Numerical simulation of the branching blood flow in a model of the femoral artery-graft junction

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Annotation. The results of numerical simulation of pulsating blood flow in a three-dimensional model of the femoral artery-graft junction are presented. The study is focused on the influence of the flow rates ratio in two branches of the branching flow on the location and size of the recirculation flow areas in the shunt and in the common femoral artery, with an emphasis on the analysis of the anastomotic zone. Areas with small values of the cycle-averaged shear stresses and increased values of the shear stress oscillation index, potentially dangerous from the point of view of the neointima growth in the shunt, are identified.

1. Introduction
Atherosclerosis of the lower extremities arteries is a disease characterized by the formation of atherosclerotic plaques in the arteries, leading to the cessation of blood flow and narrowing of the vascular lumen, up to its complete plugging up. The popliteal, femoral and tibial arteries are most often involved in the pathological process. The early, untreated stages of the disease are treatable. Femoral-popliteal bypass surgery involves inserting a shunt (biological or synthetic prosthesis) to provide blood flow around the thrombosed area of the femoral artery (Fig.1). Even in the case of a successful operation, the imposed shunt, as well as the patient's own artery, may become clogged, and then there is a need for a repeated operation. One of the possible causes of blockage of operated arteries is the proliferation of the endothelial layer of the vessel wall (intimal hyperplasia) near the anastomosis, being the junction of the artery and the shunt, as a reaction to mechanical damage [1-3].

The mechanisms that stimulate the proliferation of the neointima are not well understood. However, a significant influence of the vortex structure of the blood flow on this process has been established. In particular, low, compared with natural blood flow, averaged shear stresses on the wall (time-averaged wall shear stress, TAWSS) and high values of the oscillatory shear stress index (OSI) create favorable conditions for its intensive growth (intimal hyperplasia) [2].

The individual characteristics of the patient's vascular system play an important role in the success of the femoral-popliteal bypass grafting and in the postoperative period of restoration of blood flow in the lower extremities. These patient-specific parameters include the spatial geometry of the femoral arteries (two samples are given in Fig.2), the bulk velocity time-dependence (“velocity curve”) formed in the iliac arteries, and peripheral resistances of the femoral and popliteal arteries. Knowledge of the influence of these parameters on the structure of blood flow in the anastomotic zone may be useful in choosing the optimal surgical tactics.
2. Geometrical model and computational aspects

A three-dimensional model of the proximal (upstream) anastomosis during femoral-popliteal bypass shunting (Fig. 3) was built on the basis of generalization of literature data and a number of patient-specific models obtained from the results of angiography using computed tomography. In this model, a shunt (D = 8mm) is attached to the common femoral artery, CFA, (D = 6mm) at a 50° angle in front of the 40° branching point of the deep femoral artery, DFA, (D = 4mm). The superficial femoral artery, SFA located below is assumed to be impassable, and its section included in the model has a reduced diameter (see Fig.3), that simulates the consequences of thrombosis.

The three-dimensional pulsating flow in the constructed rigid model of the proximal anastomosis was calculated based on the Navier-Stokes equations for the incompressible fluid, setting density $\rho = 1000 \text{ kg/m}^3$ and viscosity $\mu = 0.004 \text{ Pa\cdot s}$.

The computations were performed with the ANSYS CFX finite-volume software using a grid consisting of about 3 million cells. The second-order scheme were applied both for spatial and temporal approximation.

The parametric computations were carried out varying the ratio of the shunt flow rate to the inlet flow rate. Below this ratio, expressed in percentage, is denoted as $Q_{sh}$. 

To set the boundary conditions at the inlet of the femoral artery and at outlet of the shunt, the form of the “velocity curve” defining the change of flow rate over time was used. It was built from the averaged clinical data for 138 patients, whose age was 56±13 years [4]. The cycle duration, $T$, corresponding to the built velocity curve was 0.86 s. At the inlet of the computational domain, the same average flow rate curve was set for all variants differing in value of $Q_{sh}$. The inlet velocity profile was assumed flat, with zero transverse velocities. The velocity curve at the outlet of the shunt was set in a shape similar to the inlet one. Consequently, the amplitude of the outlet velocity curve was varied depending on a chosen $Q_{sh}$ value (Fig. 4). At the outlet of the deep femoral artery, the zero reduced pressure (relative to the reference one) was set using the type of boundary condition “opening”. The no-slip condition was set on the walls of the model, including the closed end of the SFA section. The initial conditions were zero fields of all velocity components and reduced pressure.
The results presented below were obtained at the peak Reynolds number equal to 1000, if evaluated with the CFA diameter and the peak inlet velocity.

![3D model of the proximal anastomosis for femoral-popliteal bypass](image1)

**Figure 3.** 3D model of the proximal anastomosis for femoral-popliteal bypass

![Pulse curves of the bulk velocity at the CFA inlet and at the shunt outlet for three values of $Q_{sh}$](image2)

**Figure 4.** Pulse curves of the bulk velocity at the CFA inlet and at the shunt outlet for three values of $Q_{sh}$

### 3. Results

#### 3.1 Unsteady velocity field

For one of the three calculated cases (half of the inlet flow goes to the shunt, $Q_{sh}=50\%$), Figure 5 shows the streamline patterns at four characteristic instances of the cycle: flow acceleration, maximum velocity, flow deceleration, and maximum reverse flow rate). The vortex structure is significantly different for the selected instances. So, at the peak of systole (0.12 T), when the highest velocity values are observed for all flow rates into the shunt, the vortex flow is weakly expressed. Immediately after systole (0.23 T), the flow begins to slow down, which causes the formation of an intense vortex flow of the fluid. In diastole (0.34T), the flow vorticity becomes less pronounced.

In systole, stagnant zones appear in the arterial-shunt junction area. It is known that the presence of stagnant zones in the anastomosis is closely related to the presence of areas of small values of time-averaged shear stresses and increased values of the oscillation shear index. These features of the flow structure in the area of the anastomosis may contribute to the development of the hyperplasia process after surgery. The largest stagnant zones are observed when the flow rate into the shunt is 30% of the inlet flow rate, which indicates the likelihood of the development of hyperplasia here. This conclusion is confirmed by the predicted distributions of TAWSS and OSI.
3.2 Averaged shear stresses fields

Figure 6 shows the time-averaged wall shear stress (TAWSS) fields. It is known that the larger this parameter, the lower the risk of developing intimal hyperplasia. As seen in the figure, the lowest TAWSS values are observed on the outer wall of the shunt near the downstream suture. Probably, it is in this place that the risk of developing intimal hyperplasia increases. Moreover, at $Q_{sh}=70\%$, in this place one can observe the highest time-averaged wall shear stresses, compared with the 30% and 50% variants. Therefore, at 70% of the shunt flow rate, the least likelihood of intimal hyperplasia is predicted.

Figure 7 shows oscillation shear index (OSI) fields. Again it is known that the lower the OSI, the lower the risk of developing intimal hyperplasia. With an increase in the flow rate into the shunt, the zone of low OSI values decreases, and $Q_{sh}=30\%$, the most pronounced areas of high values of OSI are observed. Hence, one can conclude that with in case of flow rate of 30% into the shunt, the greatest probability of developing intimal hyperplasia is might be expected.

Thus, based on the calculations of the pulsating flow in models of femoral artery-graft junction, we can assess the relative risks of developing intimal hyperplasia in the proximal anastomosis zone. The highest probability of neointimal growth is observed in the presence of the largest stagnant zones at the anastomosis site, small values of TAWSS and large values of OSI. This means that in case of shunting with the lowest of the considered shunt flows (30%) is subject to the greatest risk of developing intimal hyperplasia, and with an increase in the flow rate, the likelihood of developing hyperplasia decreases. These findings can be used to create a theoretical basis for the causes of intimal hyperplasia after surgery, which can be used by vascular surgeons, for example, when choosing the required diameter of the prosthesis or the sewing technique of a shunt to the artery.
4. Conclusions
For a representative model of the femoral artery-graft junction, data were obtained on the influence of the flow rates ratio in the two branches of the branching flow on the location and size of the recirculation flow areas in the shunt and in the common femoral artery. Areas with low TAWSS values and increased OSI values, potentially dangerous from the point of view of neointimal growth, have been identified.

The data obtained in the work for three variants of the relative flow rate into the shunt allow one to conclude that in case of the minimum flow rate into the shunt (30%) the highest risk of developing intimal hyperplasia might be expected, and with an increase in the flow rate (up to 70%), the likelihood of developing hyperplasia decreases. The data obtained can be taken into account when choosing the size of the prosthesis and the implantation technique, depending on the measured peripheral resistance at the outlet of the femoral and popliteal arteries.

Acknowledgements
The study was carried out in the framework of Project No.20-65-47018 supported by the Russian Science Foundation.

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