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IN VITRO EXPERIMENTAL INVESTIGATION OF AORTIC VALVE TILT ANGLE ON HEMODYNAMIC FLOW PATTERNS

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Abstract. *Aortic stenosis (AS) is the most common valve disease. Transcatheter Aortic Valve Implantation (TAVI) has become the preferred treatment for high-risk or inoperable patients with severe aortic stenosis that could be a life-threatening condition when left untreated. Due to the nature of the TAVI procedure, a variability on the tilt angle of the deployed valve is expected. The present work, investigated the effects on the flow field in the ascending aorta due angle variation of the prosthetic valve effective orifice. Understanding the hemodynamic patterns of blood flow in the ascending aorta is important because they are closely related to the development of cardiovascular diseases. To this end, a patient-specific vascular phantom was produced by a 3D printed model and transparent silicon resin. A special setup was designed to allow measurements of the 3D flow at different cross sections of the aorta. A stereoscopic particle image velocimetry system (stereo-PIV) was implemented to yield instantaneous and averaged turbulent flow information. Preliminary results obtained indicate that the velocity field in the ascending aorta is strongly affected by the inlet flow direction into the aorta.*

Keywords: *Transcatheter aortic valve replacement, stereoscopic PIV, in vitro* patient-specific phantom, Turbulent flow

1. INTRODUCTION

Transcatheter Aortic Valve Implantation (TAVI) was firstly presented as an alternative treatment for high-risk surgical patients with severe aortic stenosis (Cribier, 2002). However, recent advances in the fields of transcatheter valves have expanded the proportion of patients eligible for TAVI intervention (Tamburino et al., 2015). In a traditional open surgical procedure, valve deployment is precise. However, a variation in final valve positioning is expected in TAVI due to the inherent nature of the procedure (Groves et al., 2014). Furthermore, because of the irregular leaflets calcification, the final valve placement may be influenced. Due to this fact, an eccentric inlet flow towards the ascending aorta may occur (Gunning et al., 2014).

Various studies suggested that the flow patterns in the ascending aorta might be affected by aortic root anatomical characteristics (Trauzeddel et al., 2015). The effects of transcatheter valve positioning on aortic flow is an important characteristic of the procedure that has not been studied in detail. Several clinical studies also support the association between abnormal hemodynamic features and various vascular diseases, such as aortic remodeling process, and aneurysmal formations (Hope et al., 2012).

Differently from *in vivo* environment where variables could not be controlled, the aorta patient-specific modeling for experimental investigations has gaining more attention from researchers worldwide. This is due, mostly, to the potential to improve understandings of hemodynamics features produced by important entrance parameters and flow boundary conditions, as the inclination of inflow jet towards the ascending aorta.

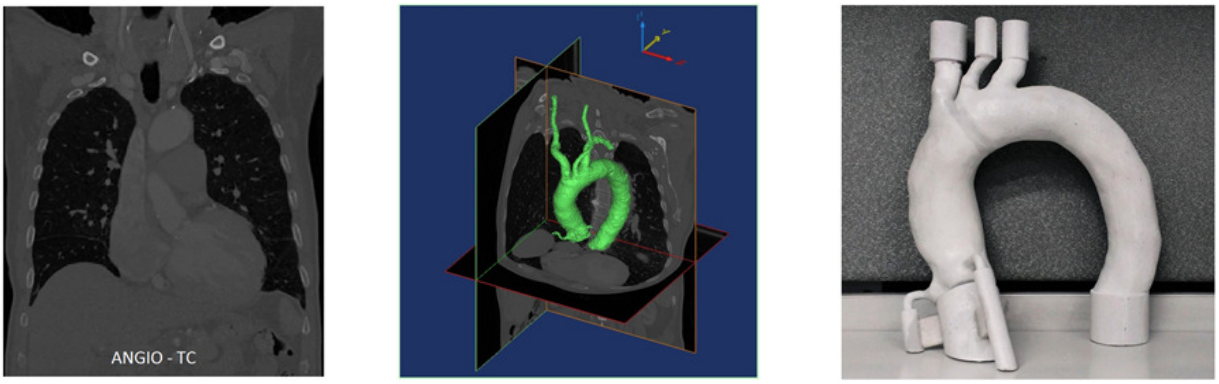
Therefore, the main aim of the present work was to investigate, using a Stereo-PIV approach, the influence of the tilt aortic flow angles on the hemodynamic features in the ascending aorta. In particular, development of helical blood flow, which depends of prosthetic valve placement and consequently inflow jet direction. Moreover, the prior knowledge of these flow patterns is important information to improve diagnosis and optimize clinical treatment by predicting possible outcomes of surgical interventions.

2. METHODS

2.1 Silicone model

A description of experimental investigation of blood flow in a realistic three-dimensional aortic model follows bellow. As stereoscopic particle image velocimetry (Stereo-PIV) is a non-intrusive laser optical measurement technique requiring an optically transparent model and working fluid, a vascular optically transparent model was constructed by using computed tomography images of patient aorta who was submitted to TAVI. As required, the Research Ethics Committee of the institution approved the present work.

A virtual 3D aortic model was generated out of DICOM images from patient exams employing the Mimics software (Materialise, Belgium), including left and right coronaries, brachiocephalic artery, left common carotid and left subclavian arteries. Each branch had its geometry slightly modified to ease hydraulic connections of hoses. The path transitions were made regarding minimal flow disturbance. After the whole image processing, the virtual geometry was printed in actual scale with a plaster powder prototyping machine (Z-Corp ZPrinter 650). The printing material was hidrosoluble and the model was coated with polyvinyl acetate glue (Figure 1).



(a) (b) (c)

Figure 1. Manufacturing stages: (a) Computed tomography images; (b) Image pre-processing and segmentation; (c) 3D printed model

The core model was fixed in a rectangular acrylic box to facilitate the casting of the silicone phantom. The recipient was filled with liquid elastomer (Sylgard 184, Dow Corning, Canada). After that, the silicone prototype was placed in a vacuum chamber to eliminate the possibility of occurrence of gas bubbles during the resin curing process. After 48 hours of curing, the model was taken off the acrylic box and the core was dissolved in water (Figure 2), leaving the aortic passage from the patient in the silicon model.

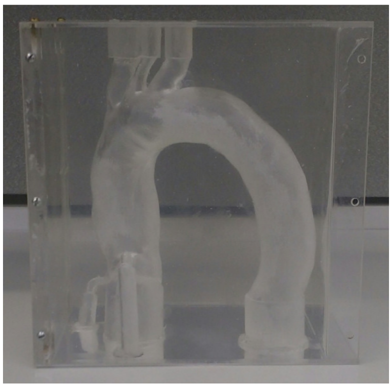


Figure 2. Silicone model

The Sylgard 184 silicone elastomer was chosen to avoid optical distortion in the PIV experiments. The phantom and working fluid must have matched refractive indexes (approximately 1,417) which was obtained by using an aqueous glycerol solution composed of 60% glycerin in volume. Outflow hoses were connected into the specially prepared holes designed to receive hydraulic connectors and they were fixed with silicone adhesive.

2.2 Experimental setup

The silicone model was incorporated in a closed hydraulic circui,t as can see in Figure 3 below. The flow was driven by a volumetric pump (NM031-1L, NETZSCH, Brazil) into the aortic model through a region equivalent to the aortic valve annulus, where an especially designed connector simulated the aortic prosthesis in its fully opened configuration. Based on the effective orifice area of a transcatheter heart valve, the connector nozzle was fabricated with 2.0 cm^2 of inner cross section area. The aortic model had six outflow passages: left and right coronary arteries, brachiocephalic artery, left common carotid artery, left subclavian artery and aorta descendent. Downstream of each branch, ball valves were installed to control the outflow distribution.

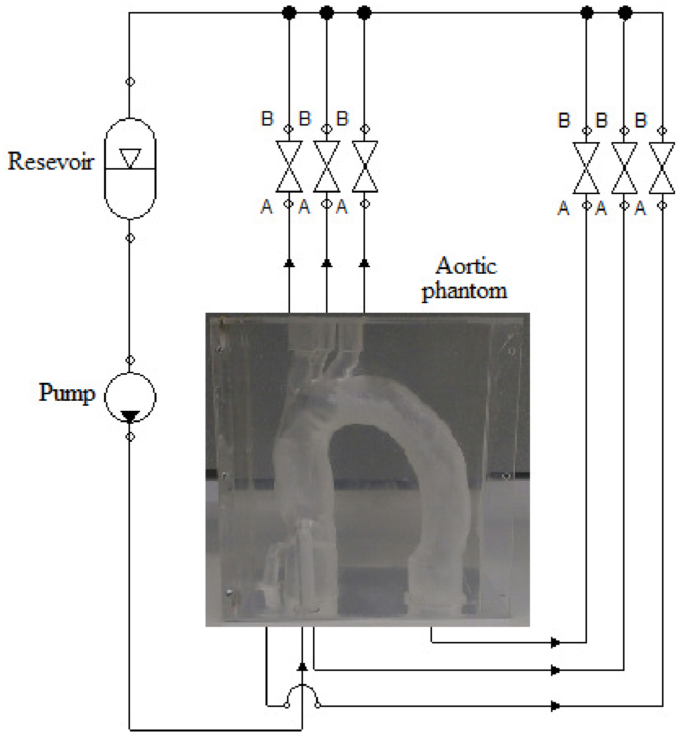


Figure 3. Experimental setup

A steady aortic inflow was adjusted to 25 L/min according to a typical reference value of the highest point of the ventricular systole. The inflow Reynolds number based on the entrance conditions was $Re_{in} = 5126$.

The variation in the aortic inflow inclination could be achieved by coupling tubes, with connectors pre-designed to ensure these azimuthal angles, in the seat nozzle previously installed in the aortic phantom. Therefore, four tubes were manufactured with the following angles of inclination: 0°, 2°, 4° and 8°. By turning tube 90, 180 and 270 degrees, the tilt angles could be set to -8°, -4°, -2°, +2°, +4° and +8°. The zero-tilt angle corresponds to the centerline of the effective orifice aligned with the center line of the aortic annulus. The negative angles tilted means an inflow orientation toward the right coronary ostium, while the positive angles point toward the aorta posterior wall. Figure 4 shows the positive and negative angle orientations.

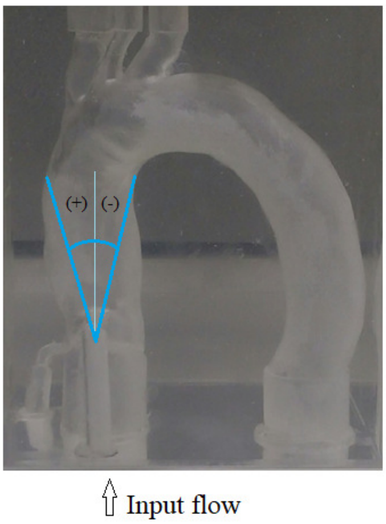


Figure 4. Jet orientation

2.3 Stereoscopic PIV setup

The Stereo-PIV system (INSIGHT 4G, TSI, USA) was constituted of a dual pulsed Nd:YAG laser (70 - 140mJ, 532nm) with two high-speed CMOS cameras (Phantom MIRO 320S, Vision Research Ametek), and mounted with 50 mm Nikon objective lenses. The specific Stereo-PIV setup is shown in Figure 5. Both cameras were positioned above the aortic model with a top of view angle of 30°. A triangular silicone prism, projected to avoid optical distortions, was positioned over the aortic phantom and precisely between the two cameras. A special procedure for the system calibration was developed and performed by using a target immersed in the glycerol solution, the same used as the working fluid. The calibration target was mounted besides the silicone model in a manner that both could be moved laterally trough a coordinate table, positioning the region of interest in the camera's field of view. The laser light sheet was placed in vertical alignment with the silicone phantom. The fluid was seeded with silver-coated hollow glass spheres with approximately 13 µm of diameter.

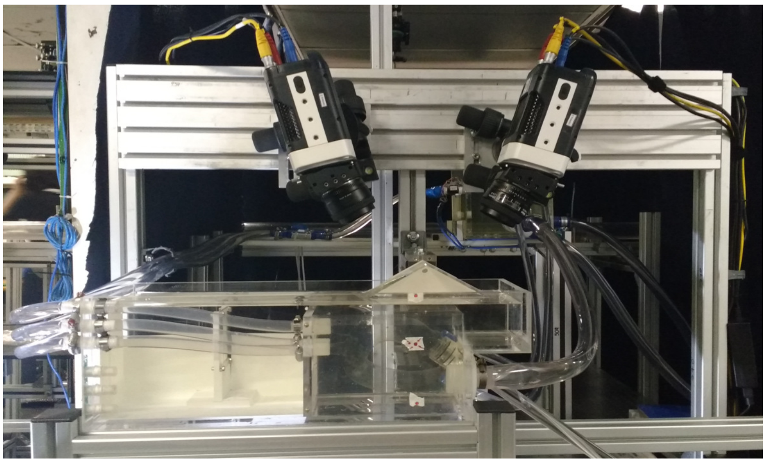


Figure 5. Stereoscopic PIV experimental flow setup

3. RESULTS AND DISCUSSION

In this section the preliminary results for the 3D flow field will be presented. The characterization of the complete flow field in the ascending aorta is still being obtained, since this is part of an ongoing research project. The resulting 3D velocity fields in the ascending aorta segment have been analyzed in cross-section plane coincident with the xy-plane, and orthogonal to the axial z coordinate, as can be seen in Figure 6. The current region of interest (ROI) for analysis comprises a length of 75 mm in the axial direction. To cover whole ROI and obtain a satisfactory flow spatial resolution, analysis were carried out at 6 transverse planes equally spaced by 15 mm along z-axis. For each studied plane, 3000 image pairs were captured and correlated with each other to produce 1500 instantaneous velocity fields. The mean velocity fields could be calculated based on those instantaneous fields.

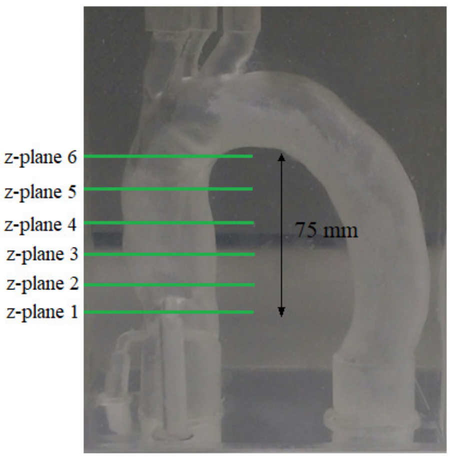


Figure 6. Selected planes for analysis

Figure 7 shows four velocity fields measured for zero-tilt angle, i.e., the inlet flow is aligned with the ascending aorta center line. The arrows in the figures indicate the in-plane flow components, while the out-of-plane axial flow component is indicated by the color maps. Based on these preliminary results, it is seen that the signature of jet-like inlet condition through the valve orifice persists along the axial direction in the ascending aorta. Indeed, the measurements shows that most of the aorta cross section is filled with virtually stagnant axial flow. Small region of high velocity is seen to move toward the aorta posterior wall as the flow progresses into the ascending part of the aorta. In figure 7(d) the main axial flow is seen to impinge on the wall. This is a relevant piece of information since aorta remodeling is frequently associated with increased shear stress imposed by the flow on the wall. The measurements seem to be confirming these clinical observations. The results presented are a flow of Q = 25 l/min, a typical peak value of the ventricular systole.

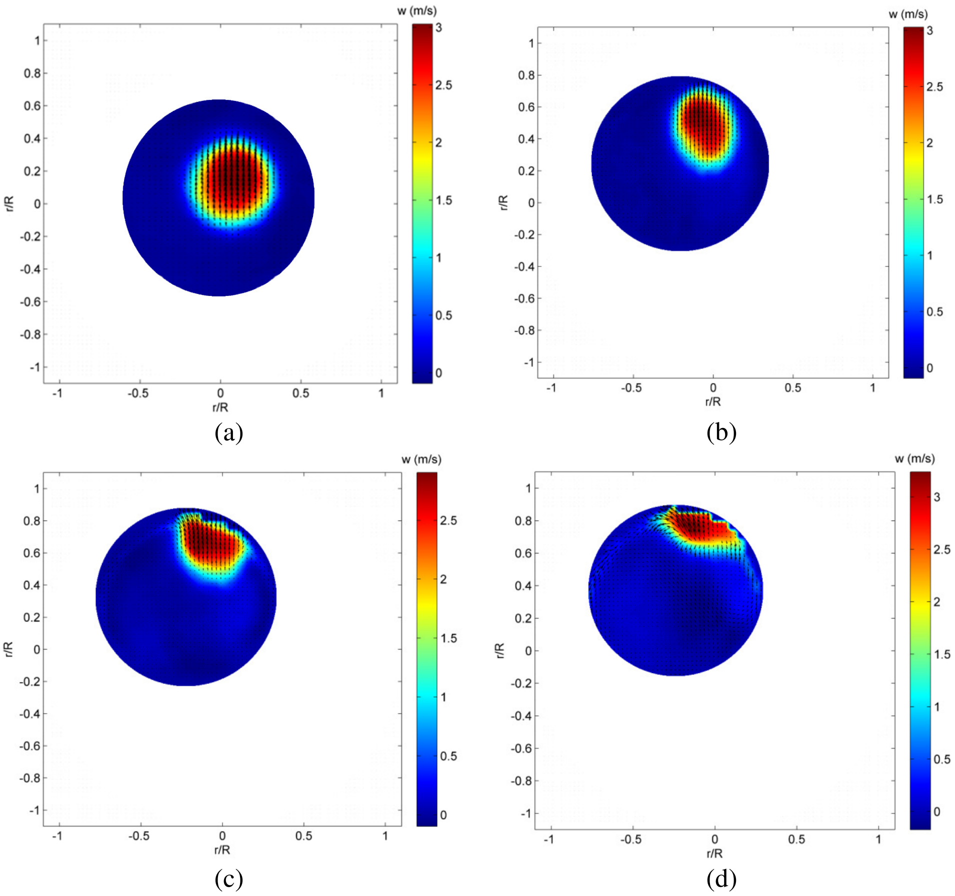


Figure 7. Axial velocity contours at transverse planes along ascending aorta for zero-tilt angle (0°). (a) z-plane 2, (b) z-plane 3, (c) z-plane 4 and (d) z-plane 5.

4. CONCLUSIONS

The present research employed 3D stereoscopic particle image velocimetry technique to obtain instantaneous and averaged velocity fields in a patient-specific aorta model. The objective of the study was to investigate the effect of the tilt angle of valvar implants on the flow filed within the aorta.

The preliminary results obtained for an inlet flow configuration aligned with the ascending aorta indicated that the jet-like inlet flow persists along the aorta, being direct toward the wall where an impinging flow pattern was observed. The flow rate was maintained constant in the study.

Different inlet flow conditions are presently being studied, what will provide a broad understanding of the influence of tilt angle of the valvar implant on the flow fields and, consequently, on the development of artery diseases.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Azevedo, B. A., Camargo, G.C., dos Santos, J.R.L., Azevedo, L.F.A., Nieckele, A.O., Siqueira-Filho, A.G., Oliveira, G.M.M,2017. “Influence of the tilt angle of Percutaneous Aortic Prosthesis on Velocity and Shear Stress Fields”. Arq. Bras. Cardiol. Vol.109, n..3.

Cribier, A., 2002. “Percutaneous Transcatheter Implantation of an Aortic Valve Prosthesis for Calcific Aortic Stenosis: First Human Case Description”. Circulation, Vol. 106, n. 24, p. 3006–3008.

Groves, E. M., Falahatpisheh, A., Su, J. L. and Kheradvar, A., 2014. “The Effects of Positioning of Transcatheter Aortic Valves on Fluid Dynamics of the Aortic Root”. ASAIO Journal, Vol. 60, n. 5, p. 545–552.

Gunning, P. S., Saikrishnan, N., Mcnamara, L. M. and Yoganathan, A. P., 2014. “An In Vitro Evaluation of the Impact of Eccentric Deployment on Transcatheter Aortic Valve Hemodynamics”. Annals of Biomedical Engineering, Vol. 42, n. 6, p. 1195–1206.

Hope MD, Wrenn J, Sigovan M, Foster E, Tseng EE, Saloner D. Imaging biomarkers of aortic disease increased growth rates with eccentric systolic flow. J Am Coll Cardiol. 2012;60(4):356-7. doi: 10.1016/j. jacc.2012.01.072.

Hamm CW, Möllmann H, Holzhey D, Beckmann A, Veit C, Figulla HR, et al. The German Aortic Valve Registry (GARY): in-hospital outcome. Eur Heart J. 2014;35(24):1588-98. doi: 10.1093/eurheartj/eht381.

Tamburino C, Barbanti M, D’Errigo P, Ranucci M, Onorati F, Covello RD, et al. 1-year outcomes after transfemoral transcatheter or surgical aortic valve replacement. J Am Coll Cardiol. 2015;66(7):804-12. doi: 10.1016/j. jacc.2015.06.013.

Trauzeddel RF, Löbe U, Barker AJ, Gelsinger C, Butter C, Markl M, et al. Blood flow characteristics in the ascending aorta after TAVI compared to surgical aortic valve replacement. Int J Cardiovasc Imaging. 2015;32(3):461-7. doi: 10.1007/s10554-015-0792-x.

7. RESPONSIBILITY NOTICE

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