Towards the numerical assessment in solving the problem of the effectiveness of vascular anastomosis in neurosurgical operations

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Abstract. In this study we considered the effect of formation of cerebral bypass for the real clinical case. Three configurations of vessels of the circle of Willis for the real patient was constructed in the pre-operative, post-operative and the alternative (virtual--without bypass formation) treatment cases. All calculations were carried out in the commercial software ANSYS CFX 17.2. It is shown that after installation of the bypass the stagnation zone in patient’s vessel was formed with the consequent thrombus formation that required an urgent re-operation. The changes of hemodynamic parameters (blood flow velocity, WSS and viscous dissipation energy values) before and after operation as well as after alternative treatment were analysed. For the first time, a quantitative difference in hemodynamic characteristics between cases of the real and virtual (alternative) methods of the operation was shown.

1. Introduction

In the network of human brain vasculature various types of pathologies can arise. One of them is an expansion of the lumen of the cerebral blood vessel, namely cerebral aneurysm (CA). According to the literature, anomalies of this type are found in 2 out of 100 people. The main danger is the potential rupture that leads to intracranial hemorrhage. The consequences of this phenomenon can be very serious: neurological deficit, disability or even death [1].

Currently, there are several pathways to treat such a pathology: endovascular treatment and microsurgery. The choice of a treatment technique is based on the experience of the neurosurgeons considering characteristics of both the aneurysm and the patient status [2]. Unfortunately, sometimes endovascular treatment approach cannot be implemented. In this case surgeons have to carry out microsurgery treatment. This kind of technique is individual for each patient and sometimes (for example, when CA has a complex geometry and difficult access) requires the formation of a vascular anastomosis, namely, bypass. Cerebral vascular anastomosis is a connection of usually separate branches of one or two brain vessels for the purpose of interaction with each other. Different types of bypasses, described in [3,4], and there are 3 ways how to connect them: side-to-side, end-to-side, end-to-end. It should be noted that for the most cases, the formation of a bypass significantly changes the geometry of the circulation, which leads to significant redistribution of the flow. These changes do not always have a beneficial effect on the cerebral hemodynamics. Thus, before carrying out an operation,
it is necessary to assess all the risks associated. A question about the necessity of a bypass formation is of paramount attention, since in some cases only arterial occlusion gives a satisfactory effect.

Nowadays, there are numerous of papers considering the hemodynamics of cerebral vessels associated with the formation of a bypass [5-11]. However, almost every study considers only individual clinical cases or a number of clinical cases, and does not present a common criteria or approaches for preoperative risks assessment. Thus, the feasibility for the placement of anastomosis has not been fully elucidated.

2. Materials and methods
This paper discusses a clinical case of a patient with CA of the left internal carotid artery (ICA). The treatment was performed at the Federal Center of Neurosurgery (Novosibirsk). According to the local ethics committee patient identification was anonymized. In order to turn off the aneurysm from the circulation, micro-surgical clipping was done. Due to the complex geometry of the CA, ICA occlusion was done. To compensate the occluded vessel, it was decided to install a bypass into M1-segment of middle carotid artery (MCA). According to the results of the operation, a thrombus formed on the bifurcation of the left anterior cerebral artery (ACA) and formed anastomosis as a result of the meeting of two streams to the middle cerebral artery (MCA). To eliminate it, the patient required an urgent re-operation.

The considered problem can be divided into several parts:

- To reconstruct pre- and post-operative circulation in the circle of Willis for considered patient and to find the area where thrombosis probably formed;
- To construct the geometry for alternative approach of treatment when cerebral anastomosis was not formed;
- To analyze the hemodynamics parameters and assess the viability of using bypass in the treatment of the pathology in the considered clinical case.

All numerical calculations were carried out with ANSYS 17.2 package (license of LIH SB RAS). The arrays of DICOM-images before as well after the operation was used to construct the geometry the vasculature. To receive the geometry for the alternative approach we removed bypass volume from the configuration representing the post-operative case.

In this study 3 numerical calculations in the ANSYS/CFX package for each of the constructed configurations were carried out. Although blood has a pulsating flow pattern, the stationary flow problem of a viscous incompressible fluid for configurations with rigid walls was solved, as it was previously established that stationary simulations can give similar time-averaged results for the calculations with the pulsating fluid flow pattern during the heart cycle [12] for the problem considering. Nevertheless, one-side FSI calculations were also carried out. A structural steel (ANSYS's default material) with modified parameters was chosen as the material of the vessels’ wall (linear elasticity model). All inlets and outlets of the configurations were fixed, so that geometry did not change the coordinates over time under the pressure of the fluid flow. For solving stationary problem, the time setting method is used. The transient period lasts 2 seconds with the time step equaled 0.05 seconds.

The Navier-Stokes equations for viscous incompressible fluid in the three-dimensional case have the following form:

\[
\begin{align*}
\rho(u\nabla u - \mu \Delta u) &= -\nabla p + F \\
\text{div} u &= 0,
\end{align*}
\]

where \(\rho\) - the density of a blood, \(\mu\) - its viscosity, \(u\) - the velocity, \(p\) - the pressure, \(F\) - the external forces, affecting on the system.

ANSYS/CFX package uses the method of finite volumes for solving problems. To obtain scheme for calculations, firstly, the system (1) must be integrated:
\[ \left\{ \begin{align*}
\int_V (u \nabla u - \mu \Delta u) dV &= \int_V \frac{\nabla p}{\rho} dV \\
\int_V \text{div} u dV &= 0,
\end{align*} \quad (2) \]

where \( V \) is the volume of a configuration. Further, using the Gauss-Ostrogradsky formula:

\[ \left\{ \begin{align*}
\int_S u(u \cdot n) dS - \int_S \mu(\nabla u \cdot n) dS &= -\frac{1}{\rho} \int_S p \cdot n dS \\
\int_S u \cdot n dS &= 0,
\end{align*} \quad (3) \]

where \( S \) is the area of a configuration surface. Multiplying by \( \rho \) the both parts of the system and presuming \( m_\alpha = (\rho u_i \Delta n_i)_\alpha \) - the mass flow through a surface of a volume element we will obtain the equation in discrete form:

\[ \sum_\alpha m_\alpha (u_i)_\alpha - \sum_\alpha (\rho \mu \frac{\partial u_i}{\partial x_j} \Delta n_i)_\alpha = -\sum_\alpha (\rho \Delta n_j)_\alpha \\
\sum_\alpha m_\alpha = 0. \quad (4) \]

Here we consider blood as a Newtonian fluid with the following values of the density and viscosity respectively: \( \rho=997 \text{ kg/m}^3, \mu=0.0032 \text{ Pa·s} \).

For each calculation, an unstructured tetrahedral mesh was used. As the blood is a viscous fluid, five prismatic layers were built along the wall in each case. To determine the boundary conditions at the inlets the average values of mass flows were calculated based on the typical values of volumetric flow for a healthy person [13]. These values are also valid for the configuration with pathology, since an aneurysm makes changes in a blood flow locally. Thus, retreating a short distance proximal from the pathology, values for healthy vessels can be set. The pressure corresponding to the average intraoperative measurements carried out at the Meshalkin’s National Medical Research Center [14] was set at the outlets. The no-slip boundary condition was set on the wall.

The equation for the viscous dissipation energy represents like:

\[ W = 4\mu \int_\Omega |\omega|^2 d\Omega, \quad (5) \]

where \( \omega = \text{rot} \vec{u} \).

3. Results

Obtained data of the velocity for all configurations before, after the operation and in the case of the alternative treatment is presented on Fig.1. The wall shear stress (WSS) in the considered configuration and in the area of anterior communicating artery (AComA) is presented on Fig.2-3. It should be noted, that in the cases after the operation and under alternative treatment the values of WSS at the AComA reach their maximum.
The Tab.1 and Tab.2 both show the values of AComA area, the mass flow through this area, viscous dissipation energy value and the special dissipation of the energy in considered configurations and in the configuration before the operation without the pathology (namely network configuration).

Taking into account the geometry changes, it is clearly seen that before the operation the left ACA was thinner than the right one with the ratio of the areas of the left ACA to the right ACA equaled to \( \frac{2.08}{3.32} \). However, after the operation, the left ACA significantly increased in diameter, and its area was almost 2 times larger than the right one (the ratio is equal to \( \frac{3.4}{1.77} \)).

4. Discussion
At this stage of the study, the FSI calculations in the future research requires a more accurate determination of the parameters of the material: wall thickness, elasticity model as well as time steps for solver.

The obtained values of the mass flows at the outlets of the configurations are in a good agreement with the changes in the diameter of the AComA: the mass flow through AComA before the operation was about 0.32 g/s and increased up to 3.07 g/s after the operation. In the case of an alternative procedure this value increased up to 3.25 g/s. It means that circulation has been redistributed through AComA from right side of brain vasculature to the left one (Fig.3).

**Figure 1.** Streamlines of the velocity field before the operation (left), after the operation (centre) and for the alternative approach of treatment (right).

**Figure 2.** WSS values in the configuration before the operation (left) after the operation (centre) and for the alternative approach of treatment (right).
Figure 3. WSS at AComA in the configuration before operation (at left) after operation (in the middle) and in alternative approach of treatment (at right).

The most important result being obtained concerns the determination of the stagnant flow region: flow that has been arisen after the formation of a bypass. This area provokes the formation of a thrombus.

If value blood flow rate through MCA, it can be noted, that for alternative configuration the flow through the left MCA is large enough, and, therefore, there was no need to form a bypass anastomosis from this point of view.

As it is seen from the Tab.1-2, the high specific energy dissipation for the network before the operation is significantly higher than after the operation (the value of this parameter reduces by almost 4 times in the calculation with rigid walls and 3 times in the FSI case). This fact indicates a significant hydrodynamic imperfection of the original network of the patient. Thus, the initial structure of the vessels is too inefficient, that led to the clotting of the vessels after the aneurysm was turned off from the bloodstream. The fore-mentioned parameter may indicate the reasons of the thrombus formation.

The goal of our further research is to examine the thrombosis models with a variation in the AComA throughput.

### Table 1. Results of numerical calculations in the configuration with rigid walls.

|                     | AComA area | Mass flow through AComA | Energy Dissipation | Geometry volume | Specific energy Dissipation |
|---------------------|------------|--------------------------|--------------------|-----------------|----------------------------|
| Before the operation| 0.2995     | 0.3253                   | 45293,4            | 92,365          | 490,376                    |
| After the operation | 0.6427     | 3.4015                   | 15574,6            | 21,1752         | 735,51                     |
| Alternative treatment| 0.5817     | 3.2496                   | 21433,4            | 17,629          | 1215,81                    |
| Before operation without aneurysm (network) | 0.2995 | 0.3253 | 35017,5 | 12,7359 | 2749,51 |
Table 2. Results of one-side FSI numerical calculations. Here the units of values are as the following: area – cm², volume – cm³, mass flow – g/s, energy dissipation – erg/(s cm³).

|                      | AComA area | Mass flow through AComA | Energy Dissipation | Geometry volume | Specific energy Dissipation |
|----------------------|------------|-------------------------|--------------------|-----------------|----------------------------|
| Before the operation | 0.288624   | 0.295823                | 46074.3            | 92,395          | 498,667                    |
| After the operation  | 0.6542     | 3.46327                 | 22980.2            | 21,1759         | 1085,2                     |
| Alternative treatment| 0.6456     | 3.49739                 | 22185.2            | 17,626          | 1258,41                    |
| Before operation     | 0.2886     | 0.295823                | 44814.5            | 13,5815         | 3299.68                    |

Conclusion
As the result of our study we restored 2 configurations of the vessels of the Circle of Willis from medical images: before and after the operation. The configuration modelling the alternative treatment was created and investigated for the first time. From the results obtained it can be argued that the performed numerical calculations adequately simulate the flow of blood in the cerebral vessels with installed bypass.

Despite the preliminary stage of the research, we have already managed to show an adequate numerical simulation of a clinical case. We also managed to simulate a real postoperative situation, which in the future will allow to determine the viability of forming a bypass and allow surgeons to change the tactic of a treatment. Besides, the dissipation after the real operation was lower than after the virtual one, that shows the correctness of the chosen approach.

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