Numerical study of blood flow in the spatial model of the abdominal aorta bifurcation: effect of an inlet conditions

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Abstract. The structure of the flow in a model configuration including a healthy bifurcation of the abdominal aorta, common, external and internal iliac arteries is investigated by a numerical method. It has established that the structure of the flow in the common, external and internal iliac arteries is characterized by a two-vortex secondary flow structure, and only in the phase of return flow, a single-vortex secondary flow develops at the exit of the internal iliac arteries. The influence of the inlet velocity profile skewness is significant only in the region upstream of the actual abdominal aorta bifurcation. In the iliac arteries, the influence of the inlet velocity profile shape is felt only through relatively weak changes in the cross-flow velocity field. Introducing a significant non-uniformity in the inlet velocity distribution does not change significantly general estimates of the minimum values of the cycle-averaged wall shear stress, TAWSS, and maximum values of the oscillation wall-shear index, OSI. This information is important for identification of the places mostly exposed to atherosclerotic vascular lesions for atherosclerotic lesions.

1. Introduction
At present, circulatory system diseases are the main cause of disability and mortality in the world. In most cases, cardiovascular diseases are associated with atherosclerosis [1]. The vascular system has vessels with irregular geometry, such as bifurcations and bends, which contributes to the emergence of secondary flows and transverse circulation of blood.

Investigations of blood flow in the region of the abdominal aorta bifurcation, presented in the literature, are mainly aimed at studying the effects of aneurysm formation and improving the methods of its treatment (see, for example, [2,3] and references there). The structure of unsteady three-dimensional flow in bifurcation and the nature of arising secondary flows are not well understood. Only a small number of works are devoted to studying blood flow in the branches of the abdominal aorta bifurcation known as iliac arteries, normal or pathological [4-6]. However, the knowledge of the blood flow specific features in the bifurcation helps to understand the causes of vessel lesions and its principal localization in certain areas of the vascular bed. This knowledge also contributes to development of general recommendations for vessels diagnostics. In addition, studies of spatially complicated blood flow in the bifurcation of the abdominal aorta and subsequent iliac artery bifurcations provide information on the inlet hydrodynamic conditions required for experimental and / or numerical modeling of blood flow in the downstream vessels (femoral arteries).
This paper presents results of numerical simulation of the flow in a model of a vascular bed section that includes the region of the abdominal aorta bifurcation and the subsequent iliac artery bifurcations. It is obvious that in case of setting any study of blood flow in a limited-in-length vascular bed section, there is always a question of inlet condition definition and evaluation of sensitivity of the studied flow to inlet condition uncertainties. Most often, researchers accept the condition of uniformity of the inlet velocity distribution. At the same time, some reports [1,7] indicate that in the lower part of the abdominal aorta a skewed velocity profile arises due to hydrodynamic processes upstream. It gives a motivation for performing a comparative numerical analysis of blood flow when specifying either uniform or skewed velocity distributions at the inlet to the considered section of the vascular bed.

2. Research objective and computational tools
The model configuration for the present blood flow study was based on the averaged geometrical characteristics of the vascular bed, which were taken from MRI studies of 12 healthy patients [8]. Patients with “non-typical” vascular curvature, occlusions, aneurysms of abdominal aorta and common iliac arteries were excluded from the mentioned study [8].

The model considered, illustrated in figure 1 (dimensions are given in millimeters), is a smoothly interconnected set of conical and cylindrical elements. The bifurcation of the abdominal aorta (AA) is close to a symmetrical configuration, all the branches of which lie in the common plane. Subsequent bifurcations (common iliac arteries, CIA) have a more complex spatial geometry: each of them is asymmetrical, and the plane of the branching vessels forms 30º angle with the axis of the common iliac arteries. The geometry of the model was built in the SolidWork 2016 software package. The ICEM CFX 2016 software package was used to generate an unstructured computational grid, consisting of 2 million hexahedral cells.

The three-dimensional unsteady Navier-Stokes equations were solved numerically using the ANSYS CFX 16.2 software package. The no-slip condition was set on the walls. The time dependences of the flow rates given in [9], illustrated in figure 2, were used to set inflow/outflow boundary conditions. At the “direct” flow phase, a velocity distribution, uniform or skewed to the front side, is prescribed at the computational domain inlet (a cross section of the abdominal aorta). Velocity distributions at the end cross section of each iliac arteries are assumed uniform when these sections play the role of an inlet (in the “reverse” flow phase). The only exception is the end cross section of the left internal iliac artery (IIA), where zero reduced-pressure condition is set.

Generally, the boundary conditions imposed correspond to the heart performance at rest with a heart rate of 70 bpm. The maximum Reynolds number, evaluated with the inlet average flow rate and the local hydraulic diameter, is of about 2000, the Womersley number is about 11.

The degree of skewness of the inlet linear velocity profile is determined by the ratio, s, of velocities near the front wall and back wall of the abdominal aorta. In the calculations presented, this parameter was ranged from 1.0 (uniform velocity distribution) to 1.5; the largest of the values examined exceeds a skewness estimate that follows from our analysis of literature data [1,7]. The results presented below have been obtained with s = 1.0 and 1.5.

3. Results
The structure of the predicted flow in the considered model configuration, similar for all values of the skewness parameter s, is characterized by the following peculiarities. There are stagnant or even reverse-flow zones (near the outer walls) in the bifurcation of the abdominal aorta, and a pair of Dean-type vortices in each of the branching common iliac arteries (figures 3, 4). In the branches of the common iliac arteries bifurcations, stagnant zones are observed at the inner wall of the external iliac artery and at the outer wall of the internal iliac artery. In the CIA, the maximum axial velocity is located at the inner wall of the vessel. In the EIA, a region of maximum velocities turns over the vessel axis when the section analyzed is shifted downstream. Remarkably that two longitudinal, approximately symmetrical vortices are observed in all the iliac arteries. A single-vortex flow occurs only in the vicinity of the IIA exit during the reverse flow phase.
Data given in figures 3, 4 allows one to conclude that in case of non-uniform inlet conditions the skewness of the longitudinal velocity distribution is maintained throughout the cycle up to the point of the abdominal aorta bifurcation. It is also noticeable that the inlet non-uniformity has some influence on the cross-flow velocity field in this part of the model. In both the iliac arteries, the influence of the inlet distribution shape is felt only through relatively weak changes in the cross-flow pattern. The flow in the external and internal iliac arteries is practically insensitive to the prescribed non-uniformity of inlet velocity.

Figure 5 shows the calculated distributions of the cycle-averaged wall shear stress, $TAWSS = \frac{1}{T} \int |\tau_w| dt$. It can be seen that the maximum shear stresses are observed in the bifurcation sites and in the internal iliac arteries, and minimum values are placed in the external iliac arteries. The latter is especially pronounced in phases of decreasing flow rate and reverse flow.

In case of the uniform inlet velocity distribution, the TAWSS values averaged over the surface of an individual vessel are as follows: 0.8 Pa and 0.6 Pa for the abdominal aorta and the external iliac arteries, respectively, 1.2 Pa for the common iliac arteries, and up to 8 Pa for the internal iliac arteries. The skewness of the inlet velocity distribution has a moderate effect on the TAWSS surface distribution. In the case presented, $s = 1.5$, the maximum difference with the uniform inlet velocity case is observed, as expected, on the front wall near the computational domain inlet (about 25%). For the common and external iliac arteries, the difference is 2-3%, and for the internal iliac arteries is less than 1%.

Figure 6 illustrates the distribution of the wall-shear stress index $OSI = 0.5\left(1 - \frac{\int |\tau_w| dt}{\int |\tau_w| dt}\right)$. The highest values of this characteristic of unsteady blood flow are observed on the outer walls of the abdominal aorta bifurcation and in the external iliac arteries, amounting to about 0.35. In the vicinity of the bifurcations, it is significantly smaller, and can be estimated as 0.1-0.15. Imposing the skewness of the inlet velocity distribution does not alter these estimates significantly.
Figure 3. Longitudinal velocity distributions at several sections of the flow pass in case of (a) uniform and (b) skewed inlet velocity distribution, instance of maximum flow rate.

Figure 4. Streamlines and cross-flow velocity distributions at several sections of the flow pass in case of (a) uniform and (b) skewed inlet velocity distribution, instance of maximum flow rate.

Figure 5. (a) Cycle-averaged wall shear stress pattern in case of uniform inlet flow and (b) difference with case of skewed inlet velocity distribution (look from front side).

Figure 6. (a) Oscillation wall-shear index distribution in case of uniform inlet flow (look from front side) and (b) difference with case of skewed inlet velocity distribution (look from back side).
4. Conclusions
For the considered model of the vascular bed section that includes the abdominal aorta bifurcation and two subsequent bifurcations, the structure of the flow predicted is characterized by presence of a clearly pronounced two-vortex secondary flow in the common and external iliac arteries.

The influence of the inlet velocity profile skewness is significant only in the region before the actual abdominal aorta bifurcation. In the iliac arteries, the influence of the inlet velocity profile shape is felt only through relatively weak changes in the cross-flow pattern. The flow in the external and internal iliac arteries is practically insensitive to the imposed non-uniformity of the inlet velocity.

The predicted surface distributions of the cycle-averaged magnitude of the wall shear stress, TAWSS, and the oscillation wall-shear index, OSI, are significantly different for the vessels included in the considered model configuration, both in qualitative and quantitative terms. Introducing a significant non-uniformity in the inlet velocity distribution does not lead to principal changes in the estimates of the minimum TAWSS values and maximum OSI values, which are important for identification of the places mostly exposed to atherosclerotic lesions.

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