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MODELING OF FLOW ALTERATIONS INDUCED BY FLOW-DIVERTER USING MULTISCALE MODEL OF HEMODYNAMICS

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Abstract: An approach to modelling hemodynamic alterations induced by flow-diverter placement in cerebral artery is proposed. Approach is based on the concept of multiscale model of hemodynamics, which utilized three types of models which are coupled together with corresponding boundary conditions. A patient-specific cerebral aneurysm was used for simulation studies. It was modelled two cases: pre-operational and post-operational with flow-diverter stent. The results showed that flow-diverter stent significantly alters intra-aneurysmal flow pattern. The major part of flow was diverted toward the normal direction along the parent artery. A stagnant flow in aneurysm sac was observed. Proposed approach could be used for planning of a treatment and for evaluation of risks in the post-treatment period for patients with cerebral aneurysm.

Introduction. Flow-diverter stents are the most perspective tools for treatment of cerebral aneurysms nowadays. The recent advantages in this field allow flow-diverters to be used for the most complicated cases, where traditional methods of treatment, like coiling and clipping, cannot be successfully applied [1, 2]. However, hemodynamic changes induced by placement of flow-diverter in the cerebral artery cannot be predicted. In this case the mathematical modeling of hemodynamics seems a promising tool to overcome this complication. Using a model of local hemodynamics, the main flow parameters such as velocity and pressure can be computed with a high precision. On the other hand, such models do not consider an influence of global factors of hemodynamics, which limits their usage. In the presented study the multiscale model of hemodynamics is used to evaluate the hemodynamics changes induced by flow-diverter stent in the aneurysm dome.

Methods. A patient-specific model of saccular aneurysm was selected for the study. Aneurysm has dimensions of $7.1 \times 6.5 \times 5.2$ mm. A corresponding model of flow-diverter was selected for treatment of aneurysm. The flow-diverter length was 20 mm, while the diameter was 5 mm. The stent braid consisted of 48 Nitinol wires.

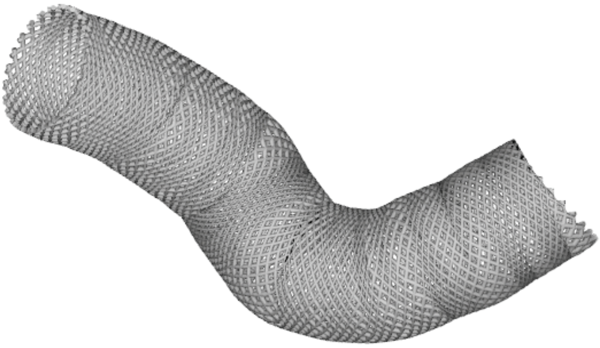

Fig. 1. A geometrical model of the flow-diverter stent

A geometrical model of the selected flow-diverter was constructed using corresponding CAD software. The constructed model of a stent is presented in Fig. 1. The virtual implantation procedure was conducted using 3D modeling software.

For the investigation of flow alterations in the aneurysm dome after the stent placement, a multiscale mathematical model of hemodynamics [3, 4], which is a set of mathematical models of circulation with different levels of detail, was used. The scheme of multiscale model is shown in Fig. 2. A multiscale model includes 0D model, 1D model and 3D model coupled together using corresponding boundary conditions.

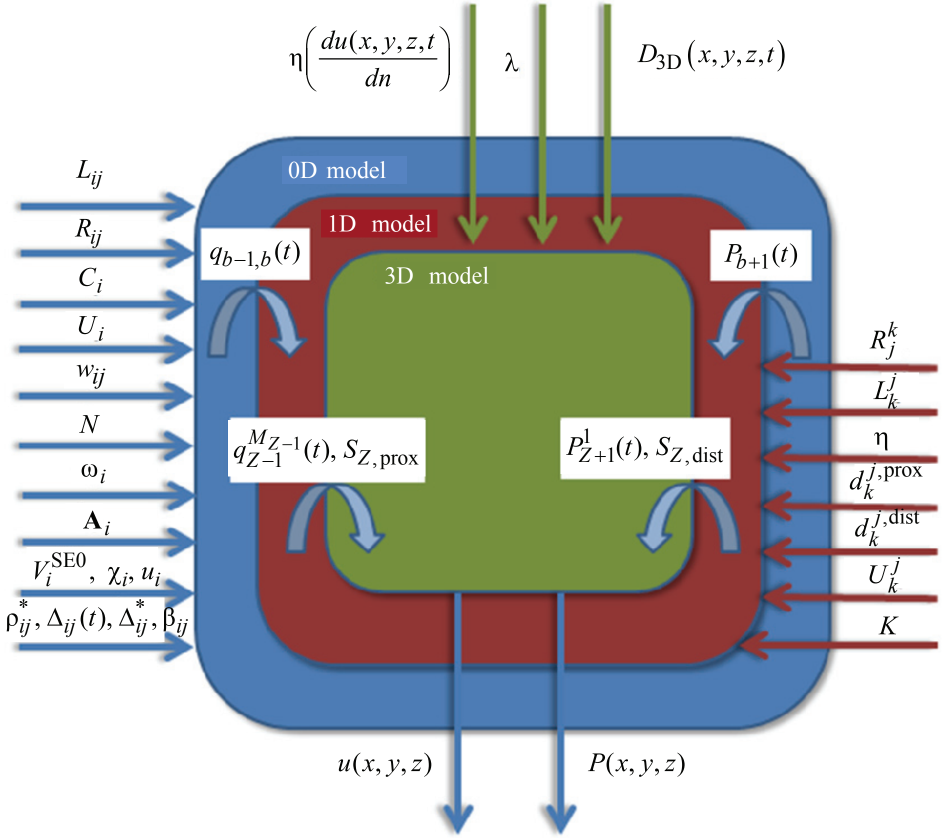

Fig. 2. A scheme of coupling models in a multiscale model of hemodynamics

The 0D model is a model in lumped parameters, which describes the blood flow in cardiovascular system in general, without detailed data in a specific region of circulation. This model includes four heart chambers, four valves, and systemic and pulmonary circulation.

A blood volume in chamber can be described as:

$$\frac{dV_i(t)}{dt} = \sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}\, q_{ij}, \quad i = \overline{1, N}, \quad j = \overline{1, N}, \quad V_i(0) = V_i^0, \tag{1}$$

where V_i is blood volume in i-th chamber; q_{ij} is blood flow from i-th chamber to j-th; w_{ij} is link coefficient; N is the number of chambers.

The blood flow between chambers can be defined as follows:

$$\begin{gathered} L_{ij}\frac{dq_{ij}(t)}{dt} + R_{ij}(t)q_{ij}(t) = P_i(t) - P_j(t), \quad i = \overline{1, N}; \; j = \overline{1, N}, \quad i \neq j; \\ q_{ij}(t) = q_{ij}^0, \qquad R_{ij}(t) = \frac{1}{\rho_{ij}(t)}, \end{gathered} \tag{2}$$

where L_{ij} is blood inertia; R_{ij} is link resistance; P_i is pressure in chamber; ρ_{ij} is conductivity.

Pressure P_i and blood volume V_i in passive chambers are characterized by the following relationship:

$$P_i(t) = \frac{1}{C_i}\left[V_i(t) - U_i\right], \quad i = \overline{1, N}; \quad i \neq \left\{1,\; c+1\right\}, \tag{3}$$

where C_i is elasticity of chamber; U_i is unstrained volume of chamber.

For left and right ventricle, pressure P_i and blood volume V_i are defined by function φ [5, 6]:

$$P_i(t) = \varphi\left(V_i(t), \omega_i(t), \mathbf{A}_i\right), \quad i = \left\{1,\; c+1\right\}, \tag{4}$$

where ω_i is volume of pseudo-cavity; $\mathbf{A}_i$ is parameters of ventricle.

Parameters $\mathbf{A}_i$ of ventricle include:

$$\mathbf{A}_i = \left\{\, h_i, V_i^0, \eta_i, V_i^{\mathrm{es}}, V_i^{\mathrm{ed}}, k_i, s_i, E_i^{\mathrm{SE}}, E_i^{\mathrm{PE}}, K_i^{\mathrm{SE}}, K_i^{\mathrm{PE}}, T_{\mathrm{sys}}(n), T(n) \right\}. \tag{5}$$

Special function ω_i describes contraction and relaxation of cardiac muscle for each of period of cardiac cycle:

$$\begin{gathered} \frac{d\omega_i(t)}{dt} = \Upsilon_1\left(\omega_i(t), \chi_i, u_i\right), \quad \text{for} \quad t \in [T(n);\; T(n) + T_{\mathrm{sys}}(n)); \\ \frac{d\omega_i(t)}{dt} = \Upsilon_2\left(\omega_i(t), \eta_i, E_i^{\mathrm{SE}}, V_i^{\mathrm{SE0}}, K_i^{\mathrm{SE}}\right), \quad \text{for} \quad t \in \left[T(n) + T_{\mathrm{sys}}(n); T(n+1)\right); \\ \omega_i(0) = \omega_i^0; \quad T(n) = \sum\nolimits_{h=1}^{n} T(h). \end{gathered} \tag{6}$$

Resistance of valves can be found using the following relationship:

$$R_{ij}(t) = \Omega\left(\rho_{ij}^{*}, \Delta_{ij}(t), \Delta_{ij}^{*}, \beta_{ij}\right), \quad i, j = \left\{(1,\, 2); (c,\; c+1); (c+1,\; c+2); (N,\, 1)\right\}. \tag{7}$$

The 1D model described the blood flow in systemic circulation, using a one-dimensional assumption. According to this assumption, all flow parameters are changing only along the length of vessel. The advantage of the model is that it describes the pulse wave propagation phenomena. The drawback is that precision of such model is not enough to describe the hemodynamics parameters in aneurysm in detail.

$$\frac{dV_k^j(t)}{dt} = q_k^{j-1}(t) - q_k^j(t), \quad k = [1; K], \quad j = [1; M_k], \qquad (8)$$
$$V_k^j(0) = V_{0k}^j,$$

where q_k^{j-1} is inlet blood flow; q_k^j is outlet blood flow.

Blood flow q_k^j is proportional to pressure drop:

$$q_k^j = \frac{\left(P_k^j - P_k^{j+1}\right)}{R_j^k}, \qquad k = [1; K], \qquad j = [1; M_k]. \qquad (9)$$

Resistance R_j^k can be obtained from Poiseuille law:

$$R_j^k = \frac{\pi\left(\frac{d_k^{j,\text{prox}} + d_k^{j,\text{dist}}}{2}\right)^4}{128\eta l_\text{k}}, \qquad k = [1; K], \qquad j = [1; M_k]. \qquad (10)$$

Pressure in segment of artery is related to blood volume in this segment:

$$P_k^j(t) = e_k^j\left(V_k^j - U_k^j\right), \quad k = [1; K], \quad j = [1; M_k],$$
$$U_k^j = \frac{1}{12}\pi L_k^j\left(d_k^{j,\text{prox}} + d_k^{j,\text{prox}} d_k^{j,\text{dist}} + d_k^{j,\text{dist}}\right). \qquad (11)$$

The most precise model is a 3D model of hemodynamics, which allows computing a three-dimensional distribution of most valuable flow parameters like velocity, pressure, wall shear stress, viscosity and so on.

Parameters $\mathbf{F}$ of cerebral artery with flow-diverter stent include:

$$\mathbf{F} = \left\{\eta\left(\frac{du(x,y,z,t)}{dn}\right), \lambda, D_{3\text{D}}(x,y,z,t)\right\}. \qquad (12)$$

Blood flow in the domain $D_{3\text{D}}(x,y,z,t)$ can be obtained using Navier-Stokes equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - \eta \Delta \mathbf{u} + \frac{1}{\lambda}\nabla P = 0;$$
$$\text{div}\, \mathbf{u} = 0. \qquad (13)$$

These three models were coupled together using inlet and outlet boundary conditions for each model. The velocity magnitude was used as an inlet condition, whereas pressure value was used as an outlet condition. Such model allows investigating the influence of disorders of systemic circulation on blood flow in aneurysm sac. For the simulation purposes the parameters of “normal” patient were used to setup a model of global hemodynamics. Patient-specific values were used to setup model of arterial tree and model of local hemodynamics.

Non-Newtonian behavior of blood could significantly influence the simulation results in regions of slow recirculating flow. Such regions are observed in aneurysm dome before and after placement of flow-diverter stent. In such case, it is important to use a model of non-Newtonian fluid. The most commonly used models are Casson, Power-Law, Bird-Carreau. In this study a Power-Law model was used due to the high precision and computational effectiveness.

Results. The software was developed to solve equations of multiscale model of hemodynamics. Modeling of flow through pores of flow-diverter requires a high-density computational mesh. This leads to a problem of high computational time to solve equations (12) – (13). To overcome this issue it was used a High-Performance Computing technique (Message Passing Interface). This technique allows spreading a computational task among the computational nodes, each of which makes a computation in parallel. Lomonosov supercomputer was used for this purpose, which is in the Top50 List of Supercomputers [7].

Two cases were modeled: pre-operational (without flow-diverter) and post-treatment (with a flow-diverter inside a cerebral artery). Equations (1) – (13) were solved during five cardiac cycles. The last cycle was used for quantitative analysis. The moment of systolic peak was used for analysis, because in this moment the hemodynamic parameters reach their maximum values.

To compare the pre- and post-treatment results the streamlines were constructed. These streamlines are presented in Fig. 3 and 4. As can be seen from the Fig. 3, in the pre-operational case, the zones of high velocity magnitude locate near the right side of an aneurysm and near the apex. A velocity magnitude reaches 0.42 and 0.27 m/s in these regions respectively. A zone of recirculating stagnant flow was found in the center of aneurysm, which leads to the rise of local viscosity in this area.

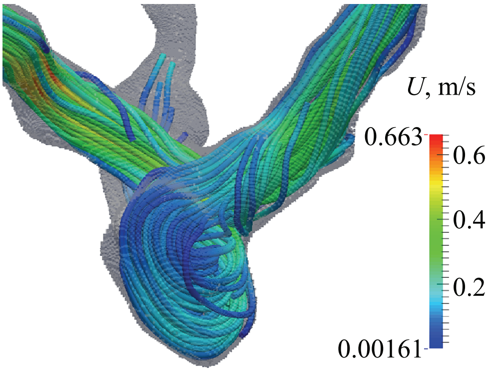

Fig. 3. Pre-operational flow-pattern in saccular aneurysm

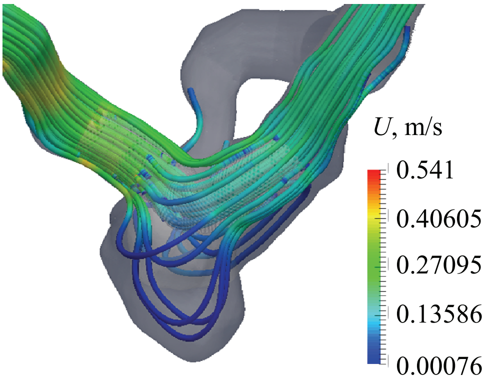

Fig. 4. Alterations of flow-pattern induced by flow-diverter

After placement of flow-diverter the flow pattern in aneurysm region significantly changes. The normal flow conditions were recovered, so the main part of the flow moves directly to the outlet segment of the parent vessel. The least part of flow goes through the pores of flow-diverter with a low velocity. This potentially will lead to formation of thrombus in aneurysm sac and occlusion. The average velocity in aneurysm dome is 0.001 m/s, which is 60 % less than in a pre-treatment case.

Conclusion. In the present study, the effect of flow-diverter placement on hemodynamic changes in cerebral aneurysm was evaluated. Placement of flow-diverter led to a significant decrease in the velocity magnitude in aneurysm sac and minimized the force acting on the aneurysm wall. Major part of blood flowed in the normal direction, preventing the aneurysm from growth in the future.

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Моделирование изменений кровотока, вызванных установкой потоконаправляющего стента, с использованием многомасштабной модели гемодинамики

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Ключевые слова: гемодинамика; генез аневризм; многомасштабное моделирование; пациент-ориентированное моделирование; церебральная аневризма.

Аннотация: Предложен подход к моделированию гемодинамических изменений, вызванных установкой потоконаправляющего стента в церебральную артерию. Подход основан на использовании многомасштабной модели гемодинамики, которая включает три типа математических моделей гемодинамики, сопряженных соответствующими граничными условиями. Для численных исследований использовалась индивидуальная модель церебральной аневризмы пациента. Смоделированы два случая: до и после установки потоконаправляющего стента. Результаты показали, что установка потоконаправляющего стента вызвала существенные изменения в характере течения крови в области аневризмы. В результате использования стента восстановлен естественный ток крови в церебральной артерии. В мешочке аневризмы обнаружена область с низким значением скорости крови. Предложенный подход может быть использован при планировании лечебных воздействий и оценке риска послеоперационных осложнений у больных с церебральной аневризмой.

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Modellierung der Veränderungen der Blutung, die von der Einstellung der stromrichtenden Anlage unter Ausnutzung des mehrgroßzügigen Modells der Hämodynamik herbeigerufen sind

Zusammenfassung: Es ist das Herangehen an die Modellierung der hämodynamischen Veränderungen, die von der Einstellung der stromrichtenden Anlage in die zerebrale Arterie herbeigerufen sind, vorgeschlagen. Das Herangehen ist auf der Nutzung des mehrgroßzügigen Modells der Hämodynamik gegründet, das drei Typen der mathematischen Modelle der Hämodynamik, die mit den entsprechenden Grenzbedingungen verbunden sind, aufnimmt. Für die numerischen Forschungen wurde das individuelle Modell des zerebralen Aneurysmes des Patienten verwendet. Es wurden zwei Fälle – vor und nach der Einstellung der stromrichtenden Anlage modelliert. Die Ergebnisse haben gezeigt, dass die Einstellung der stromrichtenden Anlage die wesentlichen Veränderungen im Charakter der Strömung des Blutes im Gebiet des Aneurysmes herbeigerufen hat. Infolge der Nutzung der Anlage war der natürliche Strom des Blutes in der zerebralen Arterie wieder hergestellt. Im Säckchen des Aneurysmes war das Gebiet mit der niedrigen Bedeutung der Geschwindigkeit des Blutes aufgedeckt. Das angebotene Herangehen kann bei der Planung der Heileinwirkungen und der Einschätzung des Risikos der postoperativen Komplikationen bei den Patienten mit dem zerebralen Aneurysmen verwendet sein.

Simulation des modifications de la circulation sanguine causée par l'installation de stent coronarien orientant des flux avec l'emploi du modèle multi-échelles de l’hémodynamique

Résumé: Est proposée une approche pour la modélisation des modifications hémodynamiques causées par l'installation de stent coronarien orientant des flux dans une artère cérébrale. L'approche est basée sur l'utilisation du modèle multi-échelles de l'hémodynamique qui comprend trois types des modèles mathématiques de l'hémodynamique accouplés des conditions aux limites. Pour les études numériques est utilisé le modèle individuel de l'anévrisme cérébral du patient. Ont été modélisés deux cas: avant et après l'installation de stent coronarien orientant des flux. Les résultats ont montré que l'installation du stent a provoqué d'importants changements dans la nature du flux sanguin dans l'anévrisme. A la suite de l'utilisation du stent a été restauré le flux naturel dans une artère cérébrale. Dans le sac de l'anévrisme a été découvert un domaine avec une faible valeur de la vitesse du sang. L'approche proposée peut être utilisée lors de la planification des influences médicales et l'évaluation des risques des complications postopératoires chez les patients atteints d'anévrisme cérébral.

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