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Numerical and experimental study of the 3D flow in a graft-artery junction model

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Abstract. Vascular graft occlusion after implantation is one of the most urgent problems of vascular surgery. This paper presents results of numerical simulation and ultrasound/strain gauge measurements of the 3D pulsating flow of blood-mimicking fluid in a model of the junction of the graft with superficial femoral artery. The calculations have pointed, in particular, at occurrence of an extensive stagnant zone with low wall shear stresses near the graft-artery junction, which can accelerate the graft occlusion. Both the simulation and the ultrasound measurements have shown that a four-vortex flow structure forms just after the graft-artery junction zone, which transforms into a two-vortex flow structure further downstream. Numerical and experimental data on the pressure drop at the graft-artery junction model were in a good accordance.

1. Introduction

In accordance with information of the World Health Organization, cardiovascular diseases are currently the most significant cause of death among noncommunicable diseases. The number of patients with these pathologies continues to grow both worldwide and in Russia, including a considerable increase in the volume of patients with atherosclerotic lesions of the arteries of the lower extremities. Consequently, reconstructive operations on the arteries of this basin are still relevant. A significant amount of surgical care falls on the femoral-popliteal segment and consists in performing femoral-popliteal bypass surgery. Since the inception of vascular surgery, the most commonly used graft material has remained own vein (autograft). However, not in all cases there is a possibility of its application. A generally accepted alternative in this situation is a synthetic graft. One of the causes of impaired patency of a synthetic vascular graft in the long-term postoperative period is the growth of neointima in the anastomotic zone. The mechanisms of this phenomenon are not fully known and may be due to the reaction of vascular tissues to mechanical damage, artificial materials, and significant disturbances of the blood flow structure [1].

Numerical and experimental simulation of blood flow is one of the tools for developing new grafts design and implantation methods [2]. Such studies help to identify disorders of the natural blood flow structure that affect the graft occlusion rate. These are vortex structures in the flow [3], stagnant zones, wall shear stresses [4] and oscillatory shear index [5], pressure drop in the graft-artery junction, and others.

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This paper presents results of numerical simulation and experimental study of the 3D pulsating flow of blood-mimicking fluid in a model of the junction (anastomosis) of the graft with superficial femoral artery. Such a junction is formed because of femoral-popliteal bypass surgery. Numerical simulation was performed using the CFD package ANSYS CFX 16.2. Experimental study was carried out with the ultrasound Doppler method. In addition, strain gauge measurements were done to evaluate the pressure drop at the graft-artery junction model.

2. Experimental model

2.1. Model geometry

Figure 1 shows a scheme of the connection of a vascular graft with femoral artery and highlights the area studied in this work. The graft-artery junction model, shown in figure 2, is based on generalized femoral-popliteal surgery data and corresponds to the case of the «end-to-side» anastomosis. The model is a smooth connection of tubes at 40° angle. The inner diameter of both tubes is 6 mm. The model has one inlet and two outlets: outlet 1 provides the main flow through the superficial femoral artery to the popliteal artery, and outlet 2 provides flow through bypass (collateral) vessels to the popliteal artery [6]. The distance between the graft and artery axes is 20 mm.

The designed model was printed of RGD720 photopolymer with a 3D printer. The chosen material provides a smooth inner model surface and the ability to transmit ultrasound. This allows performing ultrasound flow-velocity measurements inside the model. There are several taps for pressure measurement at the inlet and outlets of the model.





Figure 1. Scheme of the graft and superficial femoral artery junction.

Figure 2. Graft-artery junction model.

2.2. Experimental setup and methods

The experimental setup is shown in figure 3. Blood was modeled with water-glycerine solution, the density and viscosity of which are equal to the blood parameters. The fluid contained fine paint particles to reflect ultrasound. The centrifugal pump (1) provided a pulsating flow with a period of 0.9 s. Using the flow controllers (2), the input flow rate (Q1 + Q2 = 1.2 l/min) and the flow ratio at

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outlets 1 and 2 (Q1/Q2 = 4) [6] were set. The flow rate was measured using sensors of electromagnetic flowmeter (3) MF 46 NIHON KOHDEN.

During the experiment, fields of two velocity components, and pressure drop between the model inlet and outlet 1 were measured. Velocity components were measured by a linear ultrasonic sensor (6) of the LogicScan 64 ultrasonic scanner, and pressure values were measured by the Braun strain gauges (4).

Remember that the ultrasonic sensor measures the velocity components projections on its axis. The sensor was installed at a 60° angle to the model axis to measure the axial velocity. From the other side, the sensor was installed at a 90° angle to the model axis to measure the transverse velocity. In ultrasound images of cross sections in the color Doppler mode, red shades indicate the flow velocity direction to the ultrasonic sensor, and blue shades indicate the flow velocity direction from the sensor.

With the specified model and flow parameters, the characteristic Reynolds number, *Re*, corresponding to the instance of maximum flow, was evaluated as 1050, and the Womersley number was about 4.



Figure 3. (left) Bulk flow rate wave and (right) scheme of the experimental setup: 1 - centrifugal pump, 2 - flow controllers, 3 - electromagnetic flow meter sensors, 4 - pressure strain gauge sensors, 5 - container with the model under study, 6 - ultrasonic sensor, 7 - electromagnetic flow meter, 8 - pressure measurement system amplifier, 9 - ultrasonic scanner.

3. Numerical model

For numerical simulation, a three-dimensional graft-artery junction model was constructed, corresponding to the experimental one. The unsteady three-dimensional Navier-Stokes equations (1) were used to simulate the pulsating flow of incompressible fluid under the given conditions.

$$\begin{cases} \frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\mu}{\rho} \frac{\partial}{\partial x_j} \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \\ \frac{\partial v_i}{\partial x_i} = 0 \end{cases}$$
(1)

Here v_i , and v_j are the velocity vector components (i, j = 1, 2, 3), p is the pressure, ρ is the fluid density, μ is the fluid dynamic viscosity, x_i , x_j are the Cartesian coordinates, and t is the time.



Figure 4. Computational grid of graft-artery junction model

Integration of equations (1) was performed using the finite volume method, as implemented in the program ANSYS CFX 16.2. Boundary conditions were consistent with the experiment. The flow wave was set at the model inlet (Fig. 3), and the flow ratio Q1/Q2 equal to 4 was prescribed for the outlets. The no-slip condition was set on the wall. As in the experiments, the characteristic Reynolds number, at the maximum flow instance, was equal to 1050, and the Womersley number was 4.

An unstructured computational grid consisting of tetrahedral elements in the flow core (Fig. 4) was built with the ICEM CFD program. The grid had a prismatic-element layer at the wall.

A grid-dependence study was performed by comparing steady-state solutions obtained at constant flow rate (inlet $V_b = 0.7$ m/s, Re = 1050) using three grids with different number of elements: 0.7, 1.2 and 2 million. Distinctions between solutions obtained with grids of 1.2 and 2 million elements did not exceed 5 %. The pulsating flow simulation was carried out using the grid consisting of 1.2 million elements. It was also revealed that decreasing the time step from 0.01 to 0.001 s did not lead to any considerable distinctions in the flow evolution.

4. Results

Figure 5 shows a Q-criterion isosurface illustrating the secondary flow structure in the model. Just downstream of the graft-artery junction zone, a four-vortex structure is formed. It has a length of about 7 calibers, and further downstream it is transformed into a two-vortex structure.

Figure 6 illustrates a three-dimensional streamlines pattern at the maximum flow instance. Here one can see a stagnant zone, in which the velocity modulus is less than 1 cm/s. This stagnant zone is formed near the junction in the outlet 2 branch. It seems to be one of the factors stimulating graft occlusion.

For the same instant, Figure 7 shows the time-averaged wall shear stress field. The most interesting area is the graft-artery junction zone. Low values of shear stress mean elevate risk of graft occlusion. In the model considered, this relates to the outlet 2 branch and to the outer side of the model graft.

For two cross sections of the model, Table 1 compares calculated and measured fields of projections of the axial and transverse velocity components on the ultrasonic sensor axis. The axial velocity distributions clearly show the maximum velocity offset from the central axis. In section 1, a reverse flow zone is observed. The transverse velocity fields point to formation of four vortices in section 2.

For the pressure field, let us compare the calculated and the measured pressure drop between the inlet and outlet 1 of the model at the maximum flow instance. The calculated pressure drop is 220 Pa, and the measured one is 250 Pa; it gives a difference of 12%.

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Figure 5. Q-criterion isosurface at the maximum flow instance.

Figure 6. Streamlines at the maximum flow instance (a stagnant zone is shown in dark blue).

Figure 7. Distribution of timeaveraged wall shear stress.

Table 1. Comparison of calculated and measured fields of projected velocity.



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Conclusions

Numerical simulation and measurements of 3D pulsating flow of blood-mimicking fluid flow in a representative model of the junction of the graft with superficial femoral artery have been carried out. Calculation data show that a stagnant zone with low wall shear stresses occurs near the graft-artery junction; the presence of such a zone can accelerate the graft occlusion. Both the simulation and the ultrasound measurements point to formation of a four-vortex flow structure just after the graft-artery junction area zone, which transforms into a two-vortex flow structure further downstream. Numerical and experimental data on the pressure drop at the graft-artery junction model are in a good accordance.

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