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Dynamics of branching blood flows at artery-bypass junctions with and without tissue overgrowth: patient-specific CFD simulation

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Abstract. The article presents the results of numerical study of hemodynamics in proximal femoral-popliteal anastomoses of real patients in case of neointimal hyperplasia. Geometric models of anastomoses were based on the clinical data obtained by computer tomography. The neointimal hyperplasia causes changes in the blood flow structure and in stagnant zones after the suture area. Due to the cross-section narrowing, the time-averaged wall shear stresses (TAWSS) in this region increase and the oscillatory shear index (OSI) decreases, and the combined index known as relative residence time (RRT) increases as well. Low values of TAWSS and high values of OSI and RRT are observed in the stagnant zone. High RRT values indicate areas with a high risk of neointimal hyperplasia.

Keywords: patient-specific simulation, femoral-popliteal anastomoses, neointimal hyperplasia, wall shear stress, oscillatory shear index, relative residence time

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Материалы конференции
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Динамика разветвляющегося кровотока в местах соединения артерии с шунтом при гиперплазии ткани и без нее: пациент-ориентированное численное моделирование

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Аннотация. В работе представлены результаты численного моделирования кровотока в проксимальных анастомозах бедренно-подколенных шунтов реальных пациентов в случае гиперплазии неоинтимы. Геометрические модели анастомозов построены на основе клинических данных компьютерной томографии. Результаты показали, что из-за гиперплазии неоинтимы и, соответственно, сужения поперечного сечения увеличиваются осредненные по времени сдвиговые напряжения (TAWSS), уменьшается индекс их колебаний (OSI) и увеличивается относительное время пребывания частиц на стенке (RRT). Низкие значения TAWSS и высокие значения OSI и RRT наблюдаются в застойных зонах. Высокие значения RRT указывают на области с высоким риском гиперплазии неоинтимы.

Ключевые слова: пациент-ориентированное моделирование, бедренно-подколенное шунтирование, гиперплазия неоинтимы, сдвиговые напряжения, индекс колебания сдвиговых напряжений, относительное время пребывания

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Introduction

Synthetic vascular grafts are most often used in surgery for femoral artery bypass. However, unlike vein graft, they are more susceptible to process of excessive tissue overgrowth (neointimal hyperplasia) in the suture area [1], especially during the first year after implantation [2]. If the cross-section of the graft is occluded, new bypass implementation operation is necessary.

Assessment of hemodynamics of the anastomosis (a branch of the vascular graft from the artery) of a real patient can play an important role in predicting the neointimal hyperplasia risk. Currently, patient-specific numerical modeling is actively used for this purpose [3-5], mostly to evaluate the hemodynamic parameters that affect the neointimal hyperplasia. The main of these parameters known in the literature are the time-averaged wall shear stress (TAWSS) and the oscillatory shear index (OSI) [3]. For simplifying flow analysis, some authors use the RRT (relative residence time) [6] being a combination of the OSI and TAWSS parameters. An important task is to analyze local changes of these parameters due to the neointimal hyperplasia at the anastomoses for a sample of patients being under specific observations. This can promote finding correlations between the neointimal hyperplasia and the distributions of wall shear stress parameters.

The aim of the work is to compare the blood flow patterns obtained on the base of patient-specific simulation for femoral artery anastomoses with and without neointimal hyperplasia.

Methods

Geometric models. The present study deals with models of real anastomoses after femoral-popliteal bypass surgery. A scheme of proximal femoral-popliteal anastomosis is shown in Fig. 1. A graft is installed bypassing the occluded superficial femoral artery (SFA). The blood flow from the common femoral artery (CFA) is divided into a graft and a deep femoral artery (DFA).

Among 10 patients under common observation, four had an neointimal hyperplasia during 12–30 months after bypass surgery. The maximum neointima thickness, ranging from 1 to 4 mm, was measured using the ultrasound technique. Anastomosis geometries of these four patients were obtained from the clinical data provided by computer tomography. The inner diameter of CFA in the studied models was in the range of 5.5 to 8.0 mm, and the graft inner diameter was 8-9 mm. Models of anastomoses with and without neointimal hyperplasia were constructed for each patient of the four selected.

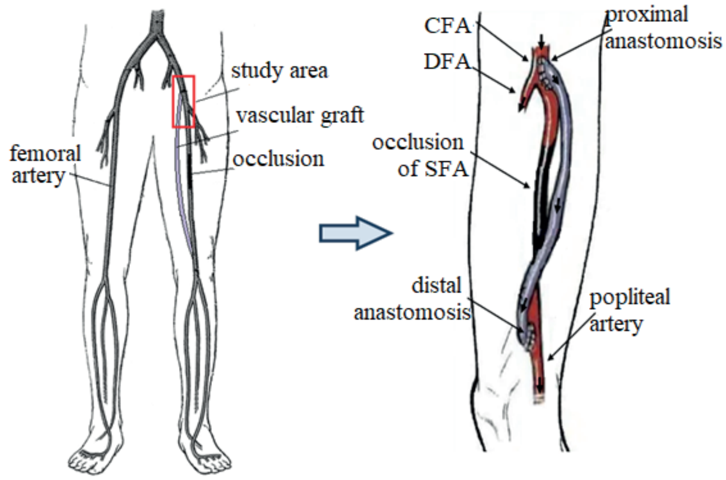

Fig. 1. Area of studied proximal anastomosis
and the blood flow scheme in femoral-popliteal bypass

Mathematical model and computational aspect. Numerical simulation was carried out by solving non-stationary three-dimensional Navier-Stokes equations. The ANSYS CFX fluid dynamics package was used. Quasi-laminar flow of viscous incompressible fluid with density of 1050 kg/m^3 and dynamic viscosity of 0.0035 Pa·s was considered, that is typical for modeling hemodynamics in large vessels. The walls elasticity was not taken into account. A typical grid consisted of about 2.5 mln elements. Spatial and temporal discretizations were of second-order accuracy. The time step was 0.01 s.

At the inlet of the CFA velocity curves were set in accordance to clinical ultrasound measurements, time-average inlet flows ranged from 300 to 800 ml/min. Inlet velocity profiles were flat. At the outlet of the graft the part of the input flow (50–70%) was set in accordance with the ultrasound personalized data. The no-slip condition was set on the walls, where velocity components are equal zero. The maximum values of the inlet Reynolds number were in the range from 1200 to 3000. The inlet Womersley number ranged from 8.5 to 14.0.

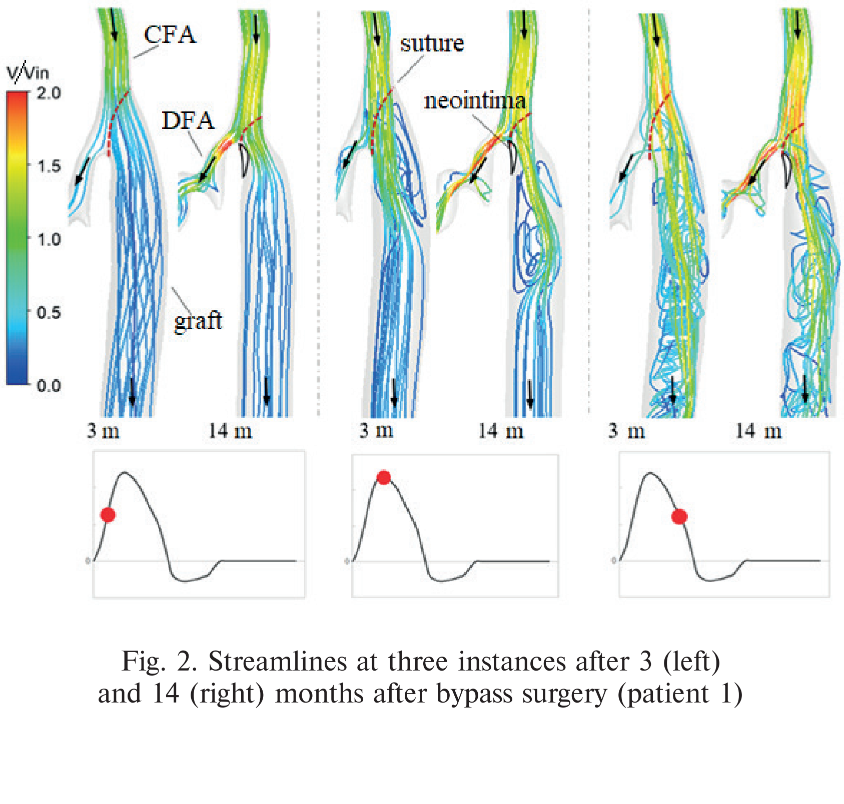

Fig. 2. Streamlines at three instances after 3 (left)
and 14 (right) months after bypass surgery (patient 1)

Results and Discussion

Fig. 2 shows streamlines at three cycle-time moments for one of the selected patients. Two constructed anastomosis models correspond to 3 and 14 months after bypass. After 11 months there have been changes in the anastomosis geometry: namely, the cross-section in the suture area has decreased and the neointima has grown in the graft inlet. The section narrowing led to a slight flow deviation (relative to the flow in the 3-month model) in the graft and a significant increase in the stagnant zone size after neointimal hyperplasia area.

The presence of stagnant zones, seen clearly at the maximum flow instant, is interconnected with areas of low values of time-averaged wall shear stress (TAWSS) and high values of the oscillatory shear index (OSI). This, in turn, points to an increase in the risk of neointimal hyperplasia.

Comparisons of shear stress parameters in the models with and without neointimal hyperplasia were carried out. In addition to the TAWSS (1) and OSI (2), the RRT parameter (3) was also considered.

$$TAWSS = \frac{1}{T}\int_0^T \left|\vec{\tau}_w\right| dt, \tag{1}$$

$$OSI = \frac{1}{2}\left(1 - \left|\int_0^T \vec{\tau}_w dt\right| \Big/ \int_0^T \left|\vec{\tau}_w\right| dt\right), \tag{2}$$

$$RRT = \frac{1}{TAWSS(1 - 2 \cdot OSI)}, \tag{3}$$

where $\overrightarrow{\tau_w}$ is wall shear stress vector, T is cycle time, t is time.

Figs. 3–6 show the distributions of the TAWSS, OSI, and RRT for each of the four selected patients with and without neointimal hyperplasia. In the figures, areas of neointimal hyperplasia are marked in gray. It can be seen that almost in all cases shear stress values in this area increase and oscillatory index decrease. This is due to an increase in the blood flow velocity in the narrowed section. The cross-section area narrowing, evaluated for the considered models as 5-20%, led to increase of time-average wall shear stresses by 50–130 %, to decrease of the oscillatory shear index by 20-30% and to decrease the relative residence time by 25–100 %. High RRT values in Figs. 3–6 (c) indicate areas with higher risk of neointimal hyperplasia (low shear stresses values and high oscillatory shear index).

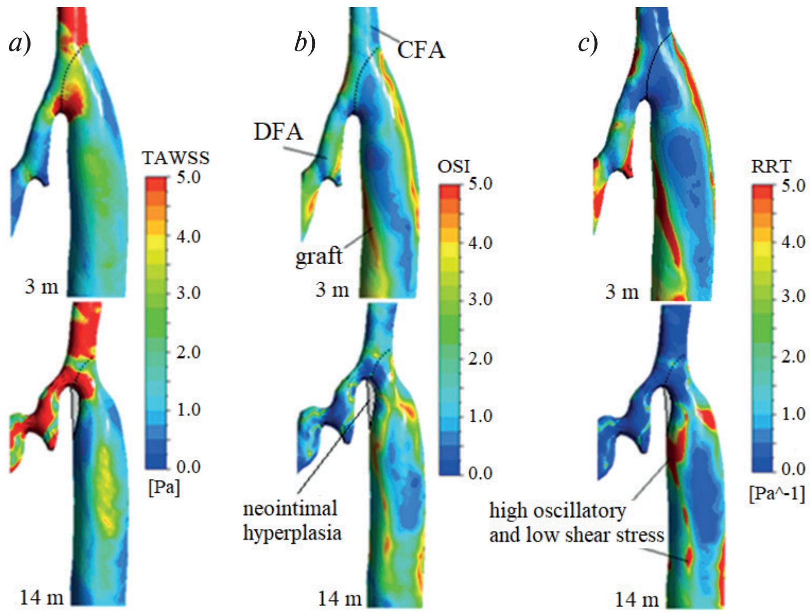

Fig. 3. Time-average wall shear stress (*a*), oscillatory shear index (*b*) and relative residence time (*c*) for 3 (top) and 14 (bottom) months after bypass surgery (patient 1)

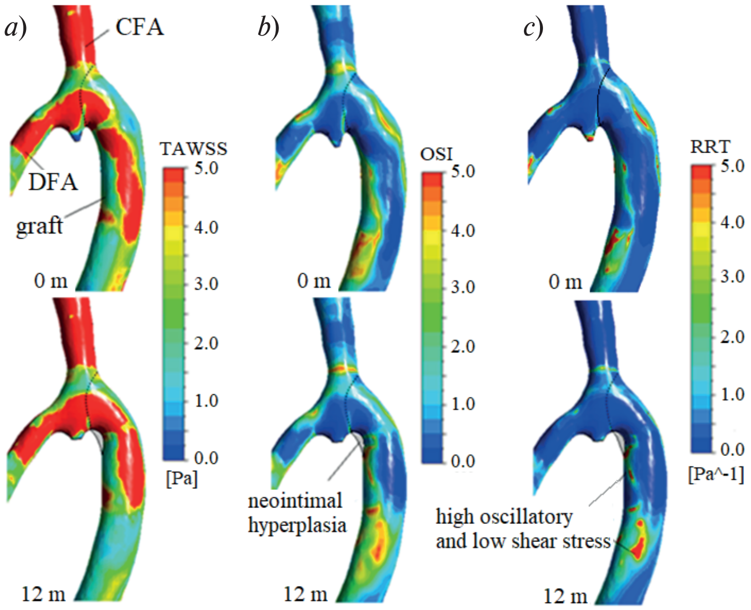

Fig. 4. Time-average wall shear stress (*a*), oscillatory shear index (*b*) and relative residence time (*c*) for 0 (top) and 12 (bottom) months after bypass surgery (patient 2)

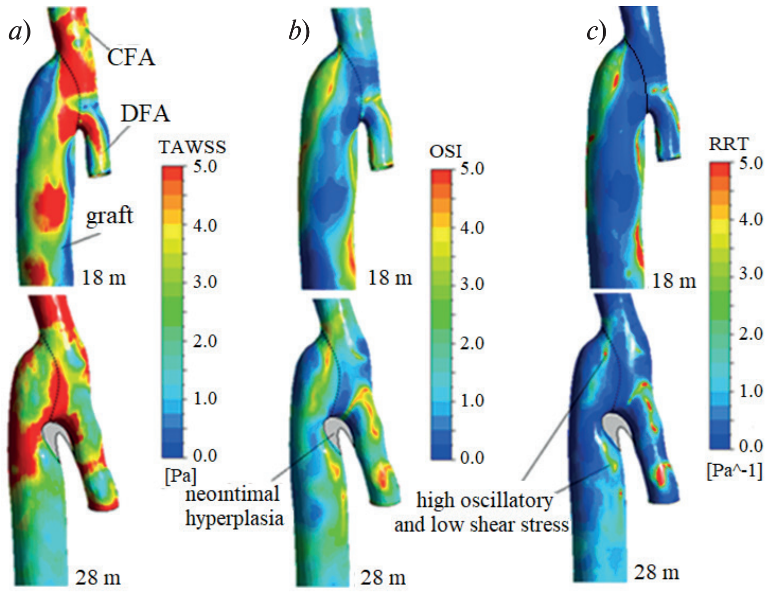

Fig. 5. Time-average wall shear stress (*a*), oscillatory shear index (*b*) and relative residence time (*c*) for 18 (top) and 28 (bottom) months after bypass surgery (patient 3)

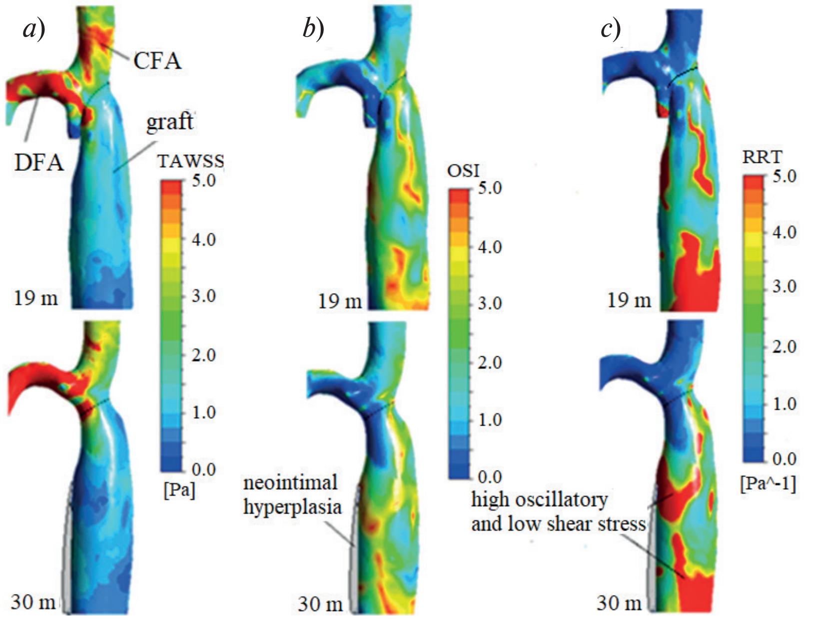

Fig. 6. Time-average wall shear stress (*a*), oscillatory shear index (*b*) and relative residence time (*c*) for 19 (top) and 30 (bottom) months after bypass surgery (patient 4)

Conclusion

Numerical study of the neointimal hyperplasia effects on hemodynamics in proximal femoral--popliteal anastomoses of real patients was carried out. It has been revealed that the neointimal hyperplasia led to an increase in stagnant zones downstream the anastomosis area.

Comparison of blood flow patterns in the models with and without neointimal hyperplasia has shown that, due to the cross-section narrowing, time-averaged wall shear stresses in this region increase, the oscillatory shear index decreases and the relative residence time decreases. In the stagnant zone, values of these parameters are worsen in terms of neointimal hyperplasia risk.

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