DIGITAL TWIN ANALYSIS OF AORTIC ROOT FLOW DISTURBANCES FOLLOWING TRANSCATHETER IMPLANTATION AND 4D MRI

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Introduction

Aortic valvular abnormalities, including aortic stenosis due to leaflet calcifications, are progressive diseases with increasing prevalence.[1] Calcification leads to malfunction of the valve which might block the heart to supply sufficient amount of oxygen-rich blood to the rest of the body. Although, surgical aortic valve replacement is the most efficient treatment option, due to invasiveness it is contraindicated for high-risk patients particularly above the age of 75. Therefore, transcatheter aortic valve implantation (TAVI) is the generally accepted standard care for aortic sclerosis.[2] TAVI is catheter-based minimally invasive procedure where the replacement valve is guided through a small incision in the femoral artery into the aortic annulus. Since the implanted valve changes the hemodynamics especially in the Sinus Valsava, an early diagnosis of blood flow abnormalities and disturbances is essential to avoid adverse outcomes. Computational fluid dynamics (CFD) and fluid-structure interaction (FSI) have emerged as approaches for assessment of aortic valve hemodynamics in idealised and personalised valve models. The present work aims at building a reliable and predictive computational (CFD and FSI) model through integration of the experimental data on the valve leaflet displacement acquired through a flow-loop in-vitro setup and 4D magnetic resonance imaging (MRI).

Methods

Fig. 1 illustrates the region of interest of the in-vitro setup (Fig. 1-A), experimental and MRI data (Fig-B,C), and computational model of the aortic valve (Fig.1-D, COMSOL Multiphysics 6.0). Through the experiments conducted with the in-vitro setup, transient pressure and velocity profiles were acquired and used as boundary conditions for both the semi-transient CFD and FSI models. The 2D axisymmetric geometric model was established by utilizing the 4D MRI scans, defining a linear deformation for the leaflets, initially assumed as rigid in the CFD model. The non-Newtonian characteristics of blood were neglected owing to the size of the artery. Given the transitional flow regime, the k-omega SST model was employed to address turbulence. Following mesh and inlet and outlet lengths analyses, CFD semi-transient simulations were performed to characterize local hemodynamic and flow disturbances in the sinus of Valsalva. These steady-state simulations considered the change of the velocity and pressure over time, as well as the valve changing geometry. After introducing mechanical properties of the leaflets, FSI analysis was performed in which the structure field is defined with mechanical properties of a healthy leaflet introduced in [3] and the aortic root handled as rigid.

Results

Despite the limited resolution (0.9 x 0.9 x 4.0 mm), the 4D MRI scans showed that the leaflet geometry was changing during the cardiac cycle. The tracked valve deformation and the hemodynamic conditions are used to validate the CFD and FSI models. Among the computational results, it is noteworthy that that turbulence levels (turbulent kinetic energy, TKE) were relatively high from peak to late systole, but otherwise remained low. Moreover, high-velocity jet flow at the valve orifice during systole and recirculatory flows in the sinus during diastole were clearly observed, as shown by the velocity streamlines (Fig. 1-D). These findings agree with literature results.[4]

Discussion

The performed semi-transient CFD analysis based on an experimental-based deforming valve geometry is an effective alternative to the computationally intensive FSI simulations. Combining this method with flow-loop and 4D MRI data enables obtaining reliable results and strengthen the experimental-computational twin, allowing an extension to the analysis of in-vivo results.

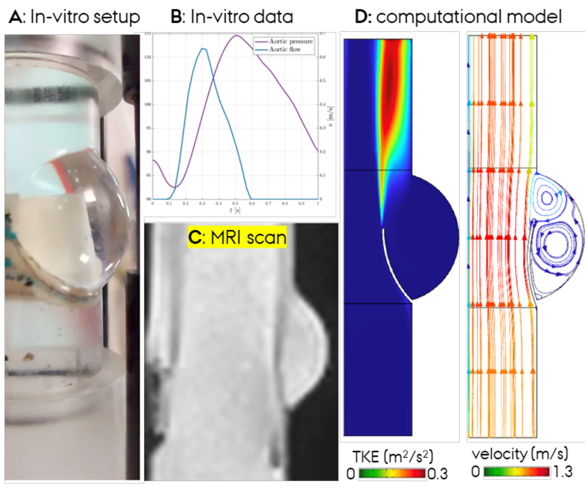

Fig. 1: *In-vitro and in-silico valve model.*

References

1. Grigorios T et al, J Biomech Eng, 30:100-107, 2015.
2. Osnabrugge RL et al, J Am Coll Cardiol, 62:1002-1012, 2013.
3. Koch BD et al, Comput Methods Biomech Biomed Eng, 13:2, 225-234, 2010.
4. Armin A et al, Inform Med, 9:191-199, 2017.