Investigating a pulsating flow in the smooth channel and at the bifurcation section with regard to the popliteal artery hemodynamics

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Abstract Experimental setup is described. Pulsating flow in a smooth channel, and steady and pulsating flows at a bifurcation section simulating the distal end of an artery anastomosis at different flow rates in the main and outflow channels are studied. Indications of laminar-turbulent transition are observed in the near-wall region of the smooth channel. Mechanisms of turbulization of the near-wall region in the pulsating flow are suggested. Vortex flow structure in the bifurcation section is analyzed.

1. Introduction

An important area of research on pulsating flows is hemodynamics in human vascular systems. The growing interest in this area has recently been attributed to an increase in the number of patients with cardiovascular diseases. Such patients are often treated with surgery through deployment of various types of stents, shunts, etc. In accordance with postoperative observations, atherosclerotic lesions of the arterial bed at the stent placement section, or an increase of neointima in the anastomotic zone with its gradual constriction and complete cessation of blood flow in the shunt, are very common [1]. Numerous studies indicate the relation between the growth rate of neointima and the hydrodynamic features of the flow in the area of the shunt or anastomosis [2–4].

The femoral-popliteal arteries most often require blood flow restoration. The peculiarities of the hemodynamics of these arteries are high amplitude of blood flow pulsations (its magnitude can exceed its average value 12 or more times) and the presence of reverse flows for much of the pulsation period [5–7]. Most of the studies of flow structure under such conditions were carried out using numerical simulation [e.g., 8]. However, the implementation of the numerical procedure encounters the well-known problem of setting the boundary conditions at the inlet and outlet of the computational domain in the case for flow reversal during part of the pulsation period.

As a rule, the Reynolds numbers of the mean bulk flow in the human femoral-popliteal arteries correspond to the laminar regime. According to the above-mentioned features of the flow rate variation during the pulsation period, the processes of laminar-turbulent transition can have a significant effect on the flow structure in these arteries. In this case, flow turbulization can also be observed at local Reynolds numbers significantly lower than the values corresponding to the laminar-turbulent transition in a steady flow. However, these processes have been studied insufficiently. In
addition, there are only few published papers, where the experimental methods were used independently, rather than to validate a numerical code [9-10]. The present paper elaborates on a description of an experimental setup developed by the authors for the study of pulsating flows and ensuring high stability of a given law of flow rate variation, high amplitude of pulsations and reproducing the reverse flow during a fraction of pulsation period. The results of experimental studies of a pulsating flow in a smooth channel and in a channel with a bifurcation simulating the distal end-to-side anastomosis are presented.

2. Experimental setup and procedure
The experimental setup for the study of pulsating flows is demonstrated in fig.1.a. The liquid flow rate in the setup is ensured by the static head created by the pressure tank. The overflow system maintains a constant liquid level in the tank. The flow rate through the test section is regulated by a batcher with a set of nozzles. The area for measuring is located in a transparent box filled with glycerin, whose refractive index is almost identical to the material of the section walls. Flow rate pulsations are generated by the reciprocal motion of a piston. Due to low drag downstream of the batcher, if compared to the drag of batcher nozzles, forced pulsations generated by the piston also propagate in the flow through the test section. The experimental setup provides reproducibility of the flow parameters and attainability of large negative values of velocity. The setup is equipped with SIV system for measuring instantaneous two-dimensional vector fields of the flow velocity [11]. Polyamide particles with a diameter of 5 microns are used as tracers. A higher concentration of particles ensures better spatial resolution and lower measurement noise if compared to PIV.

Two types of the test section were used in the present studies: a smooth tube with an inner diameter d=17 mm (main artery) and the identical tube with a lateral bifurcation at an angle of 60 degrees, simulating the connection of the shunt with the main artery (distal end of the end-to-side anastomosis) (fig. 1,b). Valves at the outlet of the main channel and the bifurcation allow adjusting the ratio of flow rates Q1/Q (and Q2/Q, respectively). Water solution of glycerin was used as a working fluid. When studying the flow in a smooth channel, the mass fraction of glycerin was 60.8%, which provided the kinematic viscosity of the solution confirmed by direct measurements \( \nu = 9.68 \times 10^{-6} \text{ m}^2/\text{s} \). In the case of a flow in a channel with bifurcation, a solution with a mass fraction of glycerin of 51.7% \( (\nu = 6.0 \times 10^{-6} \text{ m}^2/\text{s}) \) was used. The length of the smooth straight section before the measurement section was 1000 mm \( (58.8 \, d) \). The studies were performed in a steady flow regime and at sinusoidal variation of flow rate with a frequency of 0.9 Hz. For a smooth channel, the experiments were carried...
out at the Reynolds number \( \text{Re}_{\text{max}} = 1200 \) based on the maximum velocity over the pulsation period \( U_{\text{max}} = 0.683 \) m/s. In this case, the pulsation amplitude of the flow velocity averaged over the cross section was \( A_U = 0.53 \) m/s \((A_U/U_{\text{aver}} = 3.46)\) and ensured the presence of reverse flow during a fraction of the period of flow rate pulsations. Here \( U_{\text{aver}} \) is the flow velocity averaged over the channel cross section. In the case of bifurcation channel, the condition \( \text{Re}_{\text{max}} = 1500 \) was used, with \( U_{\text{max}} = 0.529 \) m/s and \( A_U = 0.46 \) m/s \((A_U/U_{\text{aver}} = 5.17)\). For the case of bifurcation channel, the flow rate ratio was \( Q_1/Q = 0; 0.125; 0.25; 0.5; 0.75; 1.0. \)

3. Pulsating flow in a smooth channel

Before the studies, the flow parameters in the measurement area of the test section were measured with accuracy in a steady flow mode at the Reynolds number corresponding to the maximum \( \text{Re}_{\text{max}} \) in the experiments. SIV measurements agree well with the theoretical profile for a developed laminar flow in a round pipe.

Figure 2, a shows the behavior of flow rate through the test section for the flow mode under study. Fig. 2, b demonstrates changes in velocity during the flow rate pulsation period at different distances \( r \) from the pipe axis. \( R \) is the pipe radius. The fluctuations of velocity near the channel wall outrun the flow velocity pulsations on its axis. The maximum phase shift observed near the wall is \(~0.12\) periods of flow rate fluctuations. Besides, the amplitude of velocity fluctuation grows when approaching the wall; the normalized (by the local flow velocity) rms fluctuations of velocity near the channel wall are 5 times higher than those in the steady flow (fig. 3). Hereinafter, by turbulent pulsations of the flow velocity we mean the pulsations of the velocity with respect to its fluctuations caused by the forced flow unsteadiness. The discovered pattern indicates possible onset of instability and transition to turbulence in the near-wall region of the pulsating flow. We emphasize here that this is not the onset of a developed turbulent flow but some initial stage of transition to turbulence.

The absolute values of the pulsation component of the flow velocity near the wall depend on the phase of forced fluctuations in the flow rate \( \phi \). The flow velocity profile in the channel changes depending on the phase of fluctuations. In some phases, there is a multidirectional liquid flow near the wall and in the central part of the channel.

Periodic flow fluctuations cause an additional force effect on the flow. Using the example of a periodic external flow around a plate, it was shown in [12] that this effect increases when approaching the wall. The thickness of the layer \( \delta_0 \) (“Stokes layer”) with most pronounced effect can be approximately estimated by the formula obtained for a flow near a flat wall performing streamwise harmonic fluctuations in a steady-state medium (the second Stokes problem) [13]: \( \delta_0 = (2\pi/n)^{0.5}, \) where \( n = 2\pi f; f \) is the pulsation frequency.

![Figure 2. Oscillograms of flow rate in the test section (a) and variation of velocity during a period of flow rate pulsation at different coordinates \( r/R \) (b).](image-url)
Measurement results yielded a significant increase in the rms fluctuations of the flow velocity $U_{RMS}$ starting from $y/\delta_0=1$ in this layer (Fig. 4). Outside this layer ($y/\delta_0>1$), $U_{RMS}$ remain approximately constant.

The above-mentioned additional force effect on the flow leads to a periodic change in the friction stress in the near-wall region (Fig. 5). In separate phases of the flow rate fluctuation, the dimensionless complex $R/U_{\text{aver}}|y=0$ reflecting the friction stress on the wall reaches values of 30. Meanwhile, estimates made on the basis of steady approaches ($\lambda=64/Re$) demonstrate the limiting value of this complex for maintaining the laminar flow in the channel, equal to 4. Here $U_{\text{aver}}$ is the average flow velocity over the section, and $\lambda$ is the drag coefficient of a smooth pipe.

Apparently, under these conditions, there is a loss of flow stability near the wall and the production of turbulent velocity pulsations with the vortex structures. The maximum turbulence generation is observed in a layer with a thickness of the order of $\delta_0$. The vortex structures are preserved during the entire period of fluctuations: $U_{RMS}$ normalized by the local flow velocity in the considered pulsation phase remain approximately constant.

4. Flow in a bifurcation channel

The flow structure in the bifurcation channel in the steady regime depends on the flow rate ratio $Q_1/Q$. At $Q_1=0$, two vortices of scale $d$ rotating in opposite directions are formed in the main channel to the left of bifurcation (according to Fig. 1,b). At the beginning of the bifurcation section, on its right generatrix, there is a separation region with the length of $2.5d$ and the transverse dimension of $0.4d$ streamlined by liquid jet. The liquid jet tends to the left generatrix of the bifurcation.

**Figure 3.** Behavior of normalized rms fluctuations of streamwise component of velocity in the channel.

**Figure 4.** Behavior of rms fluctuations of flow velocity from the transverse coordinate.

**Figure 5.** Derivatives of streamwise velocity component along the pipe radius.
At $Q_1/Q=0.125$, part of the flow enters through the main channel. In this case, the flow in the main channel tends to its lower generatrix, and a separation region with increased vorticity is detected near the upper generatrix. The transverse size of the flow separation region in this mode is $0.85d$, and its streamwise size is about $3d$.

A further increase in $Q_1/Q$ leads to a stretching of the streamwise dimension of the flow separation region in the main channel with a simultaneous decrease in its transverse dimensions. Flow structure in the bifurcation does not change significantly (Fig. 6,a).

![Flow visualization in the bifurcation region at steady regime at Re=1500: a – Q1/Q=0.5; b – 0.75.](image)

**Figure 6.** Flow visualization in the bifurcation region at steady regime at $Re=1500$: a – $Q_1/Q=0.5$; b – 0.75.

A significant restructuring of the flow is observed upon reaching $Q_1/Q=0.75$ (Fig. 6,b). The transverse size of the flow separation region near the upper generatrix of the main channel decreases to $0.26d$, and the length of this region increases to approximately $4.5d$. In the outlet channel at this regime, the flow near both generatrices is observed in the direction of the main flow, while a reverse flow takes place in the center. A further increase in $Q_1/Q$ leads to the practical disappearance of the flow separation region in the main channel. A closed separation region in the bifurcation near its right generatrix is formed. At $Q_1/Q=1.0$, the flow structure in the main channel refers to a developed pipe flow with some deformation over the bifurcation region. One stationary $d$-scale vortex is formed in the bifurcation section. The visualization indicates a possible flow turbulization in the separation regions at all $Q_1/Q$ ratios.

The flow structure also depends on the flow rate ratio $Q_1/Q$ in the pulsating flow. At $Q_1/Q=0$ in the acceleration phase, a separation region is formed on the lower generatrix of the bifurcation region. Flow separation in the reverse flow is observed already to the right of the bifurcation on its lower generatrix (see Fig. 1,b). In this case, large-scale vortices of scale $d$ appear in the main channel to the left of the bifurcation. The rotation direction of these vortices changes depending on the phase of flow rate fluctuations (if the flow rate is positive, it is clockwise, if the flow rate is negative, it is counterclockwise, a smaller scale) (Fig. 7,a).

At $Q_1/Q=1$, when the flow direction in the bifurcation changes, multidirectional vortices appear: with a forward flow, counterclockwise, and with a reverse flow, clockwise (Fig. 7,b). In the initial phase of flow acceleration, a small separation region is formed on the lower generatrix of the main channel to the left of bifurcation, and then it quickly disappears.

At $Q_1/Q=0.5$ in the phase of flow acceleration, a separation region appears on the lower generatrix of the bifurcation. In this case, the flow in the main channel is practically unseparated (Fig. 7,c). In the deceleration phase, a small separation region arises on the upper generatrix of the main channel to the left of the bifurcation; it begins to increase in the deceleration phase and sharply increases in size up to scale $d$ at transition to reverse flow. This region has a complex vortex structure (Fig. 7,d).
Figure 7. Flow visualization in the bifurcation region at pulsating regime: a – Q1/Q=0; b – Q1/Q=1; c – Q1/Q=0.5 (flow acceleration phase); d – Q1/Q=0.5 (reverse flow beginning).

Conclusions
The pulsating flow structure in the smooth channel and in the bifurcation region with the presence of a reverse flow during a fraction of the pulsation period has been studied experimentally. Under these conditions, indications of transition to turbulence in the near-wall region have been observed. A possible mechanism of flow turbulization has been described. Flow visualization in the bifurcation channel in steady and pulsating flows has been obtained. Features of the vortex flow structure in the bifurcation region have been revealed. The dependence of this structure on the flow rate ratio in the main channel and in the bifurcation section and on the phase of flow rate pulsation has been shown.

Acknowledgments
The study was supported by the Russian Science Foundation, project no. 20-61-47068 (scientific results) and FRC Kazan Scientific Center of RAS (FMEG-2021-0001) (SIV method testing).

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