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NUMERICAL STUDY OF A FLOW IN THE CEREBRAL ARTERIAL CIRCLE

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Abstract

Blood is supplied to the brain by two internal carotid and two vertebral arteries. These arteries join to form the cerebral arterial circle (also called the Circle of Willis or the CoW). This unique arrangement of human vessels ensures blood supply to the brain in spite of any pathology in the geometry of arteries supplying the brain.

Computed Tomography was used in this case for imagining the CoW and the arteries supplying it. The images obtained during the test were employed to develop a numerical model of one particular patient's vessels geometry. Nowadays, with the use of numerical methods, it is possible to simulate a real flow within the region where no other method can be used, and thus one can analyze an influence of the pathological narrowing onto the cerebral perfusion.

Using Computed Tomography, a large series of two-dimensional X-ray images were taken along the patient's axis during one test. The distance between individual images was 0.6 mm. Vessels - as they are soft tissues - have to be visualized with contrast. On the basis of those images, a three-dimensional path of the single artery was studied and its geometry was generated in CAD software (SolidWorks). Then, a 3D mesh was generated using the CFX Mesh code. The numerical experiment, with use of the Ansys CFX code, was carried out for different velocities within the physiological range. Blood was modelled as a Newtonian fluid.

Key words: Circle of Willis, blood model, CT reconstruction, blood flow, human vascular system

NOMENCLATURE

A2 – 2 segment of ACoA
ACA L,A1 – Anterior cerebral artery A1segment
ACoA L – Anterior communicating Artery (left)
ACoA R – Anterior communicating artery (right)
BA – Basilar artery
CoW – Circle of Willis, cerebral arterial circle
ICA L – Internal carotid artery (left)
ICA R – Internal carotid artery (right)
MCA L – Middle cerebral artery (left)
MCA R – Middle cerebral artery (right)
P – Posterior Artery
PCoA L – Posterior Communicating artery (left)
PCoA R – Posterior Communicating artery (right)

1. INTRODUCTION

The Cerebral arterial circle (Circle of Willis or the CoW) is one of the most important arterial systems in human body. Its task is to deliver blood to the Central Nervous System. A break in the blood supply to the brain longer than 10 sec. causes unconsciousness. Within this time, the cerebral cortex may be damaged and in spite of return at the proper blood flow, all the intellectual functions may never return [5]. The other reason why the CoW is considered to be unique is its structure and a very complicated geometry that causes many diagnostic problems and difficulties. Modern diagnostic tools and methods do not allow one to estimate results of surgery with

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high accuracy. Due to the crucial function played by the CoW, such an operation is always an enormous risk for the patient's life and a challenge for the surgeon. Development of computer science enables us to model many phenomena, including those occurring in human body. Present diagnostic methods, especially computer tomography, enable the reconstruction of complex geometrical structures in the Computer Aided Design software. Thus, the blood vessel system, which is very complicated and characteristic for each individual, has been reconstructed on the basis of computer tomography images. A flow simulation of the liquid modelling blood through the unique geometry of the vessel system of the particular person allows one to estimate regularity of the inflow of blood to the CoW and threads caused by possible pathologies.

2. RESEARCH OBJECT

The first step of the flow simulation through the cerebral arterial circle was a 3D geometry reconstruction consisting of its main arteries and its unique topology. The geometry was based on images gained during the computer tomography examination. The methodology used to reconstruct the geometry in the CAD system is presented in figure 1.

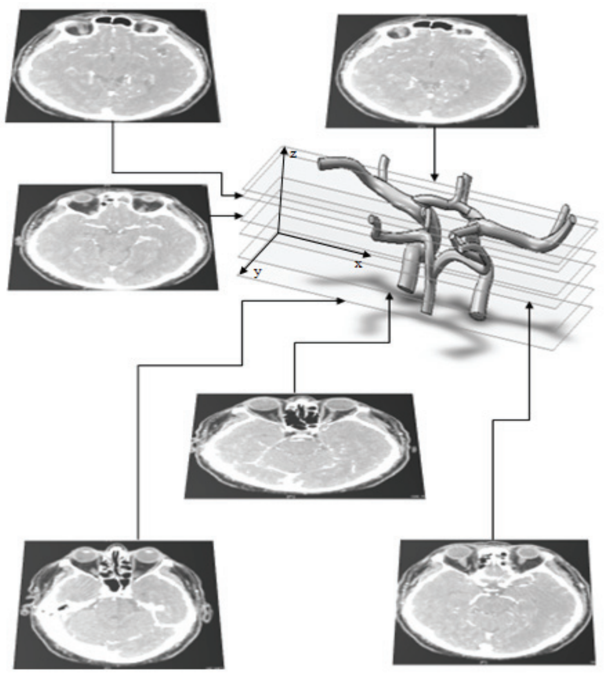

Fig. 1. Method used to reconstruct the artery geometry on the basis of Computer Tomography images.

A reconstruction of the 3D artery model structure was achieved by creation of virtual planes following the tomography image planes. Then, coordinate points corresponding to the artery centreline were placed on them. Finally, the points were connected with a spline. The same procedure was used for all arteries. The last stage was a radius assignment in the places the arteries join. The reconstructed structure of the cerebral arterial circle is presented in green in figure 2.

For purpose of this numerical experiment, an unstructured mesh was created. The Ansys CFX Mesh software was used to generate a mesh. Tetrahedral and prism elements were used in the near-wall regions. Prismatic elements for good refinement of the mesh in the boundary layer were employed.

Channels of arteries were extended to avoid an influence of inlet and outlet boundary conditions on the flow in the regions under analysis. The extension of channels is marked in blue in figure 2.

A Newtonian model of blood was used in the presented numerical experiment. The dynamic viscosity coefficient was defined as $\eta=0.00345\ Pa \cdot s$ (according to different sources, the blood dynamic viscosity coefficient may differ in the range $3\div4\cdot10^{-3}\ Pas$). The density of blood was defined as $\rho = 1040\ kg/m^3$(human blood has a constant density in the range of pressures analyzed but depending on age, sex and other factors - it can vary in the range $1035\div1070\ kg/m^3$) [7,8,10].

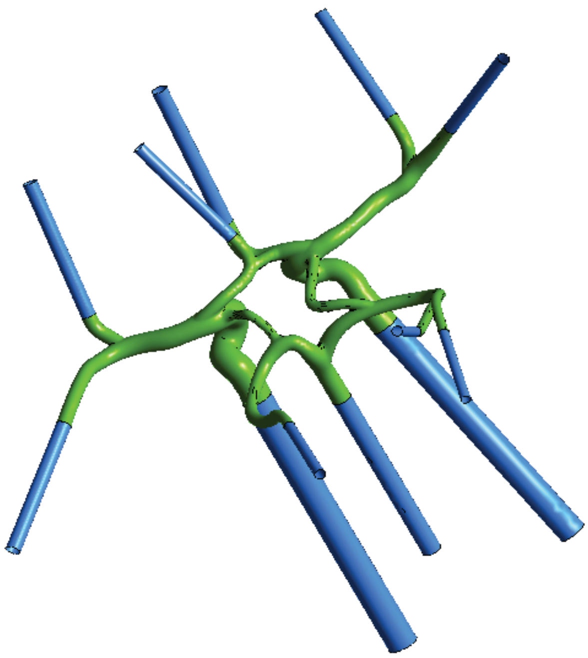

Fig. 2. Reconstructed Circle of Willis (green) and extensions of inlet and outlet channels (blue).

A SST (Shear Stress Transport) turbulence model was used in the numerical experiment. It is based on two models – the k-ε and the k-ω Wilcox model. The SST model is used due to its good velocity estimation in boundary layers for low Reynolds numbers. The only requirement in this case is mesh refinement to achieve the y^+ parameter below 20 [11]. In the case for which velocity in the system was highest, the maximum y^+ in the domain was equal to 2.43. The calculations were conducted as a steady state case. The walls of the arteries were assumed nondeformable.

The reconstruction of geometry of the arterial structure in the presented form allowed us to examine some selected configurations of the blood supply to the system. To achieve a proper velocity distribution at the inlet cross-section of the arteries supplying blood to the CoW, a Prandtl model [6] was used. This allows for preparing a shorter extension channel than in case of a homogeneous velocity distribution in the inlet cross-section. If the Prandtl model and shorter inlet extension channels are used, the calculation time is shortened by 40%.

3. RESULTS

The numerical experiment was conducted for three different sets of boundary conditions. Inlet conditions were based on the ultrasound test. Velocity in vertebral arteries and the basilar artery differs from that in internal carotid arteries (see figure 3). An influence of supply changes was tested. The values of the defined velocities are in the range of physiological values and they were assigned according to Doppler ultrasound measurements [9]. Differences in velocity values at the inlets follow a pulsation of the flow caused by heart beat. It is then possible to analyze a flow in the CoW for different stages of the heart cycle. Due to difficulties in pressure measurements in cerebral arteries, the boundary condition for all outlet cross-sections in all three simulations was the same and equal to 11kPa. Sets of boundary conditions are listed in table 1.

The visualization of a flow inside the CoW was the main aim of the presented numerical experiment. A comparison of the results of three simulations is shown in figure 4. As has been expected, higher

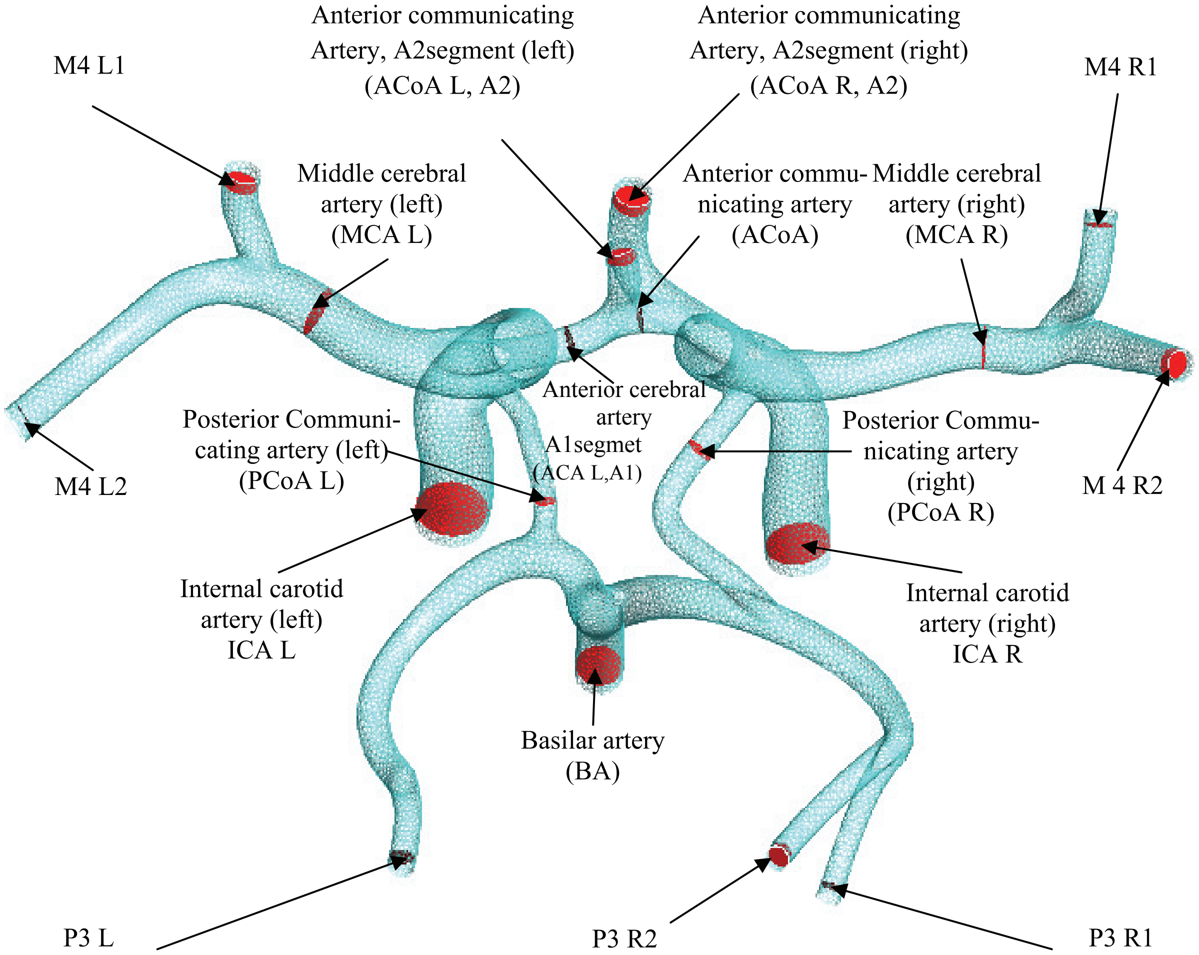

Fig. 3. *Description of boundary cross-sections and test planes.*

velocities in the system are observed if a higher velocity was defined at inlets. As can be seen in the figures, a flow through the cerebral arterial circle may be divided into two parts – front and back. In all cases, front arteries (ACoA, MCA) are supplied mainly by carotid arteries and the back part (P) is supplied by the basilar artery. Posterior communicating arteries (PCoAL and PCoAR) are employed only if a difference in the mass flow between front and back parts is significant. In simulation 1 case, some flow is observed from the basilar artery towards the front part of the CoW, whereas in the case of simulation 3 it is opposite. Simulation 2 may be considered as the equilibrium between the front and back part cases.

Table 1. *Boundary conditions applied in the tested cases.*

	Inlet			Outlet
	ICA L	BA	ICA R	
Simulation 1	0.2 m/s	0.25 m/s	0.2 m/s	11 kPa
Simulation 2	0.3 m/s	0.25 m/s	0.3 m/s	11 kPa
Simulation 3	0.5 m/s	0.3 m/s	0.5 m/s	11 kPa

A distribution of blood through the cerebral arterial circle to different parts of the brain was the object of interest. When one part of the brain is active, the absorption of oxygen, and thus the blood saturation is higher than for the other parts. If this lasts for a relatively long time, one can expect an enlargement of the diameter of the arteries supplying this particular part. The artery diameters of the patient examined are larger on the right-hand side of the CoW structure, which probably follows from a higher demand for oxygen in this region of the brain.

For all the experimental cases, most of blood is supplied to the CoW by the Left Internal Carotid Artery (see figure 5). It is caused by the particular anatomical structure of the examined person. This structural asymmetry illustrated in figures 3 and 4 follows from abnormalities in blood flowing out of the basilar artery (i.e. atherosclerosis in the basilar artery or in one of vertebral arteries). As a result of that flow insufficiency, the blood flow is compensated by the ICA L. It should be emphasized that inlet velocities for both ICA were of the same value.

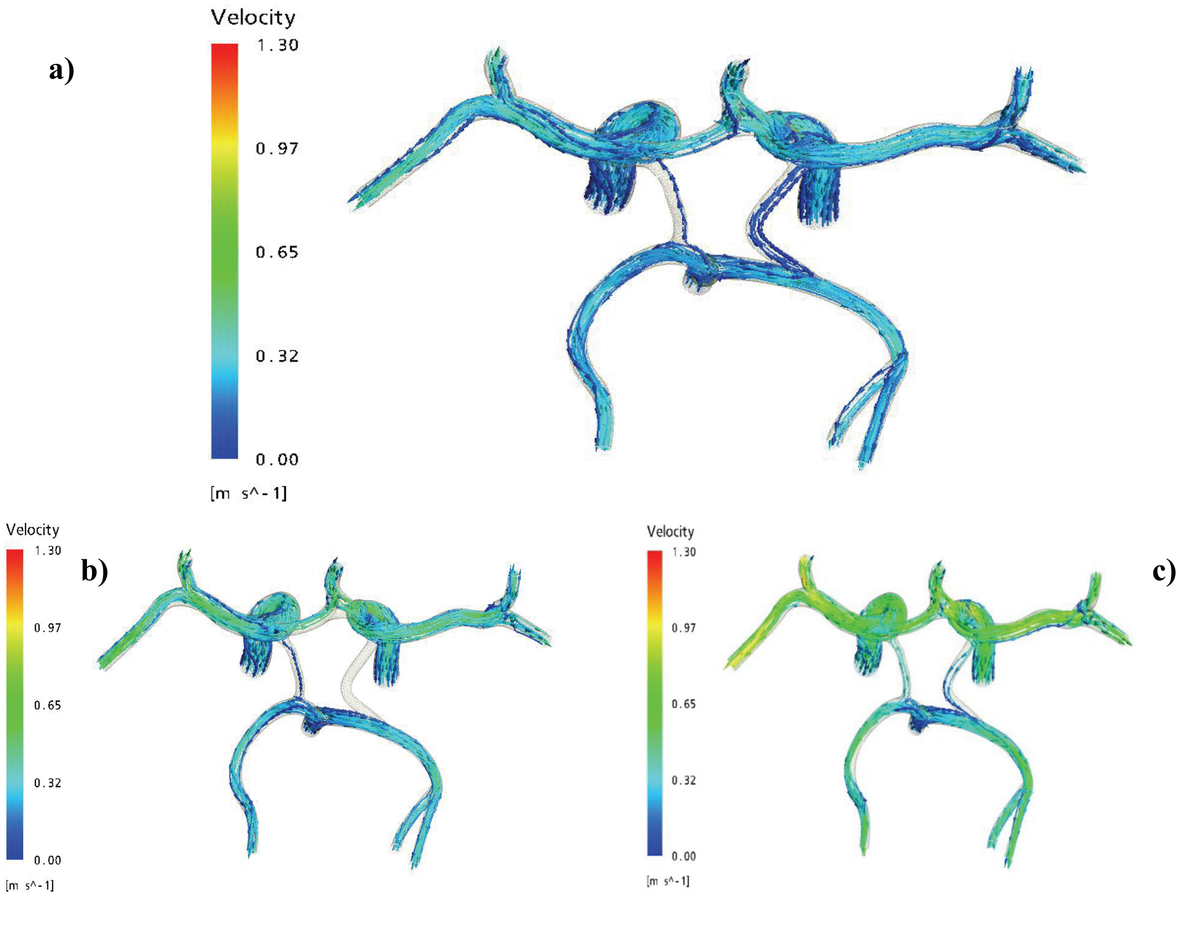

Fig. 4. *Visualisation of a flow for three cases a) simulation 1, b) simulation 2, c) simulation 3.*

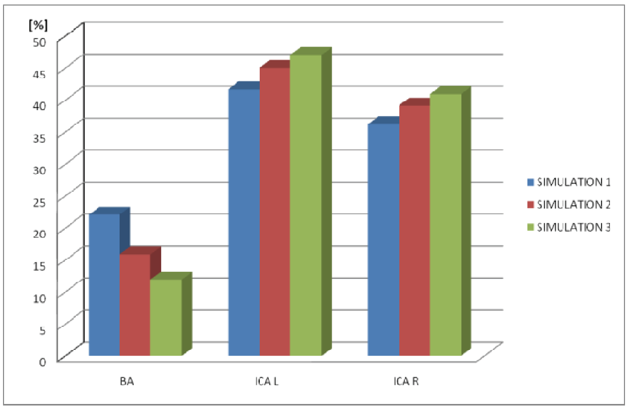

Fig. 5. Balance of the blood mass flow supply for all arteries.

A balance of the outflow is presented in figure 6. A correlation of the blood flow in the CoW with the anatomical structure is confirmed. The inlet velocity increase causes a proportional increase of outlet velocities only for relatively large arteries of a diameter higher than 2.7 mm. When smaller vessels are concerned, an influence of the boundary layer on velocity may be of a higher magnitude.

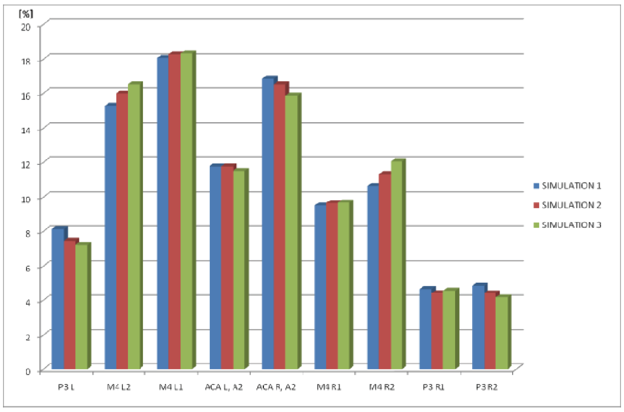

Fig. 6. *Balance of the blood mass flow outflow for all arteries.*

One of the most interesting aspects of the cerebral arterial circle is an existence of Posterior Communicating Arteries. For the first simulation, a mass flow rate for both PCoA is similar – nearly 0.2 g/s and is directed from the back to front part of the CoW. In the simulation 2 and 3 case, a flow is reversed. It may be stated that simulation 2 represents the equilibrium between the front and back brain blood supply. In figure 7, a flow rate through PCoA L, PCoA R and ACoA is compared.

The mass flow visualized in the graph in figure 7 does not correspond proportionally to the inlet velocity changes. Thus, the structure geometry is a determinant factor for the flow in the cerebral arterial circle.

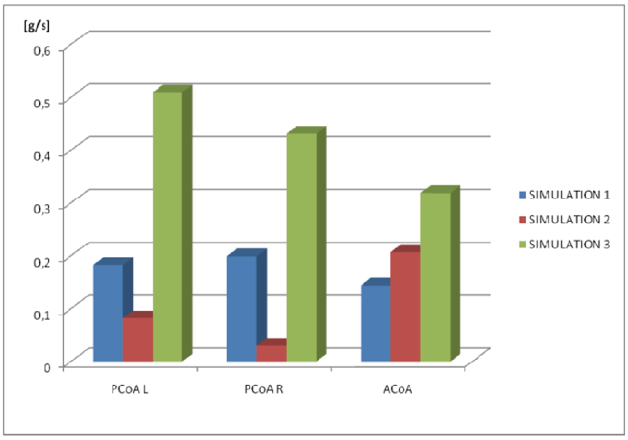

Fig. 7. *Mass flow through Communication Arteries for all cases simulated.*

4. CONCLUSIONS

The simulations conducted within the presented numerical experiment show a significant influence of the geometrical structure of the CoW on the blood flow. In the case under examination, most of blood is supplied to the brain through the ICA L in the range from 42% up to 47 %, whereas through the ICA R, it is from 36% up to 41%. The basilar artery supplies from 12% to 22% of blood. A conclusion may be drawn that the insufficient flow through the basilar artery is compensated by blood from the ICA L. As a result, the left side of the examined system delivers 65% of the total blood supplying the brain. The long-lasting overload of a part of arteries may be the reason of aneurysm occurrence in the arterial system.

An analysis of the flow can help in finding optimal flow rates supplying blood to the brain and then in proposing a type of surgery the patient should undergo. Numerical simulations of the cerebral arterial system can be used in the future as a part of the diagnosis for patients having arterial system disorders.

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SYMULACJE NUMERYCZNE PRZEPŁYWU W KOLE TĘTNICZYM MÓZGU

Streszczenie

Głównymi tętnicami dostarczającymi krew do mózgu są dwie tętnice szyjne wewnętrzne oraz dwie tętnice kręgowe. Naczynia te łączą się w jamie czaszki tworząc koło tętnicze mózgu (koło Willisa). Układ ten ma za zadanie zapewnienie prawidłowego ukrwienia mózgu bez względu na zmiany patologiczne w geometrii naczyń zasilających mózg.

W pracy tej posłużono się komputerową tomografią, jako sposobem obrazowania naczyń krwionośnych. Zastosowanie obrazów z TK pozwoliło na zbudowanie modelu numerycznego koła Willisa dla indywidualnego przypadku danego pacjenta. W chwili obecnej posługując się metodami numerycznymi możliwe jest odtworzenie rzeczywistego przepływu krwi w obszarze, jak i zbadać wpływ anomalii w budowie naczyń na ukrwienie mózgu.

Podstawą do zbudowania modelu były serie obrazów pozyskanych w czasie badania z wykorzystaniem tomografii komputerowej. W metodzie tej generowany jest obraz 2D na płaszczyznach prostopadłych do głównej osi pacjenta. Płaszczyzny oddalone są od siebie o 0,6 [mm]. Dla uwidocznienia naczyń krwionośnych, które są tkanką miękką, dodano środka kontrastującego. Na podstawie tych obrazów odwzorowano trójwymiarową ścieżkę osi każdego z kanałów. Kolejnym etapem było przeniesienie danych do programu SolidWorks. Następnie wygenerowana została siatka przestrzenna, do wykonania której wykorzystano oprogramowanie CFX Mesh. Symulacje przeprowadzone zostały dla różnych charakterystycznych wartości prędkości z zakresu prędkości fizjologicznych występujących w układzie krwionośnym. Krew została zdefiniowana jako ciecz Newtonowska.

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