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# NUMERICAL INVESTIGATION OF HEMODYNAMICS PATTERNS AFTER TRANSCATHETER AORTIC VALVE REPLACEMENT (TAVR)

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**Abstract.** *Transcatheter Aortic Valve Replacement (TAVR) has become a powerful alternative for patients with aortic stenosis and a high risk to face a traditional open chest surgery. The objective of the research was to analyze, using Computational Fluid Dynamics (CFD), the hemodynamic effects caused in the aorta by the inclination of the prosthetic valve orifice in its final positioning. The study was carried out on the basis of a particular patient who was undergoing to TAVR. A 3D model was generated from computed tomography angiography and image segmentation of the aorta. To represent a pulsatile flow, different mass flow rates were imposed at the inlet valve. The turbulence was modeled with the two-equation  $\kappa$ - $\omega$  SST model. The influence of small variation of tilt angles of the inlet flow on the velocity and pressure fields are discussed. It is shown that small variation of the tilt angles can significantly modify the nature of the flow, displacing the location of vortices and altering the location and value of the highest values of pressure.*

**Keywords:** *Transcatheter Aortic Valve Replacement, turbulence, CFD, hemodynamic*

## 1. INTRODUCTION

Transcatheter aortic valve replacement (TAVR) is a procedure that replaces a stenotic aortic valve with a prosthesis. It is installed in the position of the aortic valve without removing it. For many years, the surgical aortic valve replacement was the standard until TAVR, developed since 2002 (Cribier, 2002), become a powerful alternative for patients with aortic stenosis and a high risk to face a conventional open chest surgery (Nishimura et al., 2017). In the TAVR procedure, a prosthesis is released in the region of the aortic annulus. It is done with the use of catheters and under the aid of fluoroscopic images and transesophageal echocardiography. With an open surgical procedure, valve placement is precise. However, more variability in the prosthesis position is expected in TAVR, due to the inherent nature of the procedure (Groves et al., 2014; Gunning et al., 2014). Further, the presence of eccentric calcifications in the aortic annulus, may avoid the full expansion of the percutaneous prosthesis, influencing in the inclination that it will acquire after its release process (Gunning et al., 2014).

It is hypothesized that the direction and angle of aortic inflow can influence helical flow patterns and related hemodynamic features in the ascending aorta (Ha et al., 2016). Computational fluid dynamics (CFD) has gained a lot of interest as a complementary tool for improving understanding of pathogenesis and disease progression in cardiovascular disease (Sun and Chaichana, 2016). In this work to validate the numerical model, comparison was performed with experimental results obtained by Azevedo (2017). Therefore, similar hypothesis were applied as the ones considered in the experimental setup.

The main objective of the research is to analyze, using CFD, how the tilt angles of the prosthetic valve affect the blood flow patterns and hemodynamics. We seek to determine which of these flow patterns are better for a particular patient, and to obtain useful information that can help to optimize the TAVR procedure for future patients in their medical treatment.

## 2. METHODOLOGY

A 3D model was generated from computed tomography angiography and image segmentation of the aorta of a particular patient who was undergoing to TAVR. The present study was approved by the Research Ethics Committee of the institution. The 3D model illustrated in Fig. 1a was taken to the Ansys Fluent software for a CFD analysis. The mesh was defined 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. 1b) was inferior to 0.3%, when the mesh was doubled.

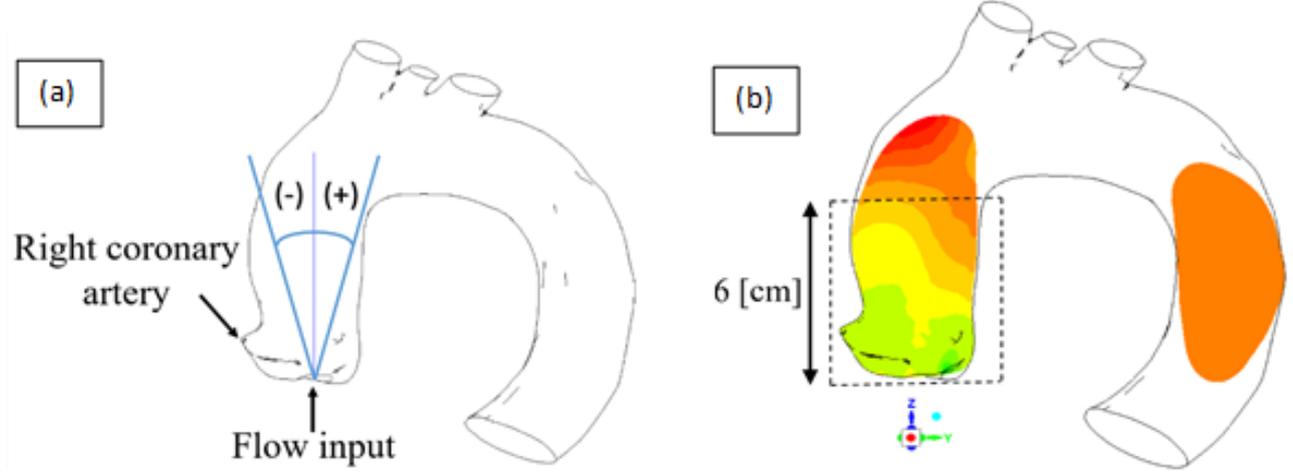


Figure 1. (a) Jet orientation. (b) Selected area for the analysis

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, as a first simplification, the aorta's surface was considered rigid. Another simplification was to neglect gravity effects, since the pressure variations are dominant over the force of gravity. According to Sun and Chaichana (2016), the blood can be considered as a Newtonian fluid, i.e., the viscous stress being directly proportional to the rate of deformation of the fluid element. In addition, under normal conditions, the blood is quite similar to water and can be considered as an incompressible fluid (Feijó, 2007; Feijoo and Zouain, 1988). Finally, the pulsatile cycle was represented as a sequence of steady state situation.

The turbulence was modeled based on the Reynolds average approximation, with the two-equation  $\kappa$ - $\omega$  SST model (Menter, 1994). The turbulence model was selected by comparing the numerical predictions with experimental data, previously obtained (Azevedo, 2017).

To determine the flow field, the conservation of mass and momentum must be solved

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

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

where  $x_i$  represents each of the coordinate axes and  $u_i$  the components of the velocity vector.  $\rho$  is the density,  $\hat{p}$  is a modified pressure

$$\hat{p} = p + \frac{2}{3} \rho \kappa \quad (3)$$

which includes the turbulent dynamic pressure ( $\kappa$  is the turbulent kinetic energy).  $\mu$  and  $\mu_t$  are the molecular viscosity and turbulent viscosity, respectively.

The  $\kappa$  -  $\omega$  SST turbulent eddy viscosity is based on a combination of the  $\kappa$  -  $\varepsilon$  and  $\kappa$  -  $\omega$  turbulence models (Menter, 1994) and the turbulent viscosity is computed from

$$\mu_t = \frac{\rho \kappa}{\omega} \xi \quad (4)$$

where  $\xi$  as a blending factor. The kinetic energy  $\kappa$  and specific rate of dissipation  $\omega$  are determined from the solution of their conservation equations (Menter, 1994).

The problem can be dimensionlized by

$$U_i = \frac{u_i}{U_{in}} \quad ; \quad X_i = \frac{x_i}{D} \quad ; \quad P = \frac{p - p_{in}}{\rho U_{in}^2} \quad (5)$$

where  $U_{in} = Q/A_{in}$  is the inlet velocity, with  $Q$  as the volumetric flow rate and  $A_{in}$  as the inlet aortic valve, which has diameter  $D$ .  $p_{in}$  is the pressure at inlet aortic valve. The governing parameters are the Reynolds number

$$Re = \frac{\rho U_i D}{\mu} \quad (6)$$

and the inlet valve tilt angle  $\theta$ .

Six input angles were investigated ( $-4^\circ$ ,  $-2^\circ$ ,  $0^\circ$ ,  $+1^\circ$ ,  $+3^\circ$ ,  $+5^\circ$ ) and they were defined taking the right coronary artery as reference (Fig 1a). The inlet plane is coincident with the plane x-y, and perpendicular to the axial z coordinate.

To represent a pulsatile flow, different mass flow rates were imposed at the inlet valve, from  $Q = 0.8$  lt/min to 25 lt/min to cover the entire pulsatile cycle. From the mass flow rate, and angle inclination, the velocity components were determined. Uniform turbulent quantities were also imposed at the inlet, with 10% of turbulent intensity (Azevedo, 2017). No slip condition was enforced at the aortic surface and zero diffusion flux was imposed at the domain exit for all variables.

To problem was solved employing the commercial software Fluent, where the conservation equations are discretized based on the finite volume method (Patankar, 1980).

### 3. RESULTS AND DISCUSSION

To better verify the influence of the inlet valve angle, analyzes are focused at a region that comprises 6 cm of the ascending aorta (Fig 1b).

Figure 2 illustrates the axial velocity component (z direction) and Figure 3 illustrates the pressure isocontours at a plane in the region selected, oriented with the center of the jet and the right coronary. The flow rate is 25 lt/min and the solution obtained with the six angles selected is shown.

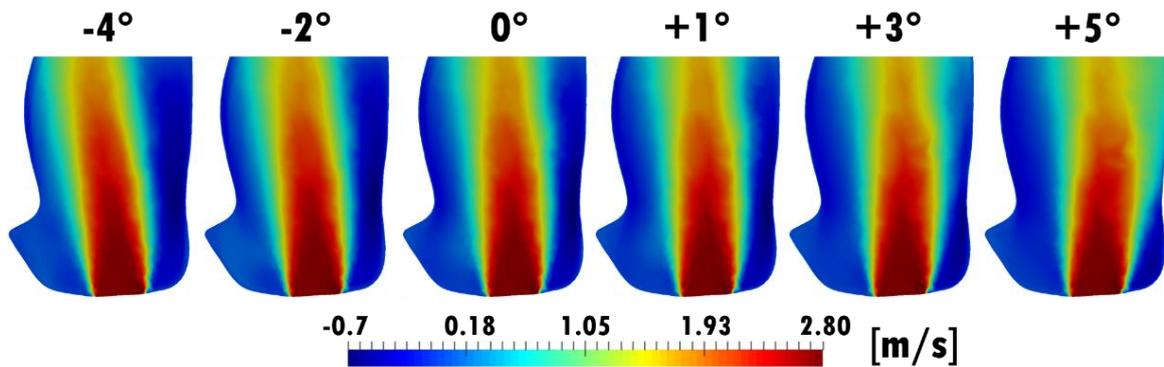


Figure 2. Axial velocity fields varying the tilt angle.  $Q=25$ lt/min

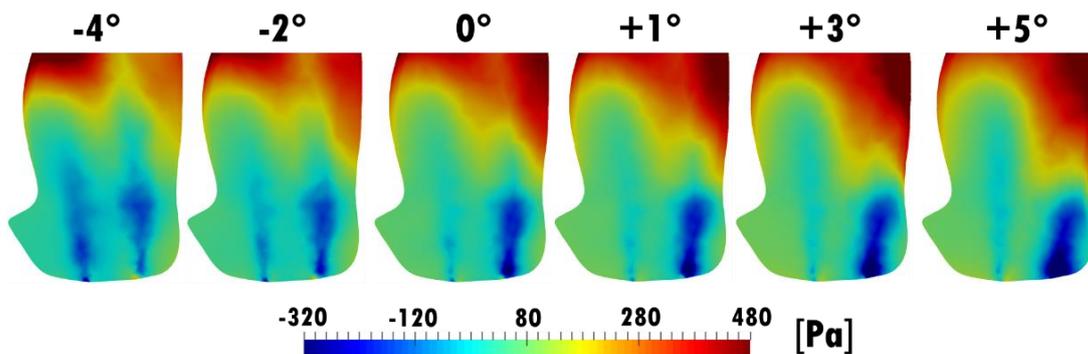


Figure 3. Pressure fields in the central plane varying the tilt angle.  $Q=25$ lt/min

Examining Figures 2 and 3, it can be seen the great influence that small variation of tilt angles have in the flow field, especially in the pressure field. It can be observed that negative tilt angles dislocates the maximum pressure to the anterior region of the ascending aorta. On the other hand, positive angles redirect the main jet towards the posterior wall, removing the maximum pressures of the anterior region.

By examining the flow field resulting from different inlet velocities, representing the pulsatile cycle, it is possible to verify the great influence that small variation of tilt angles have in the pressure field.

To obtain a complete spatial visualization, the properties were analyzed in different transverse planes, distributed every 1cm from the entrance and again covering 6 cm of ascending aorta.

Figure 4 shows the distribution in the geometry of the axial velocity and Figure 5 shows the distribution of the dimensionless pressure. Analyzing Figure 5, the main jet from the inlet can be clearly seen, as well as recirculation regions around it. Further, in Figure 6, a large pressure can also be observed at the aortic surface, due to the jet impingement.

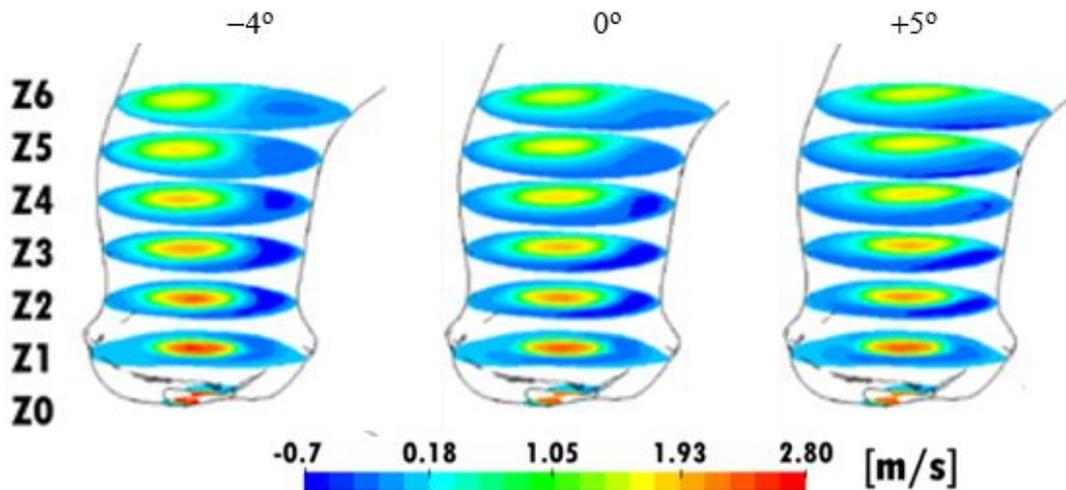


Figure 4. Axial velocity contours at transverse planes in geometry, for different tilt angles.  $Q=25\text{lt}/\text{min}$

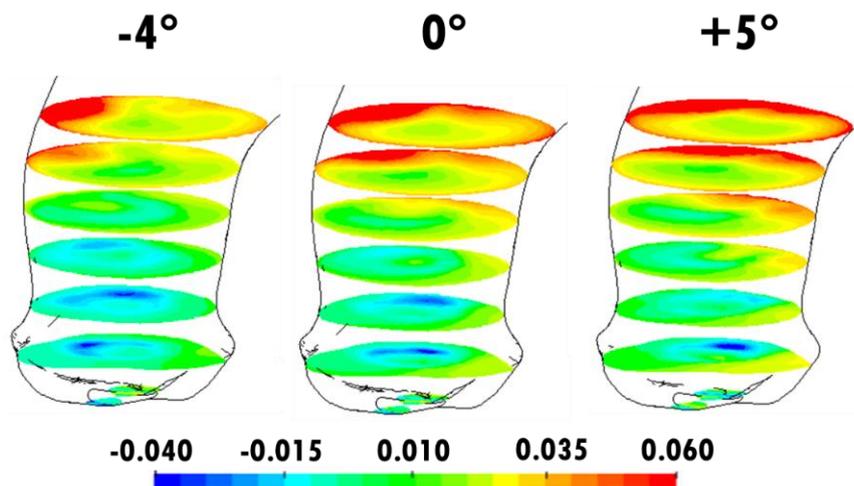


Figure 5. Dimensionless pressure contours at transverse planes in geometry, for different tilt angles.  $Q=25\text{lt}/\text{min}$

#### 4. CONCLUSIONS

The influence of the inlet tilt angles on the flow field are discussed. It is shown that small variation of the tilt angles can significantly modify the nature of the flow, displacing the location of vortices and altering the location and value of the highest pressure. These hemodynamic features may be relevant in the aortic remodeling process and the mechanical stresses may influence the durability of the prosthetic valve.

#### 5. ACKNOWLEDGEMENTS

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## 7. RESPONSIBILITY NOTICE

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