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NUMERICAL SIMULATION OF FLOW IN A PATIENT WITH ASCENDING AORTIC ANEURYSM

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Abstract. *The aneurysm occurs when there is an over-normal dilation of the artery diameter. Aneurysm of the ascending aorta is usually asymptomatic, therefore, it is frequently identified accidentally during imaging exams of a patient with other clinical indications. The causes of this type of aneurysm are not known precisely. To help understand the phenomena, the present study analyzes the flow inside an aorta of a patient with aneurysm of the ascending aorta. The patient under study has undergone two computerized angiotomography exams in different years, and during this time span, a significant growth of the aneurysm dilatation was not observed. A 3D model was generated from computed tomography angiography and image segmentation of the aorta. The flow was obtained with a commercial software ANSYS Fluent v17.0. The turbulence flow was modeled with the two-equation* κ - ω *turbulence model. The flow distribution inside the aorta is investigated. The identification of particularities of the flow related to ascending aortic aneurysms might help future patients in their medical treatments.*

Keywords: *aneurysm, CFD, turbulence, hemodynamic*

1. INTRODUCTION

Aneurysm is an irreversible dilation that exceeds the normal diameter of the artery, it occurs when transverse diameter of artery exceeds one and a half times the normal diameter for the age and weight of patient.

Aorta is the largest artery in the circulatory system. It can be divided in five parts, the first one, focus of the present work is known as ascending aorta. It begins at the root of the aorta (which communicates with the left ventricle of the heart) and continues to the height of the sternal angle, where the aortic arch begins.

Aneurysm of the ascending aorta is usually asymptomatic, and its assessment occurs accidentally during imaging exams of patients with other clinical indications (Dudzinski and Isselbacher, 2015). Its evolution occurs in a silent way, however, its complications, like rupture and dissection of the aorta, are catastrophic events (Elefteriades, *et al*., 2015).

Cecchi et al. (2010) conducted a study to associate shear stress on the wall of blood vessels and damage to the patient. It was demonstrated how the change in the shear stress can cause the occurrence of aortic aneurysm, leading to the growth or rupture of the aorta.

Malvindi et al. (2016) performed a computational analysis of fluid flow in an ascending aortic aneurysm before dissection related to a unicuspid aortic valve. The study found an increase in the pressure of the posterior wall of the ascending aorta and this was related with complications in the disease.

Azevedo et al (2017) and Celis et al (2017) investigated the effect of the inlet valve jet angle in the flow distribution inside an ascending aorta. It was shown, that small angles changes can significantly alter the region of high pressure and wall shear rate.

The main objective of this research is to analyze, using Computational Fluid Dynamics (CFD), the flow field inside an ascending aorta of a patient in the presence of an aneurysm. The patient has undergone two angiotomography examinations in two different years, and it was observed that during this time span, the aneurism did not grow. We aim to identify flow characteristics that can induce the growth of aortic aneurysm, obtaining useful information that can help to prevent the aneurysm's growth for future patients or help in their medical treatment.

Geraldo (2017) performed a CFD study a preliminary study of the flow inside an aortic geometry. He verified that an aortic geometry's slight modification is not enough to force aneurysm dilatation, although it may modify velocity and pressure along blood flow, due to maintenance of pressure and wall shear stress fields

2. METHODOLOGY

The computed tomography angiography (CTA) exams of a patient who did not present significant growth of the aneurysm dilatation in a time span of two years was selected for analysis. This research was approved by the ethics committee of the National Institute of Cardiology, INC/MS. From a series of CTA slices, the DICOM (Digital Imaging and Communication in Medicine) images were transferred to the software Mimics (Materialise, Belgium) and an image segmentation was performed with the software FIJI, generating a 3D model. Fig. 1a shows the patient's aorta in 2013 and Fig. 1b the aorta of the same patient in 2015. The enlarged aorta's diameter at its root is clear. It can also be seen, that its size remained approximately constant in the two years span among the exams, indicating that the aneurism did not grow.

To determine the flow field, a mesh was created with 400.000 nodes, which was selected after a grid test, where the difference of the pressure drop at the selected area (indicated in Fig. 2) was inferior to 0.3%, when the mesh size was doubled.

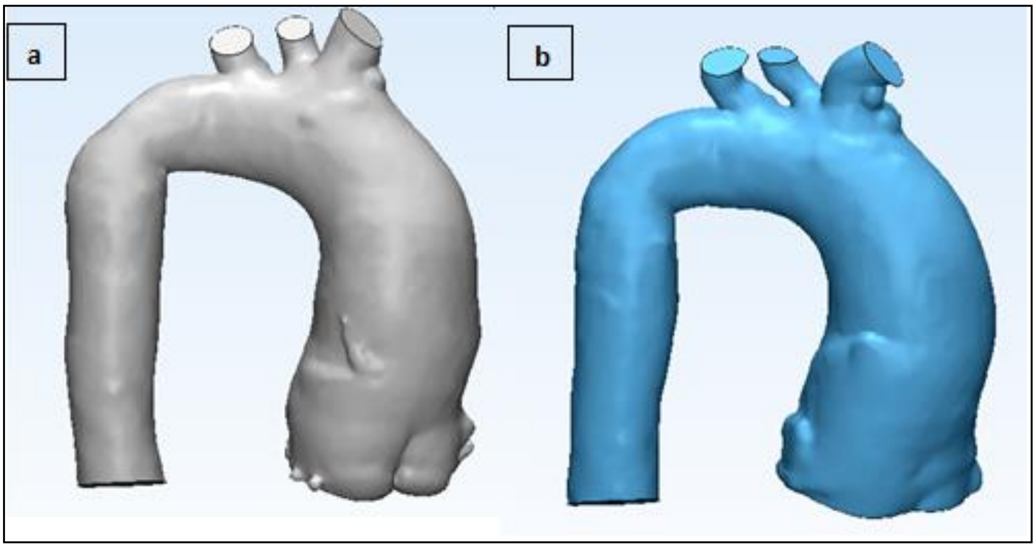


Figure 1. Segmentation of aorta in (a) 2013. (b) 2015.

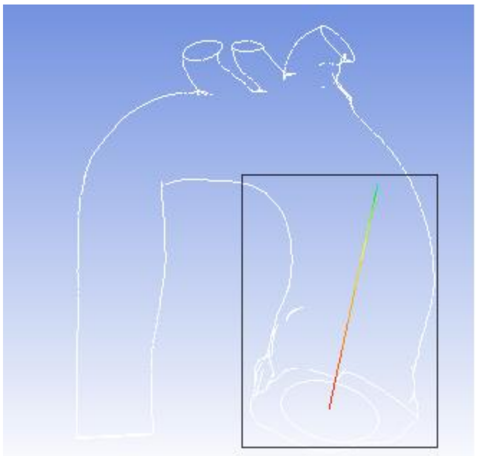


Figure 2. Selected area for the analysis

The focus of the present work is to determine the flow field in the ventricular systole. During this period, the aortic walls are distended, providing their maximum diameter, with small variation due the vascular complacency. Thus, the analysis is performed here considering the maximum flow rate, which is twenty-five liters per minute, assuming steady state, which is a more critical situation.

As a first simplification, the aorta´s surface was considered rigid, due to its small complacency. Another simplification was to neglect gravity effects, since the pressure variations are dominant over the force of gravity. According to Sun and Chaichana (2016), due to the large aorta diameter, the presence of the red blood cells can be neglected and the blood can be considered as a Newtonian fluid. In addition, under normal conditions, the blood can be considered as an incompressible fluid (Feijó, 2007; Feijoo and Zouain, 1988). The turbulence was modeled based on the Reynolds average approximation, with the two-equation κ−ω SST model (Menter, 1994). The turbulence model was selected by comparing the numerical predictions with experimental data obtained in a similar aorta (Azevedo *et al*, 2017; Celis *et al*, 2017).

To determine the flow field, the time average conservation of mass and momentum were solved:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_j u_i}{\partial x_j} = -\frac{\partial \hat{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{(\mu+\mu_t)\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right]\right\} \tag{2}$$

where x_i represents coordinates axes, u_i the time average component of the velocity vector, ρ the density, μ the molecular viscosity, μ_t the turbulent viscosity and $\hat{p}$ is the modified pressure, which includes the turbulent dynamic pressure, where κ is the turbulent kinetic energy

$$\hat{p} = p + \frac{2}{3}\rho\kappa \tag{3}$$

The κ - ω SST turbulent eddy viscosity is based on a combination of the κ - ε and κ - ω turbulence models (Menter, 1994), and the turbulent viscosity model is computed by

$$\mu_t = \frac{\rho\kappa}{\omega}\xi \tag{4}$$

where ξ as a blending factor. The turbulent kinetic energy κ and the specific rate of dissipation ω are determined from the solution of their conservation equations (Menter, 1994).

$$\frac{\partial(\rho u_j \kappa)}{\partial x_j} = P_k - \beta\,\rho\,\omega\,k + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_k \mu_t)\frac{\partial \kappa}{\partial x_j}\right] \quad ; \quad P_k = -\overline{\rho\, u_j\, u_i}\frac{\partial u_i}{\partial x_j} \tag{5}$$

$$\frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma\rho}{\mu_t}P_k - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1-F_1)\frac{\rho\sigma_\omega^2}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{6}$$

The problem is dimensionalized by

$$U_i = \frac{u_i}{U_{in}} \quad ; \quad X_i = \frac{x_i}{D} \quad ; \quad P = \frac{p - p_{in}}{\rho U_{in}^2} \tag{7}$$

where $U_{in} = Q / A_{in}$ is defined as the inlet velocity, with Q as the volumetric flow rate, A_{in} as the inlet aortic valve area, which has diameter D and p_{in} the pressure at inlet aortic valve.

It was assumed that the inlet aortic valve was not deformed during the two years, and the same uniform velocity normal to the inlet was imposed for both cases. It was assumed a 5% of turbulent intensity at the inlet and the length scale to estimate the inlet specific dissipation was defined equal to in inlet valve diameter. No slip condition was imosed at the aorta´s surface. As it can be seen in Fig. 1, there are four outlets. The outflow flow rate distribution was defined based on average values in the human body (Alastruey et al., 2016). The outflow boundary condition at the descending aorta was 69.1%, at the three arteries at the top of the arch were defined as 19.3% (brachiocephalic artery), 5.2% (left carotid artery), and 6.4% (left subclavian artery).

Besides, the geometric shape of the aorta, the flow governing parameter is the Reynolds number

$$\mathrm{Re} = \frac{\rho U_{in} D}{\mu} \tag{8}$$

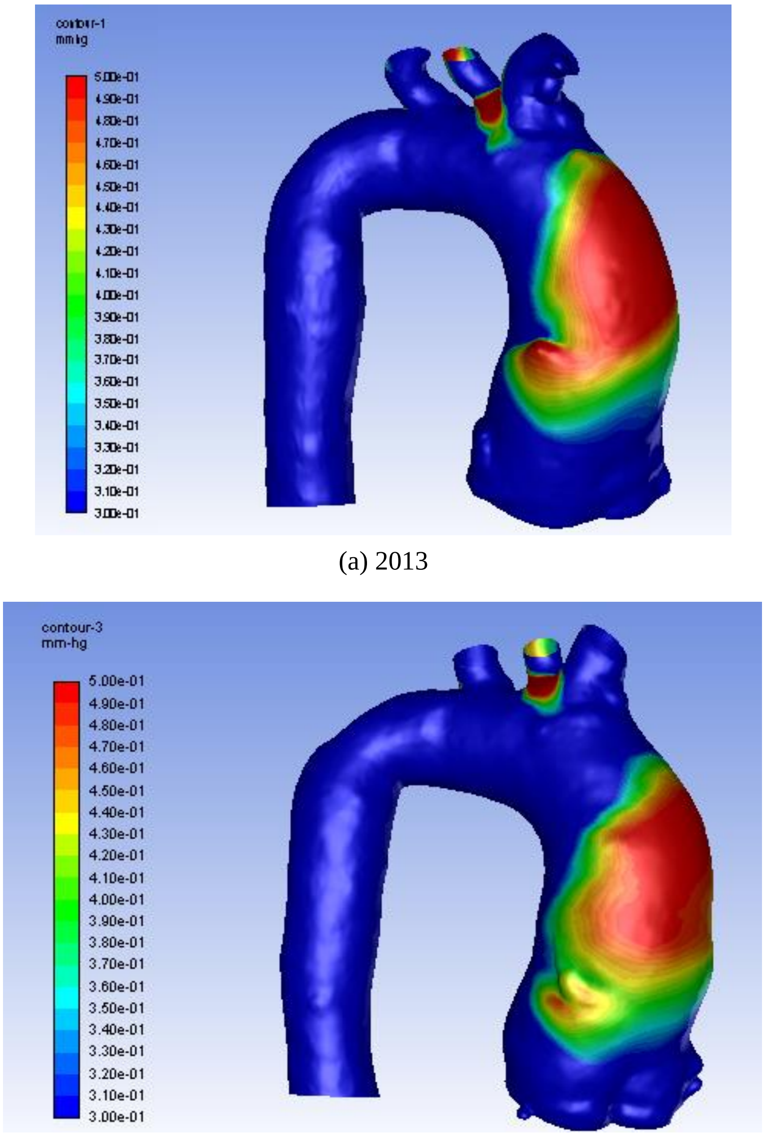
The Reynolds number corresponding to the present case is 2270. Although the Reynolds number is not very high, the jet flow through the inlet valve is turbulent as observed experimentally by Azevedo *et al* (2017), who measured the turbulent intensity in a similar aorta.

3. RESULTS AND DISCUSSION

Figure 2 indicates the region of interest. On that figure, a line aligned with the inlet jet was sketched, indicating the main direction of the inlet flow and the point of impingement at the aorta surface.

The first parameter evaluated from both exams was the volume of the area of interest. It was observed a variation inferior to 3% confirming that the aneurism of the selected patient did not grow up during the time interval between exams.

One of the most important parameters to analyze is the pressure distribution at the aorta´s surface. According to Frauenfelder *et al*. (2007), the pressure on the aortic wall is a vital factor for the risk of aneurysm rupture. Figure 3 illustrates the pressure distribution at the aorta´s surface. The pressure is presented in millimeters of mercury (mmHg) and it is defined in reference to inlet pressure, which corresponds to the systolic pressure. Examining Fig. 3, it can be observed a region of high pressure (4mm Hg – 5 mmHg) near the aorta´s root. Note also that the highest pressure occurs at the impinging jet flow region, as expected. It can also be observed that although the size of this region of high pressure has increased from 2013 to 2015, the maximum pressure was maintained. Since the size of the aneurism was approximately constant (the size of the aneurysmal diameter did not vary), it can be inferred that the size of the high-pressure region is not significant as its value.



(a) 2013

(b) 2015.

Figure 3. Pressure distribution. (a) 2013. (b) 2015.

4. CONCLUSIONS

The flow field inside the ascending aorta of a selected patient obtained from an exam in 2013 and another in 2015 was numerically examined, by comparing the pressure distribution at the aorta´s surface. It was verified that the aneurism did not grow up. The maximum pressure corresponding to the two exams was maintained the same, indicating that the non-increase of the aneurysm can be related to pressure level.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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