The modeling of hemodynamic changes in cerebral arteries and cerebral aneurysms under condition of cerebral angiospasm

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Authors: E. Grigorieva\textsuperscript{1}, V. Krylov\textsuperscript{2}, A. Prirodov\textsuperscript{2}, A. Gavrilov\textsuperscript{2}; \textsuperscript{1}Fryazino/RU, \textsuperscript{2}Moscow/RU
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Aims and objectives

Angiospasm is the most frequent and serious complication of nontraumatic subarachnoid hemorrhage (SAH) and accounts for 23% of disability and mortality associated with SAH (2,3). Repeated bleeding from arterial aneurysm is another reason for defining adverse outcomes of treatment, which are found in 17.3 % of cases (2).

There are some known risk factors for vascular spasm and re- rupture of the aneurysm, obtained from the study of the disease, estimates of the intensity and extent of hemorrhage, the anatomical features of the aneurysm (its location, size, shape, etc.). Systemic hemodynamic factors and regional nature may also be predictors of re-rupture of the aneurysm and the risk of cerebral ischemia due to vasospasm (4).

The objective of the investigation is to study the changes of blood streams and main hemodynamic parameters with the help of mathematical modeling of blood flow through cerebral arteries and in cerebral aneurysm when the vessel lumen is constant and in the case of various variants of angiospasm.
Methods and materials

We used the computer simulation to determine the changes of hemodynamic parameters in aneurysm, occurring due to angiospasm of afferent vessels by an example of the model of cerebral aneurysm created with the usage of computer design as well as by 2 examples of models of basilar aneurysm and anterior communicating aneurysm based on the data of computed tomography angiography (CTA). We examined the influence of changed blood flow velocity and shape of blood flow profiles on to the wall surface shear stress especially under conditions of blood flow changes because of various variants of afferent vessels angiospasm.

For both groups of experiments believed that the movement of blood through the vessels subjects to the laws of hydrodynamics (1).

To simplify the understanding of the physical processes it's assumed in most of our studies that the vascular wall is not rigid and deformed when passing pulse wave, therefore, the motion of a viscous fluid takes place on the walls of its inhibition, extending deep into the flow from the wall for some distance.

For execution of mathematical modeling of blood flow was needed to determine its nature - laminar or turbulent. Our preliminary study showed that Reynolds number for the blood flow in the vessels and intracranial aneurysms is in the range from 500 to 2800 or more. Therefore, blood flow in the cerebral arteries can't be considered as laminar. In the simulation, we also believed that blood is incompressible and does not alter the viscosity depending on the speed (so called Newtonian fluid). So that movement of blood through the cerebral vessels can be described by the continuity equation of fluid flow and the Navier-Stokes equations for incompressible flows (5)

Solution of the equations is performed numerically using the finite element method. Numerical solution of equations allows us to obtain the values of hemodynamic parameters at each point of the vessel and the aneurysm, where the fluid is moving. To solve the equations introduced appropriate initial and boundary conditions. To describe the geometric models of vessels and aneurysms used about 240,000 volumetric finite elements, which were separated. At the boundaries of vessels and bending elements mesh wondered smaller and more regularly for more accurate calculation of the interaction with the walls of the blood vessel. To study the shear stress on the simulated vessels served pulsating flow rate sine wave with a minimum value of 0.3 ml / s, the maximum value of 1 ml / s and the oscillation period of 1s, which roughly corresponds to the real conditions of the passage of the pulse wave. On the walls of blood vessels used fluid slip condition to the wall. The density of blood was taken as 1050kg/m3, blood viscosity - 0,004 Pa · s, which corresponds to the values for normal blood (2). Temperature and external forces in the calculation of the flow does not take into account.
To investigate the hemodynamic processes occurring in the aneurysm and the impact of narrowing of the lumen of the afferent vessel on to hemodynamics in the aneurysm, the computer-aided design simulation was used. The inner diameter of vessel was 3mm, which corresponds to the average diameter of the middle cerebral artery (4). Spasm portion has a diameter of about 1.5 mm, corresponding to moderate angiospasms by the data of radiological methods (cerebral angiography, and transcranial Doppler) (4). (Fig.1)
Fig. 1: Building of 3D-anatomical model of vessels and aneurysm: A - visualization of 3D CT data. B - 3D-frame, received by usage of matching cubes algorithm. C - 3D-anatomical model, resultant smooth surface of vessels and aneurysm.

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Results

The simulation results of hemodynamic characteristics for peak pulse wave model without angiospasm and with local spasm of afferent vessel produced on computer models are shown in Figures 2-3. We see, that increasing of curvature of afferent vessel leads to increasing of blood hitting area within the aneurism. In the case of local spasm of afferent vessel the blood flow velocity was increased significantly in the spasm vessels' portion and, consequently, in the aneurysm. In an unchanged aneurysm afferent vessels flow rate was ~ 0.1 m / s, against the vessel spasm resulting ~ 0.8 m / s. Simultaneously in the narrowed part of the vessel the blood stream was more concentrated and has changed its direction in aneurism, as shown in Figure 3B. If in case the unmodified vessel (Fig. 2A), the flow hits the wall of the distal aneurysm and out of it in a proximal neck portion. In the case of spasms vessel (Fig. 2B, 3B), the flow enters the aneurysm proximal neck portion and out in its distal part. At the same time along the surface of the aneurysm a significantly higher flow rate is observed.

The calculated wall surface shear stress that occurs on the inner surface of vessels and aneurysms due to viscous friction of the blood are shown in Figure 4. Vascular spasm of the afferent vessel leads to significantly increasing of the area and the impact force on the aneurism’s wall and accordingly, the increasing of wall shear stress in the vessel as well as in the aneurysm. So that, the local spasm of afferent vessel resulting to significantly higher shear stress in the aneurysm in place of the shock wave hits (~ 15Pa, for red) than if no spasm of afferent vessels (~ 4PA corresponds to the color blue).

For the construction of anatomical models of vessels and aneurysms in the individual patients the data obtained from the CT-angiography were used. 3D visualization of the CT data set produced by the scan volume (1,10,14,36). Construction of a three-dimensional mesh surface vessels and aneurysms performed using marching cubes algorithm (24,27,31). The resulting grid for removal of noise smoothing algorithm has been processed (Fig. 1).

Different forms of afferent vessels spasm were modeled on 3D anatomical models, including diffuse spasm of the whole afferent, local spasm directly in front of the aneurysm and spasm of the afferent vessel in two places: directly in front of the aneurysm and its distal portion (so-called tandem spasm). Flow modeling simulated under the same conditions as in the computer-aided design models.

In the same way with models constructed using computer-assisted design of the anatomy, it is obvious that the vessel spasm resulting accompanied by a significant increase in the rate of flow and change in profile both in the vessel and aneurysm, as shown on Figure 5. Moreover, it is noted that the most severe changes of blood hit in aneurysm is observed in the case of so called tandem spasm. It is obvious when comparing of flow rate at points TA, TB, TG and TV on the surface of the aneurysm (Fig.5). The flow rate at point TG (0.93m/s) is almost 2.8 times greater than at point TA.
(0.33m/s), that means the kinetic energy of the flow at point TG is 7.9 times larger than at point TA. The same way, the shear stress in the wall of the aneurysm in the region of the TG is 7.6 times higher than at corresponding point on the wall of the aneurysm in TA and is higher than in the areas corresponding to the remaining points. The simulation results show that two consecutive areas of spasm form the more "focused" shape of blood flow with more concentrated flow hit on the wall of aneurysm.

The interesting hemodynamic situation may arise in the aneurysm, which is formed at the confluence of two blood vessels (for example anterior communicating artery aneurysm). The direction and shape of blood flow in such kind of aneurysm considerably change at a spasm of one of afferent vessels (Fig.6). In the absent of spasm blood flow of every A1 segment of anterior cerebral artery will proceed through the aneurysm to the A2 segment corresponding artery. In the case of the spasm of one A1 segment blood flow in it will be separated because of the higher speed and re-directed through aneurysm to the opposite A2 segment of anterior cerebral artery. Thus, a crossing of the blood flow in aneurysm forms and the flow pattern basically changes. The higher speed in the narrowed vessel causes a pronounced increase in shear stress, especially in the point of maximum blood strike in the neck of aneurysm (Fig.7 shows maximum shear stress in OA as 4.9Pa, in OB 18.5Pa). As we see, the surface area of the aneurysm with high shear stress of more than 9 times greater then in the absence of spasm.
Fig. 2: The shapes of blood streams in the vessels, whose surfaces were built with the help of computer design. The directions of blood streams are shown by lines of blood flow directions. The values of blood flow velocity are marked by colors, which are corresponded to the velocity scales in figures. The yellow arrows show the direction of blood flow in afferent vessel.

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Fig. 3: The shapes of blood streams in the vessels, whose surfaces were built with the help of computer design. The directions of blood streams are shown by lines of blood flow directions. The values of blood flow velocity are marked by colors, which are corresponded to the velocity scales in figures. The yellow arrows show the direction of blood flow in afferent vessel.

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Fig. 4: The shear stresses occurring in the walls of vessels and aneurismal walls because of blood flow. The values of shear stresses are shown by colors, corresponding to scales in figures. The yellow arrows show the direction of blood flow in afferent vessels.

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**Fig. 5:** The blood streams in afferent parent vessel with aneurysm and in aneurysm itself under various conditions of angiospasm. # - vessel without angiospasm; # - vessel with angiospasm along the entire its length; # - vessel with angiospasm close to aneurysm; # - vessel with two consequential spastic areas. The red arrows show the areas of angiospasm. The yellow arrows show the directions of blood flow. The blood flow velocity in arteries and aneurysms is shown by lines of fluid flow. The color of line corresponds to the blood flow velocity. The correspondence scale between color and velocity value is in figure at the left.

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**Fig. 6:** The distribution of blood streams in afferent vessels without angiospasm (# and #) and in case of angiospasm of one of afferent vessels (# and #). The images in figures #, #, # and # are given from opposite points of vision (from the anterior and posterior points). Legend: ##1, ##2 - the left segments #1 and #2; ##1, ##2 - the right segments #1 and #2. The red arrows show the areas of angiospasm. The yellow arrows show the directions of blood streams. The values of blood flow velocity correspond to the scales presented in figures at the left.

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Fig. 7: The shear stress in aneurysm. # - without angiospasm of vessel, # - angiospasm of one of #1-segments. The red arrow shows the area of segmental angiospasm. The yellow arrows show the directions of blood streams. ## and ## show the areas of increased values of shear stress at the level of shear stress threshold equal to 3 Pa. Legend: ##1, ##2 - the left segments #1 and #2; ##1, ##2 - the right segments #1 and #2. The values of shear stress correspond to the scales presented in figure at the left.

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Conclusion

The mathematical modeling allows assaying, understanding and visual presenting the processes occurring during blood flow through the vessels and in aneurysm as well as their changes because of angiospasm. The creating of mathematical models of hemodynamic changes under condition of angiospasm will allow understanding and predicting the character of complications which can be occur in acute period of hemorrhage (e.g. repeated rupture of aneurysm), that is of great importance for selection of surgical strategy.
Personal information

Elena V. Grigorieva, MD, PhD, Department of Radiology, Scientific Research Institute of Emergency Care named after N.V. Sklifosovsky, Moscow, Russia, iara333@yahoo.com

Vladimir V. Krylov, MD, PhD, Chief of Department of Neurosurgery, Scientific Research Institute of Emergency Care named after N.V. Sklifosovsky, Professor, Academician of Russian Academy of Medical Science, Moscow, Russia, manuscript@inbox.ru

Alexander V. Prirodov, MD, PhD, Vice Chief of Department of Neurosurgery, Scientific Research Institute of Emergency Care named after N.V. Sklifosovsky, Moscow, Russia, aprirodov@yandex.ru

Andrey V. Gavrilov, PhD, Head of the Laboratory of D.V. Skobeltsyn Institute of Nuclear Physics of the Federal State-funded educational institution of the higher professional education "M.V. Lomonosov Moscow State University", Moscow, Russia, gavrilov@multivox.ru
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