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Virtual Planning of Extra-Intracranial Bypass with Numerical Investigation of Hemodynamics

Evgenia BLAGOSKLONOVA[a], Daria DOLOTOVA[a,1], Nataliya POLUNINA[b], Valentin STEPANOV[b], Anastasia KISELEVA[c], Ivan ARHIPOV[a], Andrey GAVRILOV[a,d] and Vladimir KRYLOV[b]
[a] *Gammamed-Soft, Ltd, Moscow, Russia*
[b] *N.V.Sklifosovskiy Scientific Research Institute of Emergency Care, Moscow, Russia*
[c] *Pirogov Russian National Research Medical University, Moscow, Russia*
[d] *Lomonosov Moscow State University, Moscow, Russia*

Abstract. Planning of bypass surgery for patients with complex cerebral aneurysms is a very complicated task. It is important to take into consideration personal anatomy and hemodynamics and make additional investigations, but unfortunately, they don't give a guarantee of good postoperative results. Recent medical imaging and computational fluid dynamics (CFD) can be helpful for the prediction of effectiveness of selected surgical technique. In the current research with the use of CT and PC-MRI data we applied computational modeling in order to make quantitative assessment of potential changes of blood flow distribution after the surgery. Virtual version of bypass surgery showed preservation of sufficient blood flow, what was confirmed with modeling results after operation. Moreover, successful verification with PC-MRI data in control sections was made. The research has shown that virtual planning with the estimation of blood flow changes can be introduced into clinical practice for simplifying and increasing efficiency of planning process.

Keywords. CFD modeling, intracranial aneurysm, extra-intracranial bypass, hemodynamics

1. Introduction

Aneurysmal dilatation of the cerebral arteries is a serious life-threatening condition. Rupture of intracranial aneurysm is the main cause of non-traumatic subarachnoid hemorrhage, which is characterized by a high frequency of mortality and disability [1].

Most unruptured aneurysms are asymptomatic and are accidentally detected during neuroimaging. After the diagnosis was confirmed the management of the patient is either a monitor or surgical treatment which aims to turn off the aneurysm from the bloodstream. Which intervention is appropriate for the certain patient is decided on the basis of the formation size, rupture risk stratification and clinical symptoms. In most cases the microsurgery or endovascular treatment are used [2]. However, traditional methods may not be feasible in the case of giant aneurysms, which the dome size is more than 25 mm.

[1] Corresponding Author, Daria Dolotova, E-mail: dariadolotova@gmail.com.

Standard approaches to the removal of such formations are ineffective, and surgeons resort to total occlusion of the parent artery proximal to the lesion. If the parent artery is a large main vessel, the stagnation of blood flow can lead to ischemic changes in respective brain region. To avoid such an outcome, surgeons use revascularization methods of bypassing the pathological area with anastomosis [3].

Estimation of relevance of bypass and its efficiency in future is the main task during bypass surgical planning. Nowadays, the balloon occlusion test with CTA is used for such purpose. Such interventions may lead to ischemia and rupture of giant aneurysm. Moreover, it’s very important to take into consideration complex anatomy of vessels and hemodynamic characteristics in the area of interest, because higher bloodstream in the healthy nearby artery can lead to various complications [4].

Looking for safer and more accurate methods of planning reconstructive neurovascular surgery, researchers are increasingly applying methods of mathematical modeling. Calculations with computational fluid dynamics (CFD) software allow quantifying the hemodynamics of a particular patient and taking into consideration various options changing initial anatomy without any invasive interventions. However, currently there are only a few studies of virtual surgical planning with quantitative assessment of hemodynamics [5,6]. Thus, the purpose of the current research was the evaluation of the possibility of applying CFD in patient-specific bypass surgical planning.

2. Material and methods

In the research we used CT and PC-MRI preoperative and postoperative data of a patient with thrombosed giant (33x34x36 mm) saccular aneurysm of the left internal carotid artery (ICA). It was decided to form an extra-intracranial wide-lumen anastomosis between the external carotid artery and the M3 segment of the middle cerebral artery (MCA) using the radial artery as a graft with occlusion of the cervical segment of the left ICA.

Post-processing of DICOM data was performed on the “Gamma Multivox D2” workstation (Gammamed-Soft, Ltd, Russia) [7]. After semiautomatic segmentation of vascular structures, three-dimensional models of the patient's arterial system were reconstructed. Then the models were exported to a commercial finite element software ANSYS Workbench 19.2 (ANSYS Inc., USA) [8]. The elimination of geometry defects was performed, and the surgery was simulated by removing part of the ICA and placing the anastomosis according to the tactics developed by surgeons. In total, three models based on the geometry of the patient's vessels before (“Preoperative” and “Virtual bypass” models) and after surgery (“Postoperative” model) were built for the study (Figure 1).

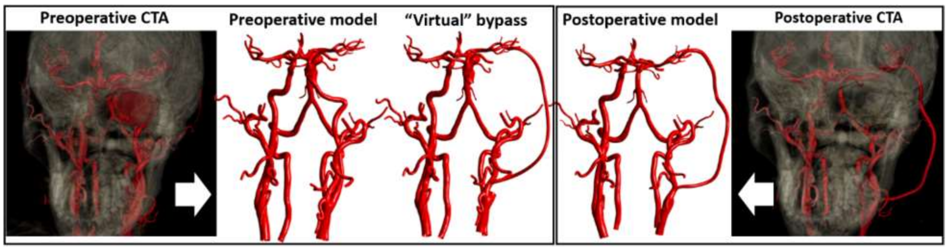

Figure 1. 3D models of the vascular geometries.

The discretisation of computational domains to finite elements and calculation were performed using the ANSYS CFX. Due to the fact that the considered part of the vascular system included large and rather rigid cerebral vessels, the elastic properties of the arterial wall and the non-Newtonian nature of the fluid were not taken into account in this study. As boundary conditions, the linear velocities before and after surgical treatment obtained during PC-MRI at the input and the opening condition at the outputs were used. The full simulation included two cardiac cycles with a total duration of 1.82s. In order to verify the simulation results, linear velocities in the selected sections of the anterior (ACA) and middle cerebral (MCA) arteries were also recorded during preoperative PC-MRI (Figure 2).

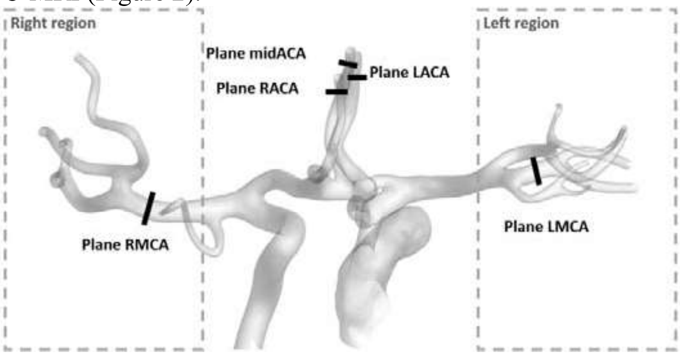

Figure 2. Control sections and regions.

3. Results

To check the correctness of the calculation, the comparison of maximum values of linear velocity of blood flow obtained from PC-MRI and results of the calculation in the corresponding sections was carried out (Table 1).

Table 1. Comparison of maximum linear velocity values in regions of interest for PC-MRI and CFD.

Location	PC-MRI Velocity, m/s	CFD Velocity, m/s
Plane LACA	0,485	0,464
Plane midACA	0,448	0,432
Plane RACA	0,347	0,322
Plane LMCA	0,311	**0,268**
Plane RMCA	0,634	**0,430**

The comparison showed a good agreement of the values in the branches of ACA, but the simulation results were lower for the sections of both MCA. Such effect may be the result of using the same values at the outputs of the computational domain.

To assess the effectiveness of the chosen intervention tactics, the total blood volume passing through each branch of ACA and MCA during the second cardiac cycle was estimated. Simulation of virtual operation indicated the efficiency of the anastomosis and showed a stable increase of the volume per cycle in all observed branches compared with the results of the "Preoperative" model. The data for the real "Postoperative" model was ambiguous, almost all outputs showed a marked redistribution of blood flow between the branches compared with the distribution in the "Preoperative" and "Virtual bypass" models. However, if we make comparison of the total volume in the areas of ACA, left and right MCA (Table 2), there is a general tendency to increase blood supply in the left part of the models with anastomosis by 40% compared to the situation before the operation, which suggests a possible minimisation of the risk of ischemia on the side of the lesion due to the chosen revascularisation method.

Table 2. Values of the total blood volume per cardiac cycle in different regions and changes compared with preoperative model.

Location	Volume per cardiac cycle for different models, ml		
	Preoperative	Virtual treatment	Postoperative
Left region	1,35	1,9 (↑41%)	1,94 (↑43%)
Right region	1,66	1,83 (↑10%)	1,4 (↓15%)
ACA branches	1,52	1,98 (↑30%)	1,58 (↑4%)

The presented data also indicates that virtual planning predicts the probable absence of decline of the blood supply to the brain through the branches of the carotid arteries in the conditions of the cessation of blood flow along left ICA. The model of real geometry after surgery confirms this assumption; the decrease in blood flow is recorded only on the right side and represents only 15% loss. The result conformed to the clinical outcome. During the control of the patient's condition 3 months after the operation, the normal functioning of the shunt, thrombosis of left ICA and aneurysm with a decrease of its size were noted. Neurological symptoms were absent.

4. Conclusion

Thus, the experience of calculation of hemodynamic parameters in the virtual planning of bypass surgery showed that this direction is promising and relevant for use in practical medicine. However, in further research it is necessary to pay attention to the complexity of boundary conditions at the outputs to obtain more accurate results consistent with the patient's data, as well as to conduct studies on a large sample, as these issues were main limitations of the study. If verification of predictive capabilities will be successful, the technique can be implemented in the clinical practice and become a useful support tool for surgeons. It will allow planning the most effective surgery strategy for a particular patient more accurately, reducing the risk of intra- and postoperative complications without unnecessary medical manipulations, and, in general, improving quality of health care provision for patients with intracranial aneurysms.

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