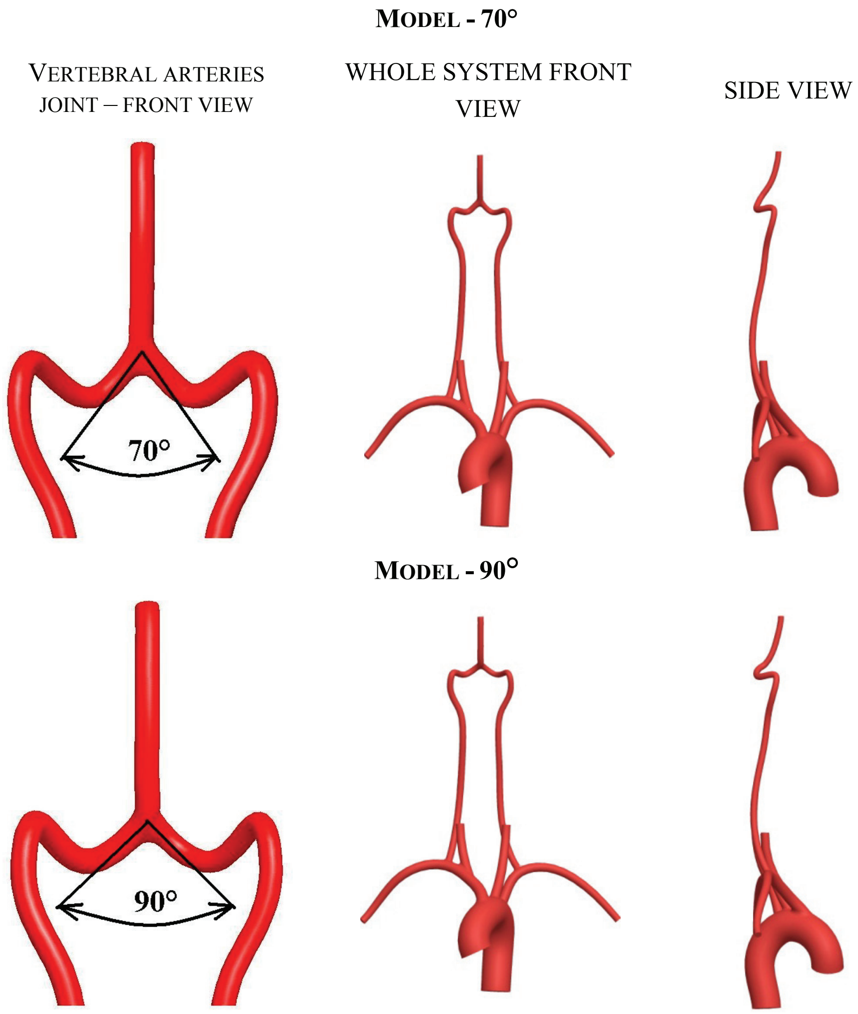

Fig. 1. Geometrical models of the examined arterial system in the region of vertebral arteries.

The models were based on many publications, anatomical atlases, images from ultrasound and angiographic examinations [3, 11]. The only difference is in the vertebral joint angle. The generated models are presented in figure 1.

The models were simplified. Some of the minor arteries were omitted. It is believed that their influence on the flow in the examined system is irrelevant.

On the other hand, it is very important to apply a proper model of fluid in this system. Blood is an extremely complex structure because of numerous functions it plays in organism. It is inhomogeneous and, moreover, its composition changes as a function of a large number of parameters. Moreover, changes in the blood viscosity and density may occur quickly or slowly. Blood is a non-Newtonian fluid. It is characterized by a non-linear dependence of shear stress on strain. For some values of strain, it may be approximated by a linear function. The assumption that blood is a Newtonian fluid is true when the diameter of the artery is relatively large [7,8,9,10,14]. In the presented experiment, diameters of arteries are from the value 3.5 mm in case of the left vertebral artery up to 28 mm in the aorta. Thus, it has been decided to use a Newtonian blood model.

A value of the dynamic viscosity coefficient of blood changes in the range $3 \div 4 \cdot 10^{-3}$ Pas. The dynamic viscosity coefficient for the described experiment was defined as:

$$\eta = 0.00345\,Pas \tag{1}$$

where η – dynamic viscosity coefficient.

It is known that density of human blood depends on many different factors as: age, sex, some medicines, etc. and it ranges from 1035 kg/m^3 to 1070 kg/m^3. Density in the experiment was defined to be equal to 1040 kg/m^3 [10].

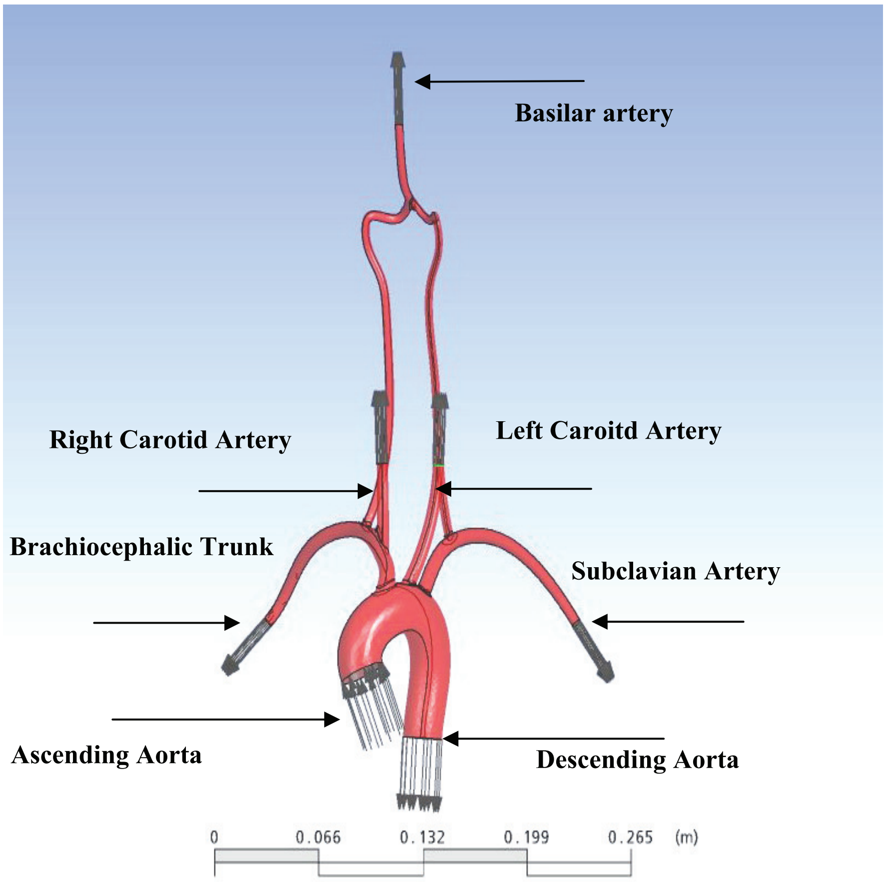

Fig. 2. Model with the defined cross sections for boundary condition assignment.

The experiment was conducted for steady state calculations. The examined system had one inlet and six outlets defined (see figure 2).

It is necessary to define proper boundary conditions to conduct numerical simulations. In the cross section called aortic ostium (see figure 2), velocity was assigned as the inlet condition, whereas in all the other artery cross sections of the model, the outlet condition with static pressure was applied. The presented models were examined with three different pairs of boundary conditions: for the inlet velocity equal to 0.5 m/s, 1 m/s and 1.5 m/s. Static pressure at the outlets was defined as 11 kPa in all the cases.

Another key factor to obtain proper numerical experiment calculation is an application of the turbulence model adequate for the flow conditions. The Shear Stress Transport model was used in the presented case. The SST model is a combination of two models – k-ε and k-ω Wilcox model. The main advantage and reason for its application in this experiment is very good prediction of the flow in the near-wall region, especially for low Reynolds number flows [1,12]. The initial conditions for the calculations were assigned automatically by the software. The unstructural meshes were created in the Ansys CFX-Mesher. They consists of tetrahedral elements in the central part of the channels and prisms in the near-wall regions. Independence tests were conducted. They showed that mesh consisting of $1 \cdot 10^6$ elements was accurate enough to achieve the y^+ parameter close to 2. This is a satisfactory level when the SST turbulence model is used. All of the cases reached convergence at a very high level. The domain imbalance of all the momentum and mass functions was smaller than 0.001% in each case.

3. RESULTS OF THE NUMERICAL SYMULATION

The aim of the conducted numerical experiment was to analyze and visualize the hemodynamic phenomena occurring in the joint of vertebral arteries for different angle connections.

Two different geometrical models for each three different boundary conditions were applied and simulated. The results of six simulations are described in this paper. In order to achieve the aim, several test the surfaces were created (see vector plots in figure 3):

- at the ends of vertebral arteries just in front of the joint,
- in the connection of the vertebral arteries,
- in the centre of the joint,
- at the beginning of the basilar artery.

Velocity profiles in the ending part of vertebral arteries highly depend on their curvature in the former part. Two 3D bends cause a deformation of the main stream velocity profile towards the outer side of the curvature. After passing through a series of bends, the velocity profile is flattened when compared to the parabolic profile typical of the laminar flow.

4. CONCLUSIONS

The conducted simulations and the analysis of the obtained results point out to a lack of back influence of the joint of arteries on the flow in their end part just in front of the joint. An increase of the velocity in the analyzed cases caused a deformation of the velocity profile in the perpendicular control surface towards the extremity of the arc of the bending (see figure 4). This phenomenon is explained by inertia forces acting on elements of the fluid.

In the joint of vertebral arteries, an interaction of the streams coming out from the left and right vertebral arteries can be seen in figure 5. In this place the velocity profile has a shape of two humps with the

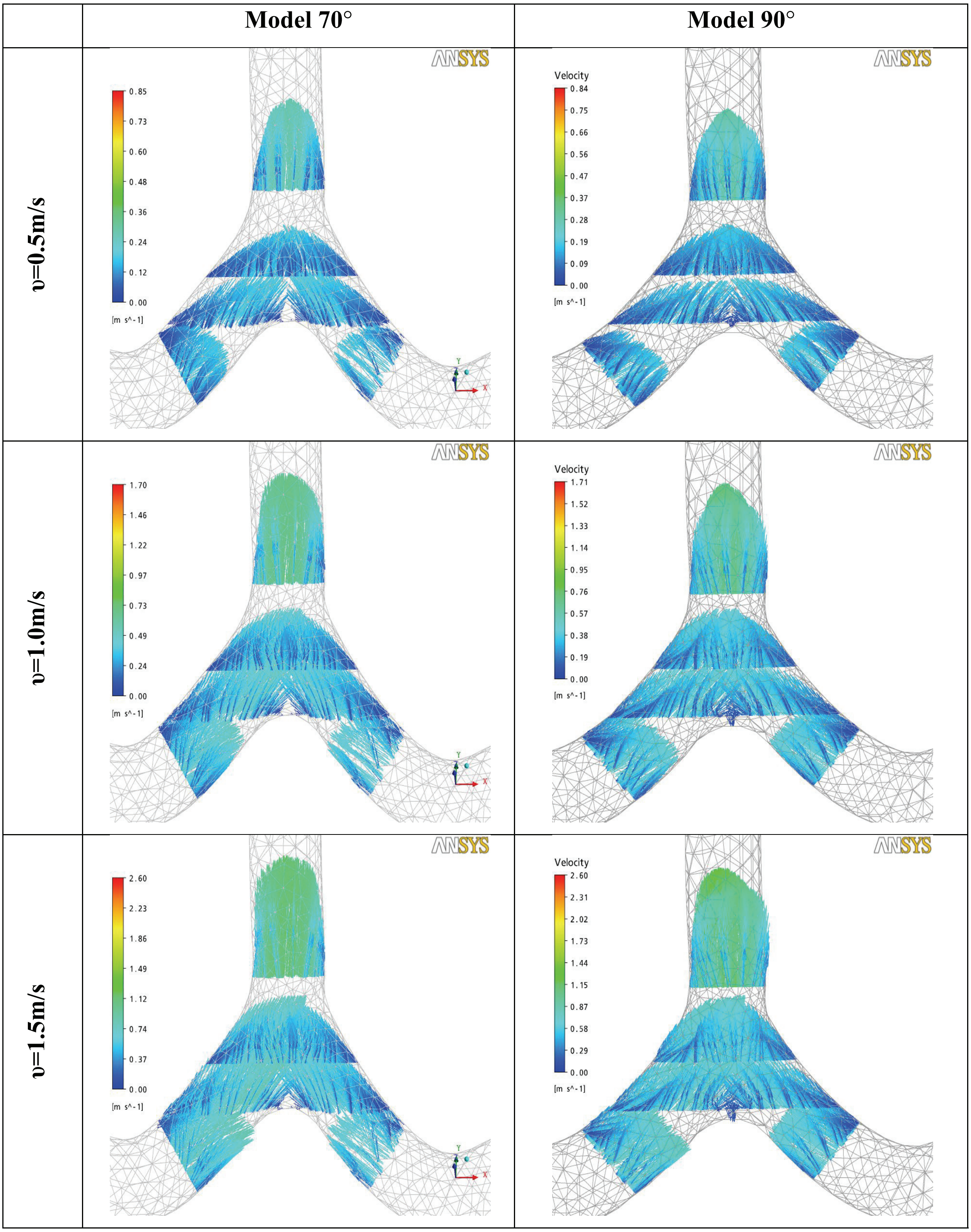

Fig. 3. Velocity profiles at the vertebral arteries joint for two geometrical models and three pairs of boundary conditions.

minimum placed in the middle following the inlet streams entering the basilar artery. Profiles are deformed in the near-wall region at the beginning of the basilar artery. Those deformations are observed independently of the velocity of the fluid flowing in the channel. They are explained by separation flows observed in this region of the system, they delay blood in the wall region. In the centre, an increase in the velocity is observed.

In the upper part of the basilar artery, far from the vertebral artery junction, a parabolic shape of the velocity profile is observed (see figure 6). The flow is stabilized and may be considered symmetrical around the vertical axis.

An increase in the vertebral arteries junction angle causes a decrease of the mean velocity for all boundary velocities assumed at the inlet to the system. The mean velocity, presented in figure 7, represents the mass flow of the fluid. Thus, for the junction angle equal to 70º, an interaction of the streams is stronger and it causes higher losses.

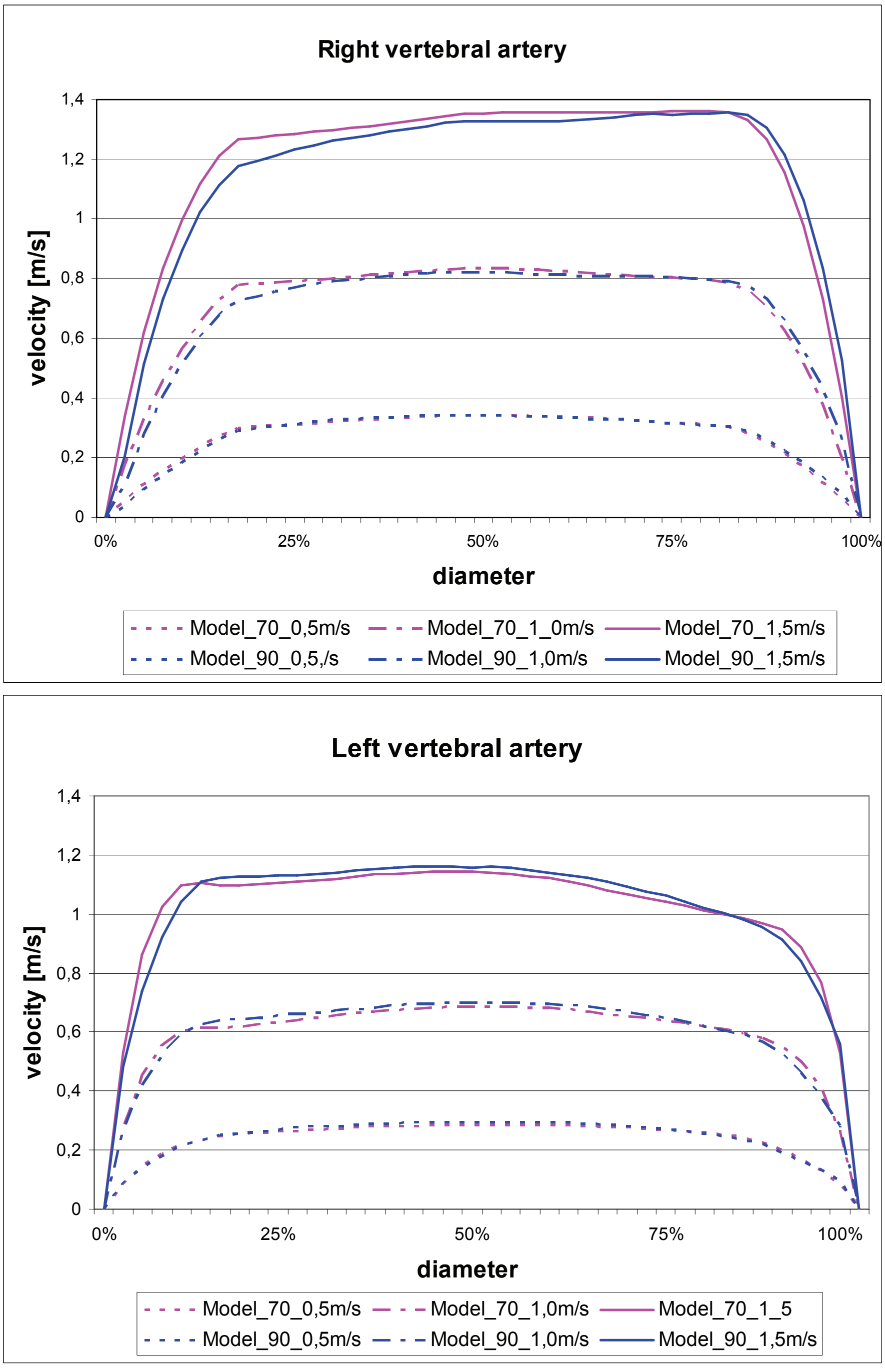

Fig. 4. *Influence of the vertebral arteries joint angle change and velocity on the shape of the velocity profile in the right and left vertebral artery.*

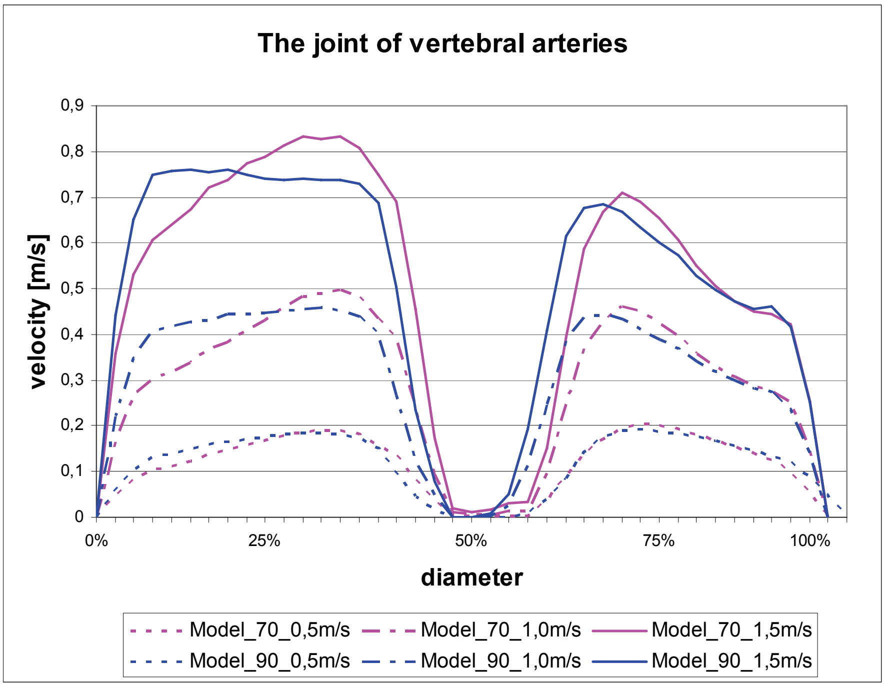

Fig. 5. *Influence of the vertebral arteries joint angle change and velocity on the shape of the velocity profile in the joint.*

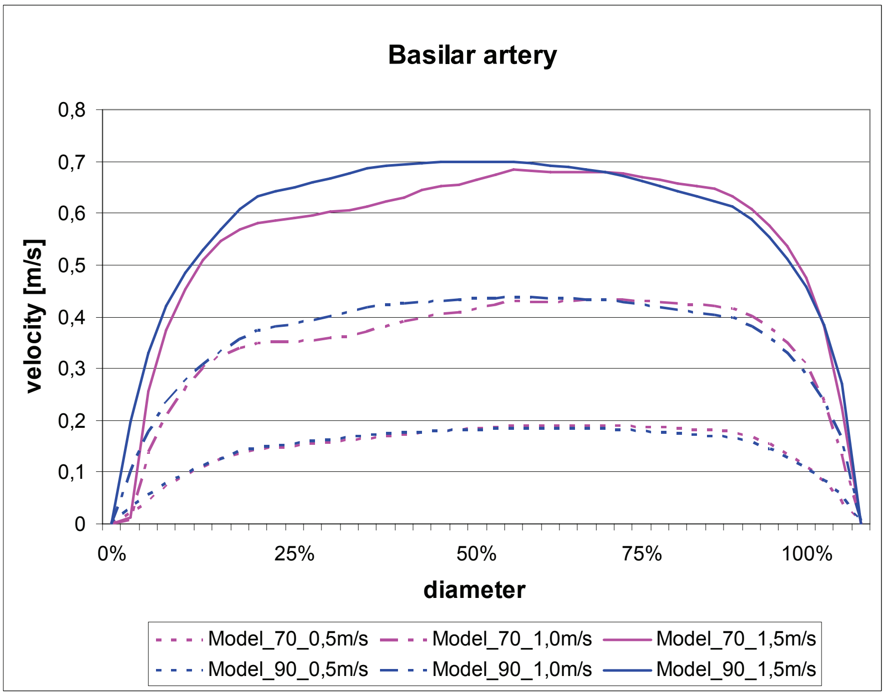

Fig. 6. *Influence of the vertebral arteries joint angle change and velocity on the shape of the velocity profile in basilar artery.*

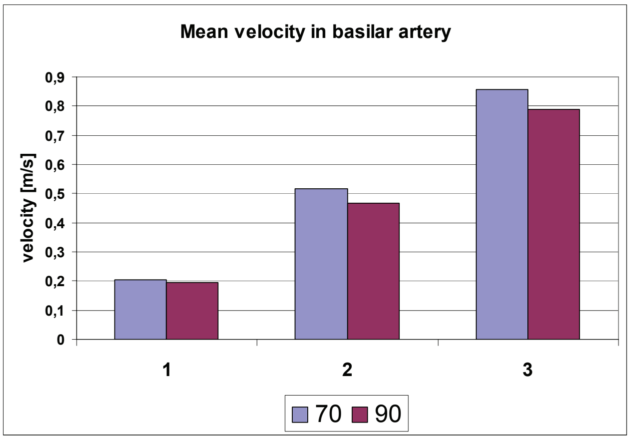

Fig. 7. *Mean velocity in the basilar artery 1) 0.5 m/s, 2) 1.0 m/s, 3) 1.5 m/s.*

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ANALIZA NUMERYCZNA WPŁYWU ZMIANY KĄTA POŁĄCZENIA TĘTNIC KRĘGOWYCH NA PRZEPŁYW KRWI

Streszczenie

Krążenie mózgowe można uznać za najważniejszy element krążenia krwi. Całkowite niedokrwienie komórek nerwowych trwające dłużej niż kilka minut jest nieodwracalne w skutkach i powoduje ich obumieranie. W związku z tym, krew musi być nieustannie dostarczana do tego regionu ludzkiego ciała. W skład głównego systemu zasilania mózgu w krew wchodzą niezależne układy dwóch tętnic szyjnych oraz kręgowych. Tętnice kręgowe łączą się tworząc tętnicę podstawną. Zespolenie to ma osobliwy charakter, gdyż tylko 2% wszystkich węzłów naczyniowych stanowią połączenia naczyń. Ponadto, ze względu na przestrzenny kształt, różne średnice wewnętrzne naczyń, różne ich długości jak również różne kąty zespolenia stanowi ono interesujący obszar badań. Ze względu na brak bezpośredniej możliwości diagnostyki tego obszaru, przeprowadzono badania numeryczne na uśrednionych wariantach geometrycznych modelu. Do ich przeprowadzenia zostały wygenerowane dwa modele 3D układu tętnic, różniących się wartością kąta zespolenia tętnic kręgowych w tętnicę podstawną, począwszy od aorty, kończąc na tętnicy podstawnej. Na wlocie do układu zadawane były kolejno trzy różne prędkości płynącego czynnika modulującego krew. Uzyskane wyniki symulacji pokazały jak zmiana kąta zespolenia i prędkości na wlocie wpływa na charakter i prędkość przepływu w badanym rejonie, który kąt byłby lepszy ze względu na hemodynamikę przypływu.

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