Numerical simulation of the spatio-temporal evolution of the flow in the model of abdominal aorta bifurcation with stenosis in the one of the common iliac arteries

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Abstract. The structure of the pulsating flow in the model of the average configuration, including the bifurcation of the abdominal aorta and subsequent bifurcation of the iliac arteries with axisymmetric hemodynamically significant stenosis in the right common iliac artery, is researched by numerical method. It has been shown that the presence of stenosis in this artery affects the flow structure both downstream and upstream: reverse-flow zones are formed and transverse flow evolution differs significantly from the structure of the flow in a healthy branch. The stenosis with the spatial curves of the model leads to the formation of a stable single-vortex flow in the external iliac artery most of the cardiac cycle. In the mentioned artery of the healthy branch various unstable patterns of two-vortex structure form during the cycle. In both internal iliac arteries, there is a transitional flow, from a two-vortex to a single-vortex motion, forms during the cycle. The influence of the presence of stenosis on the structure of the transverse flow in the internal iliac artery is insignificant. The most likely regions for atherosclerotic lesions of the vascular wall, characterized by the minimum values of time-averaged wall shear stresses and the maximum values of oscillatory shear index, are the stenosis region and the external wall of the common iliac artery.

1. Introduction
Like other arterial system diseases, abdominal aortic bifurcation pathologies require accurate diagnosis and tactics to improve treatment outcomes. Numerical studies of blood flow in vascular models provide information on the flow structure, thus complementing the clinical diagnosis. Besides, flow simulation in models based on averaged geometric and hydrodynamic parameters, incorporating the spatial tortuosity and curvature of vessels and the modes of heart, forms knowledge about the general patterns of flow in a selected section of the vascular bed. Understanding the characteristic structure of blood flow in a healthy vessel and one with pathologies helps to determinate the causes of pathological lesions of vessels, as well as the predominant localization of these lesions, which allows improving clinical diagnostic tactics. Also, the results of spatial blood flow studies in the abdominal aortic bifurcation and subsequent bifurcations of iliac arteries refine the hydrodynamic input conditions for numerical and physical simulation in downstream vessels (femoral arteries).

This study presents results of a numerical simulation of the flow in a spatial average configuration, including the region of abdominal aortic bifurcation and subsequent iliac bifurcation with axisymmetric stenosis in the right common iliac artery. The first studies of the blood flow structure in
this vascular bed section were carried out in the 1980s [1], computational and experimental studies in simplified models, which do not consider spatial curvature, were often discussed in literature [2,3], and also these studies are limited to the abdominal aortic bifurcation, without considering the flow in subsequent iliac arteries. This article is a continuation of the study [4] in which experimental research of the blood flow structure was conducted using ultrasonic Doppler method. Numerical simulation in this study is refining research that allows deciphering complex ultrasonic images of vortex structure. The study focuses mainly on comparative analysis of flow structure in healthy and pathologically modified branches, in particular, the effect of hemodynamically significant stenosis on the flow structure and the distribution of shear stress in subsequent iliac bifurcations.

2. Research objectives and computational aspects

The curved model of the statistically average configuration of abdominal aorta and iliac arteries was based on averaged clinical data from about 800 patients [5-11]. The model includes a section of the abdominal aorta (AA) with inlet diameter D=18 mm, which divides into the right and left common iliac arteries (CIA) with the dimmer D=10.8 mm (figure 1, a). And then the common iliac arteries are divided into external (EIA, D=9.0 mm) and internal (IIA, D=5.5 mm) iliac arteries. The total length of the model is 215 mm. Differences from the axis of the outlet section of the abdominal aorta are 20° for the left CIA and 25° for the right one. The angle between the IIA and the EIA is 30º (side view) and 40° (front view). The angle between the axis of AA and the plane of the CIA is 160°. Hemodynamically significant axisymmetric stenosis is located in the right CIA with length Ls = 22 mm and drift diameter Ds = 5.9 mm. The stenosis index (by area) STI = (1 – Ds²/D²) 100 % = 70 %. The transformation of the radius R in the stenosed region along the vessel axis is described by the formula:

\[ R = 0.5Ds + 0.5(D - Ds)\cos(\pi y/Ls), \quad -Ls/2 \leq y \leq Ls/2. \]

The geometry of the model was designed in the SolidWork 2016 software package. The ICEM CFX 2016 software package was used to generate an unstructured computational grid, consisting of 3 million hexahedral cells.

![Figure 1](image_url)

**Figure 1.** (a) - Model of abdominal aortic bifurcation and iliac arteries [5-11] and (b) - average statistical flow rate curves for healthy arteries in abdominal aortic bifurcation [12-14]. AA - abdominal aorta, CIA - common iliac arteries, EIA - external iliac arteries, IIA - internal iliac arteries.

The numerical simulation of the flow in the presented model was conducted assuming laminar nature of the blood flow. The three-dimensional unsteady Navier-Stokes equations for incompressible Newtonian fluid with constant viscosity were solved numerically using the ANSYS CFX 16.2 software package. There are the following fluid parameters: dynamic viscosity coefficient \( \mu = 0.004 \text{ Pa c} \); density \( \rho = 1050 \text{ kg/m}^3 \). The time dependences of the flow rates were used to set the
inlet boundary condition for AA, the outlet boundary condition for the right, left EIA and left IIA (according to Table 1). And zero reduced-pressure condition is set for right IIA. The values and the ratios of the flow rates in iliac arteries were selected for the healthy branch based on clinical data obtained from the examination of 15 patients (figure 1, b) [12-15]. The distinctive feature of the pulsating mode in the selected segment of the vascular bed is a return flow in the phase of the diastole. The characteristic mean flow velocity at the maximum flow rate, arteries diameters and the corresponding values of the Reynolds number in the model branches are presented in table 1.

| Vessel      | D, mm | Vb, cm/s | Re  |
|-------------|-------|----------|-----|
| AA          | 18    | 30       | 1418|
| REIA with stenosis | 9     | 30       | 709 |
| RIIA        | 5.5   | 65       | 938 |
| LEIA        | 9     | 40       | 945 |
| LIIA        | 5.5   | 80       | 1155|

3. Results
The numerical simulation has confirmed that a complex vortex flow structure in the abdominal aortic bifurcation is influenced by the geometry, the stenosis, and the pulsating mode. The almost total symmetry of the abdominal aortic bifurcation allows conducting a comparative study of the flow structure in healthy and stenosed branches. The characteristic moments of the cardiac cycle are presented in the phases: of increasing flow rate (0.1T), maximum flow rate (0.17T), decreasing flow rate (0.3T) and maximum return flow rate (0.45T), where T is the pulsation cycle period, T = 1 s. A complex vortex structure, transforming along the selected segment of the vascular bed, is formed in the given model during the cycle (figure 2).

**Table 1.** Maximum mean flow velocity Vb and Reynolds number in the model branches.

**Figure 2.** Streamlines in the abdominal aortic bifurcation model at the characteristic moments in cardiac cycle.
A flat velocity profile is set and there is no transverse flow at the inlet of the abdominal aorta. During the whole cardiac cycle, reverse-flow zones do not form in AA; the maximum axial velocity is shifted to the back vessel wall due to the abdominal aorta bending. The bifurcation region is characterized by the presence of a reverse-flow zone at the outer wall of the branch with stenosis in the decreasing flow rate phase (0.3T). Any reverse-flow zones and transverse currents during the rest of the cardiac cycle are not observed.

The regular structure of the flow changes significantly behind the stenosis, which influences both downstream and upstream areas - the reverse-flow zones are formed, and the vortex structure of the transverse flow is different from the observed in a healthy branch. During the cardiac cycle, the reverse-flow zone is formed at the inlet of the stenosed CIA, the dimensions of which reach the maximum size (40% of the cross-section area) during the decreasing flow rate phase. An even larger reverse-flow zone is formed behind the stenosis, it occupies about 50% of the CIA in cross-section area during most of the cardiac cycle. At the same time, the influence of the stenosis on the formation of reverse-flow zones downstream (in the EIA and IIA) is almost non-existent, with the exception at the decreasing flow rate phase – reverse-flow zone is recorded in the EIA at the outer wall, occupying 20% in the cross-section area (figure 3).

The analysis of the structure of the transverse flow in the CIA leads to the conclusion that a stable two-vortex flow behind the stenosis in the increasing and maximum flow rate phases is transformed into a single-vortex flow in the decreasing and return flow rate phases. The flow evolution is significantly different in the CIA for a healthy branch. A wide variety of irregular vortex structures are predicted during the cycle: till the return flow phase, a four-vortex flow is generated and then transformed into a single-vortex flow from the moment of maximum return flow (figure 3).
The transverse flow along the entire length of right EIA, in a pathologically modified branch, is characterized by the formation of a stable single-vortex flow of almost entire cardiac cycle. There is no swirling flow in a healthy branch along the entire length of EIA and only a stable two-vortex flow is formed closer to the outlet of the vessel from the moment of maximum flow rate (figure 4).

There is a transitional flow from two-vortex to single-vortex in both IIA during the cycle. The presence of stenosis affects only the vortex structure in the return flow phase: a single-vortex flow is formed in a healthy branch, and there are not clearly expressed vortex structures in the stenosed branch (figure 4).

Figures 6 present the distribution of parameters characterizing the effect of the flow on vessel walls – the time-averaged wall shear stresses - TAWSS (1) and the oscillatory shear index - OSI (2).

$$\text{TAWSS} = \frac{1}{T} \int [f_w] dt$$

$$\text{OSI} = 0.5 \left( 1 - \frac{\int f_w \, dt}{\int |f_w| \, dt} \right)$$

It can be seen that the maximum values of TAWSS are observed at the bifurcations regions, at the stenosis and at the internal iliac arteries, the minimum - in the abdominal aorta and the external iliac arteries. The highest values of OSI for unsteady blood flow are observed on the outer walls of the CIA, on the inner wall of the right CIA, before and behind the stenosis and in the right IIA with a value of 0.35-0.5. It is known that areas with low cycle-averaged wall shear stresses and with high wall-shear stress index values are most likely to be affected by the vascular atherosclerotic lesions. Thus, it can be concluded, that the stenosis area and the external wall of a healthy CIA might be affected by this pathological modification. The presence of hemodynamically significant stenosis in CIA may most likely lead to further growth of atherosclerotic plaques in these regions and disturbance of the vessel’s passability.

![Figure 5](image)

**Figure 5.** Distribution of (a) - time-averaged wall shear stresses, (b) - oscillatory shear index.

### 4. Conclusion

A complex vortex flow structure is formed during the cardiac cycle in the spatial model, including average bifurcation of the abdominal aorta and the subsequent bifurcation of the iliac arteries with axisymmetric stenosis in the right common iliac artery. The presence of hemodynamically significant stenosis in the CIA combined with the spatial curves of the model leads to the formation of reverse – flow zones before and behind the stenosis. The structure of the transverse flow is characterized by a
clearly expressed single-vortex flow at the end of the cardiac cycle in the EIA along the entire length of the vessel in the stenosed branch, in contrast to a healthy branch, in which the unstable two-vortex flow develops. The presence of the stenosis upstream affects only the flow structure in the return flow phase: a single-vortex flow is formed without the stenosis and with the stenosis – the vortex structure is absent. The regions most exposed to atherosclerotic lesions of the vascular wall, characterized by the minimum TAWSS values and the maximum OSI values, are the stenosis region and the outer wall of the CIA.

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