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Numerical investigation of swirling flow in the graft with a spiral ridge

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Abstract. In the present work, numerical simulation was conducted for a typical connection of a vascular graft (prosthesis) and an artery to assess the effect of inducing swirling flow, which is believed to remove unfavourable flow environment. A parametric study on the spiral ridge geometrical features that was conducted showed that the ridge height and pitch have significant effects on inducing swirling flow, and revealed the potential of improving the efficiency of such design. Simulations were carried out for two models – a standard graft and the one with an optimal spiral ridge. Hemodynamic parameters were compared and the results showed that the graft with a spiral ridge is more effective. The induced swirling flow was generally found to be decreasing particle residence time within the connection of the graft and artery region and the host artery, which may be beneficial to the graft patency rates.

1. Introduction

Currently available synthetic vascular grafts perform well as large-caliber replacements, but their long-term flow capacity is discouraging in small-caliber applications such as lower extremities surgery. This failure is mainly a result of an unfavorable healing process with surface thrombogenicity, due to the damage of endothelial cells and thickening of the inner layer of a blood vessel caused by hemodynamic disturbances [1]. In this case there is a need for repeated surgery.

Numerous experimental studies performed recently have made it possible to register the helical blood flow in different parts of the cardiovascular system using such methods as phase contrast cardiovascular magneticresonance and the ultrasound colour flow imaging [2]. While the physiological importance of secondary motion in circulation has clearly been highlighted in the literature, the benefits of helical/spiral prostheses in vascular conduits have been firmly established [3].According to clinical studies, the swirl number characterized by the ratio of the maximum circumferential to the maximum axial velocity is 0.1-0.3 for the femoral artery[4].

There are two main types of experimental vascular grafts with swirling flow. The first type is a helical graft developed by Caro and colleagues [5]. However, its spatial tortuosity can be destroyed by surrounding tissues. The second is a graft with an internal spiral ridge introduced by Vascular Flow Technologies Ltd [6]. Both types have been clinically tested and introduced into clinical practice. These types of grafts reduce the thickening of the inner layer of a blood vessel but not fully solve this problem.

The aim of the present work is the numerical simulation of blood flow in the graft with a spiral ridge model, its geometric parameters optimization and comparison with the standard linear graft.

2. Methods

2.1. Geometric models
The geometry studied in this work represents a connection of a graft with inner diameter D = 6 mm and an artery (D = 6 mm) at an angle of 40°. This model has a one-pitch-long internal spiral ridge with spiral pitch (S), height (h) and width (w = 2.5 mm). The effects of the ridge have been studied through the variation of spiral pitch (S = 30; 40; 60 mm) and height (h = 1.8; 2; 2.2 mm).

2.2. *Mathematical model*
Three-dimensional unsteady Navier–Stokes equations were solved in order to simulate the flow in the graft model. The computations were performed with the ANSYS CFX code by the control volume method with second-order accuracy in space and time. Navier-Stokes equations were used as governing equations.

A uniform velocity profile and a variation in the mean flow velocity during the cycle were specified at the inlet boundary. The mean velocity curve was obtained from the flow rate curve reproducing the results of clinical measurements of blood flow in the femoral artery of healthy volunteers by phase-contrast magnetic resonance imaging [7]. The time period of the flow cycle T = 0.9 s. The velocity increase phase makes up 22% of the total cycle time. The maximum mean flow velocity for the period $V_{b\,max}$ = 0.94 m/s. The phase of the mean flow velocity decrease is characterized by the reverse flow associated with the motion of the pulse wave through the vessels. At the outlet boundaries of the graft the flow rates were specified as 1/4. No-slip boundary condition is applied to all walls and a rigid wall model is assumed.

The computations were performed for a liquid with properties similar to blood: the dynamic viscosity coefficient μ= 0.004 Pa·s, the density ρ= 1000 kg/m^3. The maximum Reynolds number percycle for these parameters was $\mathrm{Re} = 2\rho R V_{b\max}/\mu$ ≈ 1500 and the Womersley number was $W_0 = R\sqrt{2\pi\rho/\mu T}$ ≈4.

2.3. *Choice of the computational mesh and time step*
The computational domains used here are based on finite-volume hybrid mesh consisting of prismatic elements for the near-wall and tetrahedral elements for the core regions and were generated using ANSYS-Meshing (Version 16.2). A series of rigorous mesh independency tests were conducted on the graft model with a spiral ridge. The computational domains with 1.5 million elements were considered to be sufficient here. The time-step size was taken to be 0.01s. In order to eliminate the start-up effects of transient flow, the computation was carried out for three periods, and the three period results are presented.

3. Results
3.1. Hemodynamic parameters
There is currently extensive and increasing evidence, correlating the localisation of atherosclerosis, thickening of the inner layer of a blood vessel to different local hemodynamic metrics - relative residence time (RRT), time-averaged wall shear stress (TAWSS) and oscillatory shear index (OSI) [8]. They are calculated according to equations

$$RRT = \frac{1}{(1-2\cdot OSI)TAWSS} \qquad TAWSS = \frac{1}{T}\int_0^T \left|\overrightarrow{\tau_w}\right| dt \qquad OSI = \frac{1}{2}(1-\left|\int_0^T \overrightarrow{\tau_w} dt\right| \Big/ \int_0^T \left|\overrightarrow{\tau_w}\right| dt)$$

where $\overrightarrow{\tau_w}$ is wall shear stress vector, T is the time period of the flow cycle.

The swirl parameter $V_{\varphi\max}/V_{z\max}$, often used to characterize flow swirling, is defined as the ratio of the maximal circumferential velocity $V_{\varphi\max}$ to the maximal axial velocity $V_{z\max}$. It is within the range of 0.1 – 0.3 for the femoral artery [4].

3.2. Graft optimization

A series of pulsatile flow simulations were conducted for the model of the graft with an internal ridge to evaluate the effects of different geometrical parameters, including spiral pitch (S) and height (h) of the spiral ridge. Fig.1 shows normalized by the standard graft wall-averaged RRT for different S and h. The optimal graft parameters (S/D = 5; h/D = 0.33) correspond to minimal RRT. RRT is almost 20% less than the one for the standard graft.

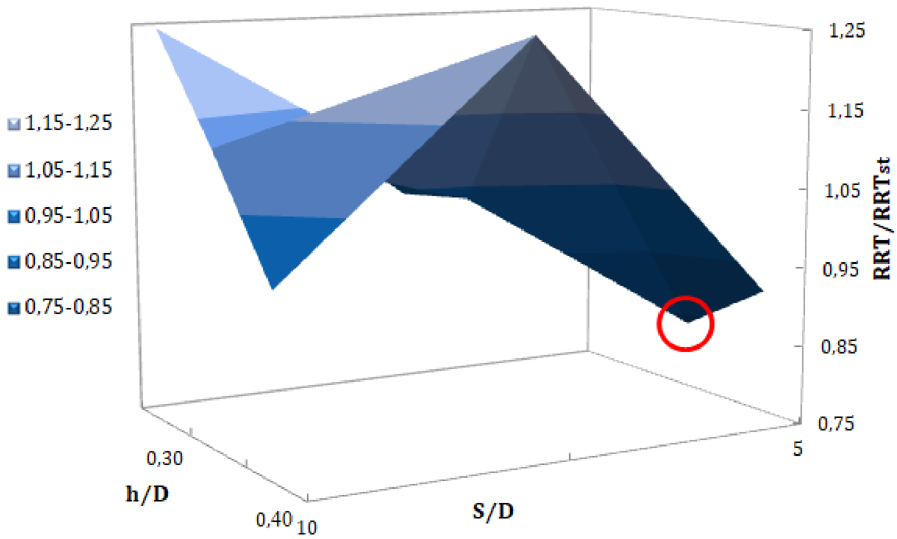

Figure 1. Normalized wall-averaged RRT

Fig. 2 shows the variation of the swirl parameter along the length of the graft and artery connection (coordinate x = 0 showed in Fig. 3). The swirl number is in the physiological range for all examined values of the spiral ridge geometric parameters. The swirl number dependence on the spiral ridge pitch is stronger than on the spiral ridge height.

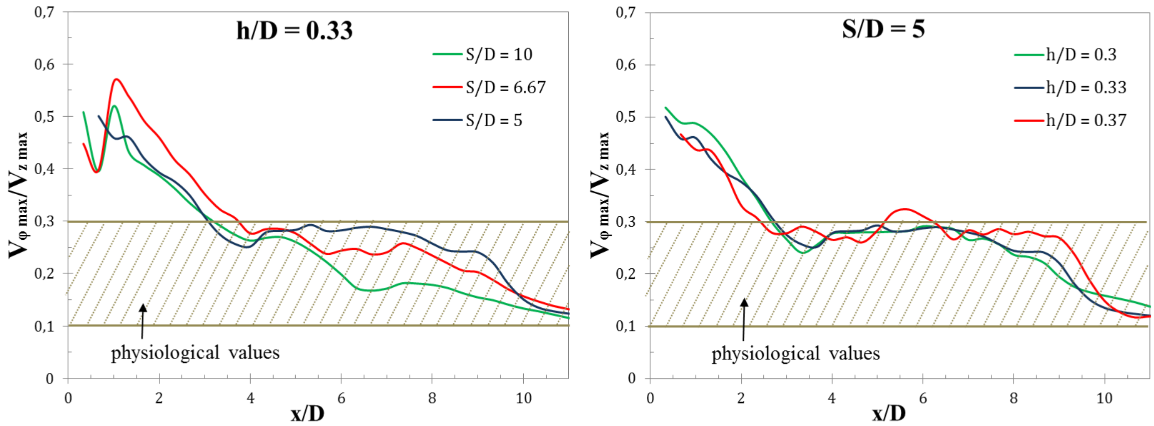

Figure 2. Variation of the swirl parameter over the length of the graft and artery connection for different geometrical parameters

3.3. Comparison with standard graft

The effectiveness of two graft designs –the standard graft and the novel graft with a spiral ridge - has been investigated in this study. While the main geometrical feature of the standard graft has already been investigated numerically by a number of researchers [1], the effects of introducing a spiral ridge inside the graft has not been studied before. The main findings from the present research will be discussed below.

Distribution of time-averaged RRT is shown in Fig.3. Elevated-RRT levels can be seen at the occluded segment of the artery and in the flow separation regions downstream of the point x = 0. The swirling flow induced by the graft with a spiral ridge has reduced the RRT values, by eliminating the flow separation in this region.

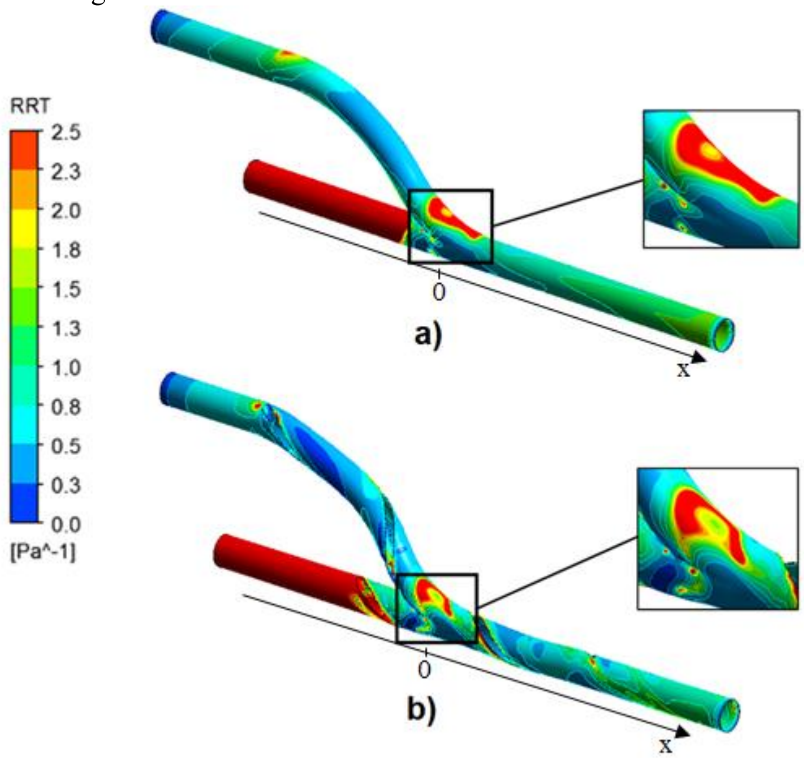

Figure 3. Distribution of RRT for the standard graft model (a) and the graft model with a spiral ridge (b)

The computations revealed that Dean vortex pairs in which the fluid rotated in opposite directions were formed in the standard graft model. The Dean vortices in Fig. 4 are visualized by Q-criterion isosurfaces; they have the form of two structures of similar shape, elongated along region downstream of point x = 0. In the graft model with a spiral ridge the Dean vortices are absent. The spiral ridge generates swirling flow with one single vortex. The most intense swirling was generated close to the branching point. The swirl attenuated downstream of the spiral ridge end.

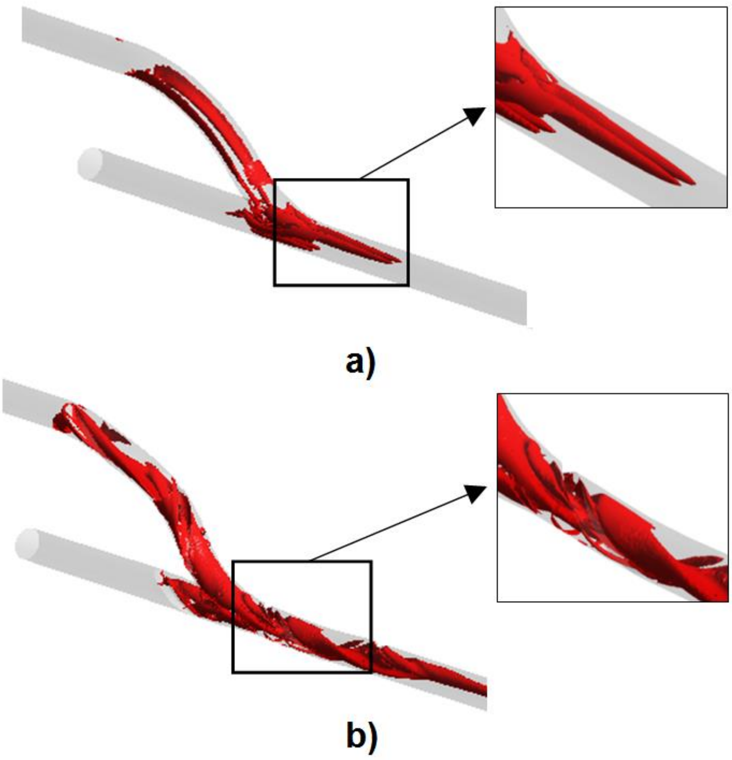

Figure4. Q-criterion isosurface (level 0.08) at the peak flow phase for the standard graft model (a) and the graft model with a spiral ridge (b)

4. Conclusions

The present study shows that inducing swirling flow into the grafts leads to positive flow features and more favorable distribution of hemodynamic parameters in the connection between the graft and artery region and the host artery, which possibly enhances the patency and longevity of the graft.

The graft model with examined values of the spiral ridge geometric parameters forms swirling flow with physiological values of swirl number 0.1-0.3 that corresponds to a healthy femoral artery. The graft with pitch S/D = 5 and height h/D = 0.33 is more effective. For it relative residence time averaged over the wall is over 20% less than the one for the standard graft model.

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