Computer Simulation of Flow through the True and False Lumen of Aortic Dissection

Saveljić, Igor; Velicki, Lazar; and Filipović, Nenad

Abstract: ***Aorta is the largest human blood vessel. This part of the body is continuously exposed to high blood pressure and shear forces. Aortic dissection is a very serious pathological condition where blood intrudes into the layers of the arterial walls, creating an additional channel (false lumen). Hemodynamic properties of blood flow through the newly created false lumen, and its dominance over the true lumen, have a significant impact on patient's life. For this reason, FEM analysis was performed for a typical aortic dissection in order to study the relationship of these lumens. Pressure, shear stress and velocity were analyzed along the dissected aorta geometry.***

Index Terms: ***Aortic dissection, Finite element method, False lumen*, *Shear stress***

1. *Introduction*

THE modern style of life, irregular diet, alcohol consumption, stress, and decreased physical activity are some of the reasons for the occurrence of hypertension, the most important risk factor for cardiovascular disease [1]. Hypertension is an acute or chronic disease of high blood pressure. There are often no recognizable symptoms, and due to that fact, it is referred to as "the silent killer". In most patients, arterial hypertension occurs without any symptoms. In order to prevent the occurrence of aneurysms and dissections, it is necessary to detect and treat it on time.

The aortic dissection is probably the most common catastrophe of the aorta that begins with a small crack in the intimal layer causing the creation of a new false lumen. The mortality rate increases by 1% with every hour of the occurrence of dissection and, in the first few days, almost 98% of patients die. In addition to hypertension [2], the development and progression of aortic dissection is associated with several major risk factors such as genetic factors [3], gender and age.

The development of computer technology contributes to the growing number of different real problem solved by mathematical modeling. Finite element method, used in this paper, has been, for many years, the dominant numerical method for solving fields of physical quantities. In our study, this method was used to determine pressure, shear stress, and velocity of dissected aorta geometry. The basic hypotheses in this study were based on the analysis of the current state of scientific fields of this scientific research:

- From the standpoint of fluid mechanics, the cardiovascular system is regarded as a system in which flow takes place with the dominance of viscose or inertial forces.
- Inertial forces are more dominant in relation to the viscosity of blood flow in aorta.
- Reynolds numbers at maximum systole goes up to Re = 4000.
- Calculation of shear stress on the wall is performed by the velocity of friction.

2. *Literature Review*

Simulations of the dynamic behavior of the fluid-blood interaction in the aorta with and without dissection, and then simulations of the flow and pressure in the obstructed branches of the aorta in the aortic arch, are of great importance in medicine. Simulations of this type can be very helpful because doctors can gain insight into further development of the disease.

Numerical methods and finite element method are used to analyze blood flow and other hemodynamic variables of the aorta and its branches. There are numerous studies that have studied changes in the healthy aorta [4], [5], the dissected aorta [6], [7], and in the aortic aneurysm [8], [9], [10] in this manner.

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Studies [11], [12] assume that the flow in the aorta is laminar, since aorta is a large blood vessel where the average flow is small, so the Reynolds number has a relatively small value [13], [14]. Concerning the characteristics of blood, most numerical studies assumed that the blood is Newtonian [15], [16], and because of this they ignored the effect of particles in large arteries. A significant number of numerical simulations is used to predict the progression of aortic dissection [17], [18], thrombus formation [19], different treatment strategy, including fenestration and stent grafts [20], [6]. Great attention is paid to the entry tears, location, size and influence on further propagation of the false lumen [21], [22]. Studies have also shown that the form of the gap may have an impact on the way of propagation of the false lumen. [13], [20].

3. *Material and Methods*

The model of dissected aorta geometry was imaged with CT (128-slice Philips scanner), in slices with 0.5 mm of thickness. The CT scans were read into Mimics v10 visualization software, where the images were segmented by thresholding to obtain 3D model (Figure 1).

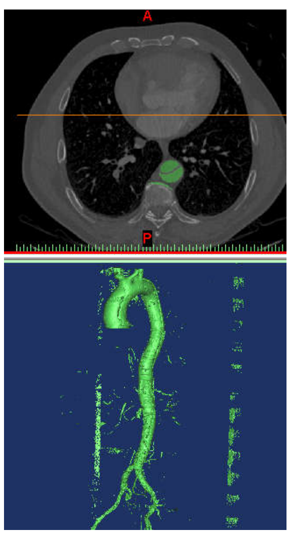


Figure 1. The process of segmentation and visualization of 3D model

After that, the geometry was converted into stereo lithography file, using Mimics and its STL+ module. The next step was the elimination of noise and sharp triangles in the model with computer manipulation using Geomagic software. Then, FEMAP was used for creation of 3D mesh. Tetrahedral elements were used as the final element. PAKF software [23] was used for numerical solution of fluid flow problems.

The Navier-Stokes equations describe the motion of viscous fluid substances. They are mathematical description of all fluid motions. The flow was assumed to be laminar, Newtonian, and incompressible. The continuity and Navier–Stokes equations are as follows:

$$\nabla \cdot \mathrm{u} = 0 \qquad (1)$$

$$-\mu\nabla^2 u + \rho(u \cdot \nabla)u + \nabla p = 0 \qquad (2)$$

where u is blood velocity, ρ density, p pressure and μ is dynamic viscosity of blood. Blood flow is simulated for average blood properties: ρ=1050 kg/m^3 and dynamic viscosity μ=0.0035 Pas. A parabolic velocity profile was assigned at the inlet of the ascending aorta. The mean value of the inlet velocity was derived from experimental measurements [24]. Physiological velocity waveform is shown in Figure 2, where velocity in a systolic peak is 1.06 m/s.

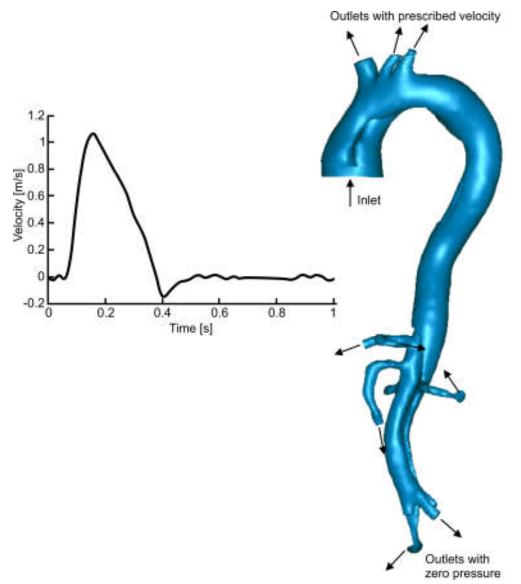


Figure 2. Boundary settings of the model

In the human aortic system, approximately 5% of the flow volume is diverted to each of the three aortic arch branches [25]. Based on the cross-section of the branches, the following peak velocities have been calculated for these three branches: 0.32 m/s through the brachiocephalic artery of the false lumen, 1.65 m/s through the left common carotid artery of the false lumen, 0.52 m/s through the left subclavian artery of the true lumen, and 0.16 m/s through the left subclavian artery of the false lumen. Zero-pressure boundary conditions were assigned at all other outlets of the model.

In this paper geometry was used from a patient aged 65, smoker, who was diagnosed with hypotension (low blood pressure), and acute aortic dissection (De Bakey type I). The size of the entry tear was 14.02 cm^2 at a distance of 71 mm from the top of the aortic arch. The volume of the true lumen was 192.24 cm^3, while the volume of the false lumen was 132.65 cm^3. There was no return entry. Figure 3 shows the anatomy of the aorta and the individual segments, in which cross-sections the analysis of the aortic dissection is performed.

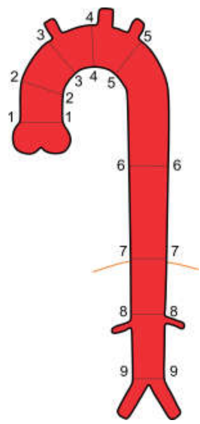


Figure 3. Anatomy of the aorta and the observed cross-sections

Before the numerical analysis, the ratios of the true and false lumen were determined, and are displayed in Table 1.

	Cross-sectional area [cm^2]			Cross-sectional area [%]	
Seg.	Total area	True lumen	False lumen	True lumen	False lumen
1	19.05	19.05	0.00	100.00	0.00
2	13.19	3.25	9.94	24.64	75.36
3	9.74	4.50	5.24	46.23	53.77
4	6.23	3.82	2.41	61.37	38.63
5	5.38	2.91	2.47	54.11	45.89
6	6.08	2.88	3.20	47.40	52.60
7	5.44	2.48	2.95	45.69	54.31
8	2.71	1.45	1.26	53.52	46.48
9	2.79	1.64	1.15	58.75	41.25

4. *RESULTS*

Numerical analysis of the behavior of the blood vessel during one cardiac cycle was conducted using PAKF Solver. The results of the pressure, shear stress, and velocity are shown in Figure 4.

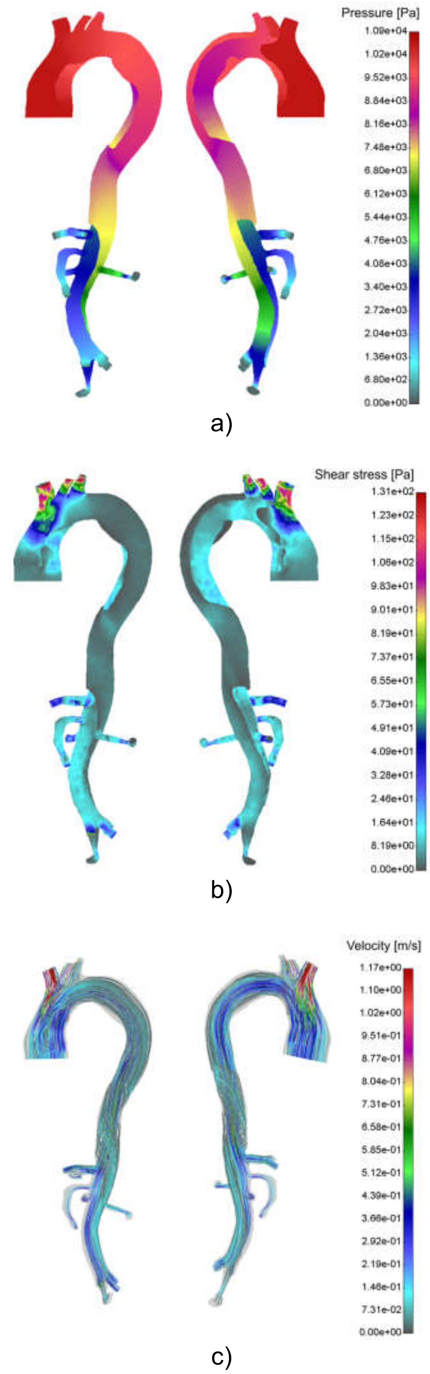
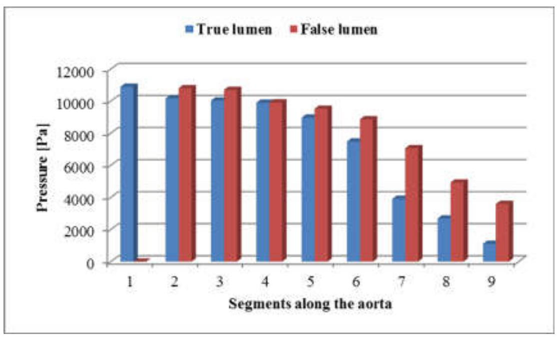


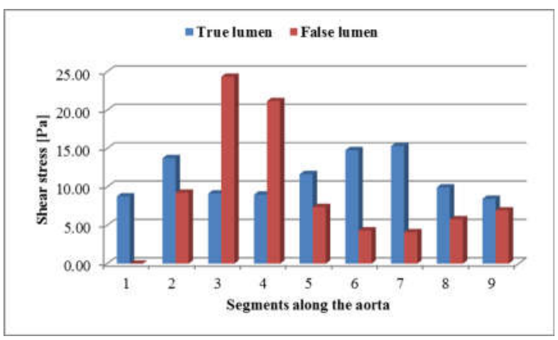
Figure 4. Results of the numerical analysis of the dissected aorta model. (a) pressure, (b) shear stress, (c) velocity streamlines

Figure 4 show that the false lumen dominates the true lumen. The false lumen has greater value of pressure along the aorta. The shear stress in the zone of the ascending aorta of the false lumen reaches a value of 9.73 Pa. The largest recorded value of the shear stress observed in the branches of the aortic arch reaches 31 Pa. Brachiocephalic trunk (flow rate 12.14 cm^3/s, or 16.82 % of the total flow rate), the left common carotid (flow rate 7.41 cm^3/s, 8.82 % of the total flow rate) and the part of the left subclavian artery (flow rate 5.61 cm^3/s, 6.69 %) belong to the flow of the false lumen, taking 44.11 % of the flow. The second part of the flow through the subclavian artery goes through the true lumen and has flow of 4.01 cm^3/s (4.76 %). Celiac tree with a flow of 9.79 cm^3/s (11.66 %), and upper mesenteric artery (with flow of 5.27 cm^3/s, 6.28 %) belong to the true lumen. Right renal artery is also supplied from the true lumen flow of 6.29 cm^3/s (7.49 %). Left renal artery belongs to the false lumen and a flow rate of 7.88 cm^3/s (9.39 %) is recorded through this branch. Iliac branches belong to the true lumen (flow through the right branch is 4.03 cm^3/s, 4.81 %, and through the left 3.34 cm^3/s, 3.99 %).

The diagram in Figure 5 shows the ratio of the true and false lumen on the basis of the analysis results.



a)



b)

Figure 5. Diagram of the relationship between the true and false lumen. (a) pressure and (b) shear stress

In the area of the aortic root, at the beginning and in the middle, where the measurements are taken, the shear stress of the false lumen has two times greater value compared to the true lumen, where a high velocity fluid flow is evident.

5. Conclusion

Cardiovascular diseases are the leading cause of death in all developed countries. Our country is in the group of countries with a high risk of dying from these diseases. Aortic dissection is one of the most serious diseases that start splitting intimal layer of the aortic wall. The aim of this simulation was to numerically determine the relationship between the true and false lumen of acute aortic dissection. It is very important to predict the behavior of the false lumen and its propagation in the further course of the development of the disease. Further research will be in the direction of determining the destiny of the false lumen after the surgery, as well as determining the Von misses stress on the wall of the aorta and prediction of potential sites for aorta rupture.

Acknowledgment

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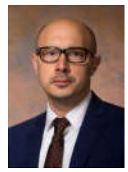

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