Using swarm intelligence optimization methods for transport functions of vascular bypasses: first results and perspectives

Iuliia Kuianova\textsuperscript{1}, Andrey Dubovoy\textsuperscript{2} and Daniil Parshin\textsuperscript{1}

\textsuperscript{1} Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia
\textsuperscript{2} Federal Neurosurgical Center(Novosibirsk, Russia)

E-mail: danilo.skiman@gmail.com

Abstract. In this paper, we consider the problem of the optimal location of the bypass graft. An electrical analogue of the cerebral vascular hemodynamic model was built, which was solved numerically using swarm intelligence methods. The optimization objective was the pressure after shunt formation in relation to the set pressure before shunting. This method was first time applied to the cerebral bypass problem, the results are in good agreement with the data of real operations.

1. Introduction
Cerebral artery bypass grafting is an important and relevant method of treating pathologies such as cerebral aneurysms, stenosis [1], Moya-Moya disease, etc. When applying cerebral bypass grafts, a number of mechanical tasks arise: the optimal angle of the bypass graft, the optimal shape of the arthricometric window, the optimal location of the anastomosis, etc. The problem of choosing the optimal installation angle of the vascular bypass was considered in [2]. Getting more information about the aforementioned problems allow to perform more efficient treatment procedures.

There are different approaches to preoperative modelling of the vascular pathologies [6, 8, 7]. It should be pointed out that for the purpose of fundamental hemodynamics research the three-dimensional modeling approaches are the most productive, as they are able to take into account a wide range of the factors (complex shape, vortex formation, etc.). These factors can be unavailable in the one-dimensional modeling or the hemodynamics on graphs. Nevertheless, such approaches are associated with serious computational volumes and the complexity of preparing a three-dimensional patient-specific model of blood vessels for conducting patient-specific calculations. Clinics frequently do not have supercomputer capacities and queuing such calculations to external supercomputers makes the use of such technologies clinically useless.

On the contrary, one-dimensional models and graph models are capable of obtaining a patient-specific result within tens of minutes, relying on a minimum of clinical information, which is usually available in a routine protocol.

In this paper, we consider the simplification of the cerebral vascular network into an electric model and reconfigure it. The aim of this study is using the particle swarm optimization for searching an optimal location of the installation of a new inlet instead of an excluded one. Such
model will be useful in the future for modeling revascularization operations of a vascular network in the treatment of cerebral aneurysms.

2. Materials and methods
2.1. Construction of mathematical model
Patient-specific cerebral vascular configuration (M, age: 22) was used for determining the parameters of the electric circuit model. The electric chains that simulate the network of cerebral vessels of the circle of Willis before and after surgery were based on the geometry models represented at the Figures 1-2 respectively. The hemodynamic parameters in terms of circuit characteristics can be interpreted as following [4]:

\[ R = \frac{8\mu l}{\pi r^4}, \quad C = \frac{3}{2}\pi r^2 \frac{r}{hE} \]  

(1)

where \( \mu \) - the dynamic blood viscosity, \( l, r \) - the vessel length and radius respectively, \( E \in (8, 16) \text{ dyn/cm}^2 \) - the Young’s module of the vessel wall, \( \frac{r}{h} \in (8, 10) \) - the coefficient of the vessel thickness. The resistance in a vascular network \( R \) is the resistance in a circuit, volumetric flow \( Q \) - the currency, pressure \( P \) - the voltage and the ratio of the volume change of the network at a given pressure can be considered as the compliance.

After the electric chains were constructed, the formulas for the pressure and the volumetric flow were derived. Considering that the voltage in an electric circuit represents the pressure in a vascular network and the current represents the volumetric flow, the expression for the vascular network pressure takes the form:

\[ \Delta P = QR. \]  

(2)

Hence, using the first Kirchhoffs law, the following formulas for the geometry before operation (Figure 1) were obtained:

\[ P_1 = P_{ICA} - Q_{ICA} \cdot R_{ICA}, \]
\[ P_{MCA} = P_2 = P_{ACA} = P_1 - Q_{MCA} \cdot R_{MCA}, \]
\[ Q_{MCA} = \frac{Q_{ICA}}{1 + R_{MCA}(C_{ICA} + \frac{1}{R_{ACA}})} \]  

(3)

where \( P_1 \) - the pressure in the node, where the electrical circuit is divided into three branches \( (R_{MCA}, R_{ACA}, C_{ICA}) \), \( P_2 \) - the pressure in the node, where the electrical circuit is divided into two branches \( (C_{ACA}, R_{ACA}) \).
In the geometry after surgery the middle cerebral artery was divided onto two parts - before (MCA1) and after (MCA2) the graft connection, as it is shown on Figure 2. Using the first Kirchhoffs law, the following formulae were obtained for this geometry:

\[
\begin{align*}
P_1 &= P_{ACA_{in}} - Q_{ACA_{in}} \cdot R_{ACA_{in}} \\
Q_{AComA} &= Q_{ICA}/(1 + R_{AComA} \cdot (C_{ACA_{in}} \cdot \omega \cdot i + 1/R_{ACA_{r}})) \\
P_{ACA_{r}} &= P_2 = P_1 - Q_{AComA} \cdot R_{AComA} \\
Q_{ACA} &= Q_{AComA}/(1 + R_{ACA}/R_{ACA_{r}}) \\
P_4 &= P_2 - Q_{ACA} \cdot R_{ACA} \\
Q_{MCA1} &= Q_{ACA}/(1 + R_{MCA1} \cdot C_{ACA} \cdot \omega \cdot i) \\
P_3 &= P_4 - Q_{MCA1} \cdot R_{MCA1} \\
Q_{MCA2} &= \frac{\omega^{2}(C_{MCA1}+C_{graft} \cdot R_{MCA2})}{Q_{MCA1}+Q_{MCA2}} \\
P_{MCA} &= P_3 - Q_{MCA2} \cdot R_{MCA2}.
\end{align*}
\]

Here, abbreviations $ACA_{l}$, $ACA_{r}$ and $ACA_{in}$ mean value in the left and right anterior cerebral artery and at the ACA inlet respectively. $P_1$ - the pressure in the node, where the electrical circuit is divided into branches $C_{ACA_{in}}$, $R_{ACA_{r}}$ and $R_{AComA}$, $P_2$ - at the branches $R_{ACA}$, $R_{ACA_{r}}$, $P_4$ - at the branches $C_{ACA}$, $R_{MCA1}$ and $P_3$ at the branches $C_{MCA1}$, $R_{MCA2}$, $R_{graft}$ and $C_{graft}$.

2.2. Numerical simulation
The pressure in the both models before and after surgery was calculated in the MATLAB package. The particle swarm optimization method with 5 particles was used to search the optimal value of the graft length and the MCA1 section length [5]. The weight correction in the considered method was performed as it is described in [3]. The specified lengths are considered as optimal if the pressure at the outlet of MCA2 is as close as possible to the MCA pressure before surgery. The optimal values were obtained for 5 different radii of the graft, corresponding to the radius of the MCA1 segment and also $\frac{2}{3}$, $\frac{3}{4}$, $\frac{4}{3}$, $\frac{3}{2}$ parts of its radius.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure3.png}
\caption{First step of the particle swarm method with 5 particles for model task}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure4.png}
\caption{Last step of the particle swarm method with 5 particles for model task}
\end{figure}

3. Results and discussion
The length of middle cerebral artery before surgery averages 7.25 cm. After the bypass formation we conditionally divide this vessel into 2 parts (MCA1 and MCA2) before and after sewn graft. The length of the MCA1 segment took a value in the range from 1.25 to 10 cm and the MCA2
length was the difference in total MCA length and MCA1 segment length. The graft length took a value in the range from 5 to 15 cm.

The results of applying the particle swarm optimization method for each considered radii of a graft are presented in Table 1. The optimal lengths of the MCA1, the graft and the pressure in a MCA after surgery, corresponding to given optimal parameters are shown. The zero number of iterations corresponds to those cases, where optimal length appeared immediately at the first random choice of particles’ location in the particle swarm optimization. Besides, in these cases, where the radii of graft are rather small, the pressure at the MCA after surgery is in good agreement with the pressure before surgery for almost any graft length from the specified range of its values. At those cases where the graft radii was greater than the MCA1 one some of the graft length was not appropriate for the operation in terms of pressure difference. Taking into account that initial length parameters are selected randomly, the particle swarm method required more iterations.

| graft radius, cm | $P_{MCA}$, mmHg | MCA1 length | graft length | number of iteration |
|------------------|-----------------|-------------|--------------|--------------------|
| $\frac{3}{4} \cdot r_{MCA1}$ | 81.31 | 1.87 | 14.67 | 0 |
| $\frac{3}{4} \cdot r_{MCA1}$ | 81.04 | 3.63 | 12.21 | 0 |
| $r_{MCA1}$ | 77.14 | 1.36 | 13.67 | 0 |
| $\frac{3}{4} \cdot r_{MCA1}$ | 73.93 | 4.89 | 10.98 | 1 |
| $\frac{3}{4} \cdot r_{MCA1}$ | 72.68 | 5 | 14.48 | 4 |

Though the obtained result is model, it is quite natural at the same time. Its clinical interpretation shows that the graft for EC-IC revascularization should not be installed too far from the bifurcation of an excluded internal carotid artery and a middle cerebral artery.

A significant advantage of such models as applied to medicine is their ability to quickly assess all possible optimal outcomes for certain values of the patients parameters, since the optimal solution may not be the only one, and sometimes the surgeon needs to keep in mind several possible ways to manipulate (backup plan), since not the most optimal location for the formation of a bypass can be taken in priority in view of the anatomical features of the patient, which cannot be taken into account numerically.

In the future, it is planned to complicate the model with several factors, such as the presence of posterior component of the circle of Willis (the basilar artery and the posterior connective arteries) and the consideration of a larger number of possible vessel radii. We are also planning to take into account the ratio of volumetric blood flow in a graft into the atmosphere to volumetric blood flow in a graft after its installation (which is measured during a real operation).

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