

The impact of the artery geometry with the sewn surgical patch on the blood flow disorders

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Abstract. The research concerns the development of geometric variants of patches sewn into the common carotid artery during surgery of the atherosclerotic plaques removal. Based on analytical methods, the geometry of the patch described by the polynomial function has been developed. The simulations of blood flow in the arteries with the sewn patch were performed. The study included the influence of the patient's diameter and the width of the chosen patch on blood flow disorders. The result of the research is the algorithm of selecting the geometry of the arterial patch to the individual geometrical features of the patient's artery. The studies result will comprise the development of software, which, upon introduction of input data related to arterial geometry, patch length and patient's blood parameters (affecting the fluid density and viscosity), shall generate an accurate contour of the patch of width causing no flow disorders.

1 Nomenclature

$h(t)$ – Heaviside step function
 l – patch length
 s – patch maximum width
PSV – peak systolic velocity
EDV – end diastolic velocity
TKE – specific turbulence kinetic energy
WSS – wall shear stress

2 Introduction

One of the most common carotid diseases is the progressive stenosis: local narrowing of the artery lumen due to accumulated atherosclerotic plaque. When the plaques reduces the artery flow cross-sectional area by 75%, the patient is qualified for surgery of the plaque removal. During surgery, the vascular surgeon performs longitudinal artery incision at the site of stenosis, removes the plaque and sutures the artery back. A very common practice used by surgeons is the so-called arterial patch that minimizes the risk of stenosis of the artery due to the stitching of tissue parts. The application of a patch reduces the risk of a stroke as compared to the primary suturing [1, 2]. The shape of the surgical patch depends largely on the surgeon performing the surgery: he selects its shape and width based on experience. Currently, there are no valid standards regarding their shape, width and length. If the surgeon incorrectly selects the shape and width of the patch, there is an increased risk of the carotid restenosis. Significantly wide patch causes an increase in the cross-section area in the artery and a positive pressure gradient. As a consequence,

in the artery at the sewing site, the boundary layer can be separated, vortices may form, which will again lead to the accumulation of plaque on the artery walls.

The article presents the results of studies on the influence of the width of a standardized arterial patch on the character of blood flow. Based on the numerical research results, the maximum patch width that can be used for a given arterial diameter value was determined. The assessment of blood flow was made based on such parameters as wall shear stresses, velocity distribution and specific turbulence kinetic energy. It has also been studied, in which phase of the cardiac cycle the flow disorders are the most substantial.

3 Analysis and modelling

3.1 Artery geometrical model

The blood flow simulation was performed for three arteries with diameters of 6 mm, 9 mm and 12 mm, respectively. Three-dimensional geometric models for the variant with a sewn-in patch of a certain width were made for each artery. It was assumed a symmetrical widening of the artery under the influence of the patch. Three cases were considered: when the radius at the widest point is 20%, 55% and 90% of the artery radius, respectively. Figure 1 shows the concept of sewing a patch. The shape of the patch is described by the polynomial function. Table 1 provides information about the geometry of applied patches. Function coefficients depend on the artery diameter, patch width and length. Due to it is possible to adjust its shape to the patient's diameter, especially: length of the surgical incision and desired width of the patch. All calculation meshes for models are structural grids, by $y + = 1$,

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Table 1. Comparison of the artery variants examined with the sewn arterial patch

patch symbol	d_{art} [mm]	d_{max} [mm]	s [mm]	l [mm]
6_20	6	7.2	3.8	40
6_55	6	9.3	10.4	40
6_90	6	11.4	17	40
9_20	9	10.8	5.7	40
9_55	9	13.95	15.6	40
9_90	9	17.1	25.4	40
12_20	12	14.4	7.5	40
12_55	12	18.6	20.7	40
12_90	12	22.8	33.9	40

with the butterfly topology applied to improve its orthogonality and skewness.

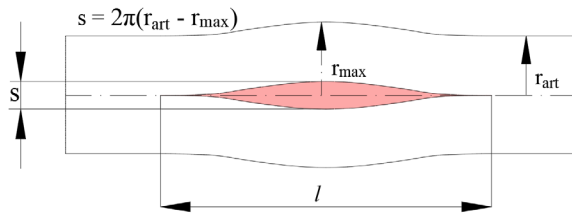


Figure 1. Modified artery model with sewed patch

It was assumed that the length of the surgical incision is constant and equal to 40 mm. The criterion for the surgical patch selection was the percentage level of the artery radius widening. The adopted values resulted from the research main purpose to analyse two extreme cases: sewing the patch as narrow as possible and very wide, which causes almost a twofold increase in diameter. Thanks to this, it is possible to distinguish the most important differences in the flow, mainly in terms of separation of the boundary layer and vortex formation.

3.2 Boundary conditions

In order to be able to determine in which phase of the cardiac cycle the blood flow disorders are considerable, it was decided to perform simulation for the full cycle of pulsation. The input data for the velocity profile used at the inlet was derived from the ultrasound Doppler examination of the carotid artery of a healthy patient [3]. Velocity distribution in cross section at the inlet is symmetric and its direction is normal to the inlet surface. At the outlet, the static pressure profile based on the 2-parameter Windkessel model [4–8] was applied. Velocity and pressure functions are presented in figure 2. The dependence of Carreau [9–11] was used as the blood model. Blood is a non-Newtonian liquid, therefore it is very important to consider the change in viscosity as a function of shear rate, especially in the aspect of WSS and turbulence [12–14]. A non-slip boundary condition was implemented for the wall. For simplicity, it was assumed that the walls are stiff: their flexibility was taken indirectly, by introducing total arterial compliance to the Windkessel model.

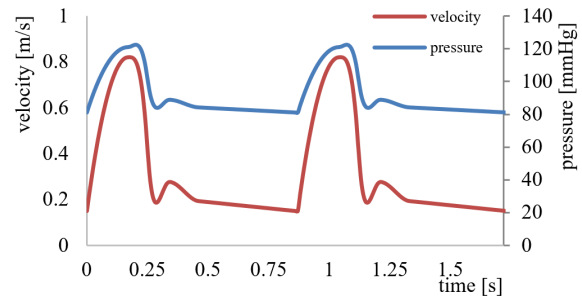


Figure 2. Velocity inlet function, pressure outlet function

3.3 Numerical setup

Numerical calculations were carried out using the Ansys Fluent software [15]. Because the blood flow are incompressible and relatively slow (maximum velocity does not exceed 1 m/s, what gives the Reynolds number below the value of 3000) a pressure-based solver was used. As a turbulence model, $k-\omega$ SST was applied. The time step was equal to 0.0001 s. The calculated flow time included one full heart pulsation: the simulation required the calculation of 8600 time steps. The value of the time step is crucial in the aspect of precise calculation of WSS [16], which was one of the key parameters considered in the analysis of the blood flow.

4 Results and discussion

Based on results, the area-weighted average of WSS and TKE was calculated using the formula 1.

$$\Phi_{ave} = \frac{1}{A} \iint_A \Phi dA = \sum \Phi_i A_i \quad (1)$$

where Φ is considered physical variable, Φ_i is value of WSS or TKE in the mesh element A_i .

Due to the average values of WSS and turbulence kinetic energy analyzed during one cardiac cycle, the time at which the blood flow disorders are the most significant was determined. A very significant influence of patch can be seen in the case of analysis of stress distribution along the wall (Fig. 3). Between 60 and 90 mm along the artery, there is a local artery dilation. It can be observed an increase in WSS. The highest stress values can be noted for the artery with the largest diameter. The width of the applied patch significantly affects the uniformity of this distribution: the larger the d_{max} , the higher the stresses. Such condensed, even six fold increase in stress may lead to a local weakening of the artery wall. This explains why aneurysms (local widening of the artery wall) often arise in arteries of very irregular geometry [17].

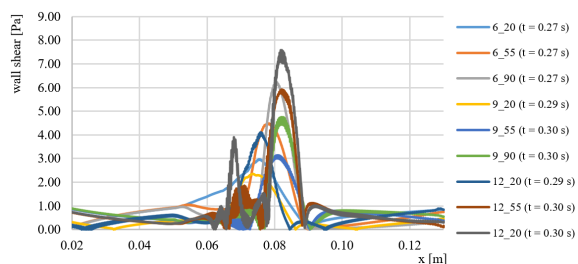


Figure 3. WSS distribution along the artery ($t = 0.27$ s)

Figure 4 shows the maximum value of the TKE in the geometrically modified part of the artery. The diameter of the artery has a very significant influence on the value of TKE: at the same relative width, the maximum value of TKE for the case of 6_20 k is 0.165 J/kg , while for 12_20, its value increases to 0.25 J/kg . Exceeding the value of 55% of the artery radius causes a rapid increase in the energy of vortices, at the time of transition between the systolic and diastolic phases.

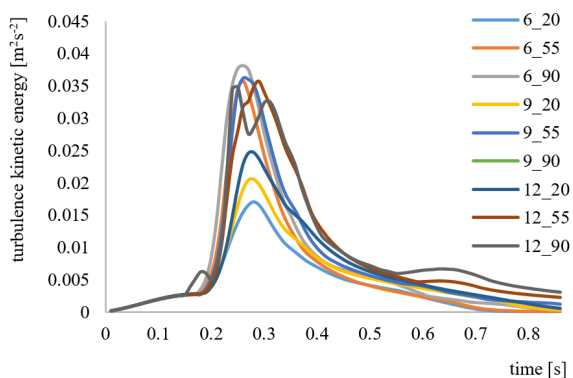


Figure 4. Specific turbulent kinetic energy function

Figures 5, 6 and 7 show the velocity distribution and velocity vectors on the axial cross-section area of the arteries models. Exactly with the predictions, the vortices occurring can be observed, especially for wider patches. They form initially in the divergent part of the artery, in the systolic phase. Due to the nature of flow, the pulse wave causes a local increase in flow resistance. The vortex generated at the beginning of the systolic phase moves along the artery, simultaneously increasing its volume. It achieves maximum energy in the transition time and they occur in the location of the convergent part of the geometry. As demonstrated: the region where the vortices arise is also places of local stress increase.

The research aimed to determine how much the impact on blood flow has the width of the arterial patch: hence very extreme, selected values. Studies have shown that, according to surgeons' presumptions, restenosis is the result of poor selection of patch width: that is why it is important to set width limits.

The result of conducted studies will be the starting point to creation of a standardized patch database, based

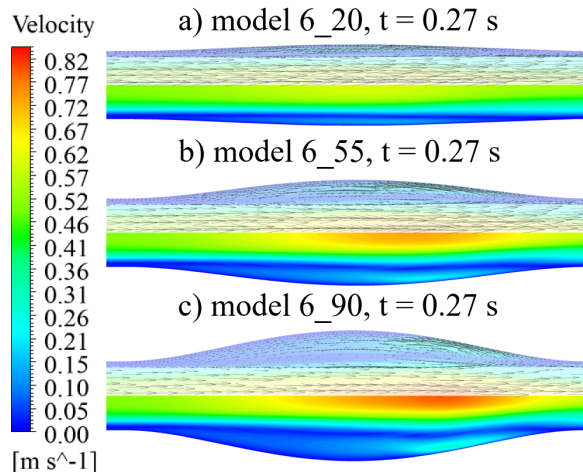


Figure 5. Velocity distribution in the artery with $r_{art} = 6$ mm

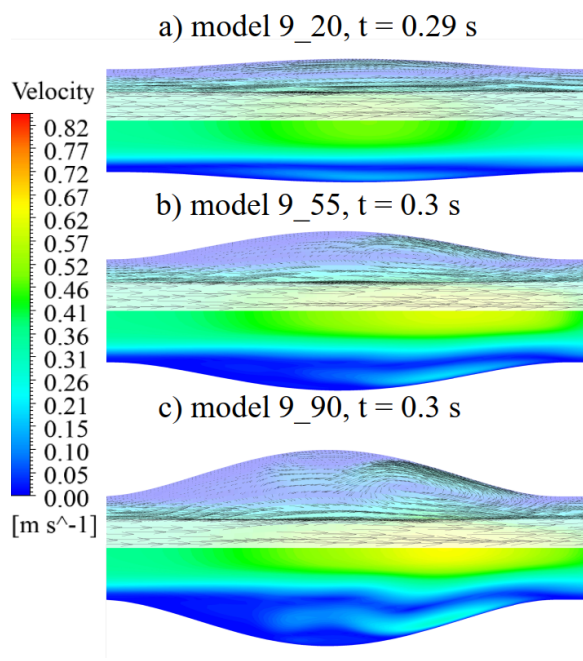


Figure 6. Velocity distribution in the artery with $r_{art} = 9$ mm

on which surgeons will choose a patch from a ready catalog of shapes. This will reduce the probability of restenosis, shortens the time of surgery because the surgeon will not have to cut the shape of a square piece of material on its own and will allow normalization of this practice because the outline of the patch will be independent of the surgeon's manual skills.

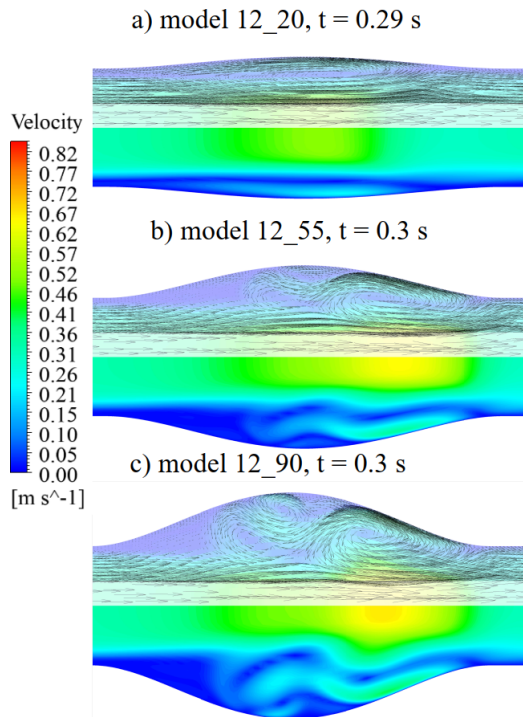


Figure 7. Velocity distribution in the artery with $r_{art} = 12$ mm

5 Conclusions

The results of the presented research allowed to formulate three crucial observations:

- The width of the patch doesn't affect significantly the mean value of WSS, but causes very rapid, local stress increase: the width of the patch should not exceed 20% of the artery radius, since already causes 2-3 times the increase in stresses. At larger widths, this increase can be up to six times.
- The larger the diameter of the artery, the smaller the patch must be: larger arteries are more susceptible to changing geometry in the context of flow disturbances. For smaller arteries, wider patches are allowed. For diameters larger than 9 mm, the width of the arterial patch used should not exceed 20% of the artery radius, whereas for smaller diameters this value should not exceed 55% of the radius of the artery.
- In the divergent part, vortices form as a result of the separation of the boundary layer. During the time, they move along the artery and reach the largest size and velocity in the convergent part, during the transition between the systolic and diastolic phase. Very large vortices occur in an artery with a diameter of 12 mm, even with a minimum widening of the flow section, a clear reverse flow can be observed. With $d_{art} = 9$ mm, the use of patches wider than 10 mm also results in strong turbulence. The smallest impact of the patch width can be observed at the smallest artery: here the vortex was

formed only when the radius of the artery was almost doubled.

The analysis of simulation data revealed that for arteries with a diameter larger than 12 mm, the application of the arterial patch is not recommended. This is because even the smallest change in the flow cross-section area is very crucial for occurring flow disturbances. The smaller the patient's diameter, the wider the patch width is acceptable. The results and the estimated limit values coincide with the practices used by surgeons. It is usually recommended to sew patches for arteries with smaller diameters because the narrowing of the artery can have dangerous effects.

6 Acknowledgements

This research was supported in part by PLGrid Infrastructure.

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