Assessing the effect of calcification in aortic valve using particle-method modelling

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Introduction

- Aortic valve disease is the malfunction of the aortic valve due to heart malformation at birth (congenital) or developed during a lifetime related to injury, age, or calcification of the valve (Fioretta et al., 2018). Calcification, in particular, may result in calcific aortic valve disease (CAVD) caused by calcium deposits on the valve leaflets, which affects mainly the elderly population with an incidence rate of 2 – 7% in the population above 65 years of age (Amindari et al., 2017).
- Over time, calcium build-up makes the aortic valve stiffer preventing full opening (stenosis) and hindering the blood flow from the left ventricle to the aorta. It may also prevent the valve from closing properly (regurgitation) resulting in blood leakages back to the ventricle.
- Stenosis starts with the risk of leaflet deformation and progresses from early lesions to valve obstruction, which is initially mild to moderate but eventually becomes severe, with or without clinical symptoms (Otto et al., 2014) and the patient has high risk of cardiac failure.

Objectives

In this work, we aim to use Discrete Multi-Physics (DMP) modeling, which enables the fluid-solid interaction, to develop a 3D model representing various stages of a calcification of the aortic valve.

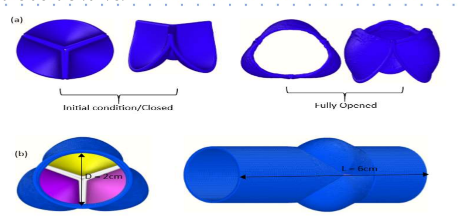

Figure 1. Valve leaflets (a) and complete geometry (b)

Methodology

This study proposes a 3D particle-base (discrete) multiphysics approach for modelling calcification in the aortic valve

Different stages of calcification (from mild to severe) were simulated, and their effect on the cardiac output assessed. The cardiac flow rate decreases with the level of calcification. In particular, there is a critical level of calcification below which the flow rate decreases dramatically. Mechanical stress on the membrane is also calculated.

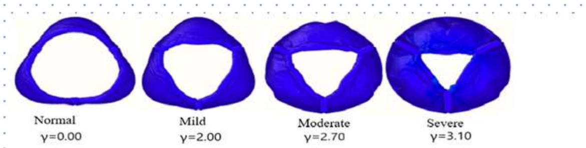

Figure 2. Severity of aortic valve stenosis in terms of orifice opening (stenosis)

Results

- In this model, the value of k was chosen to control the stiffness of the valve and model calcification. The higher the value of k, the stiffer the valve. In our model, higher values of k are used to model a higher degree of calcification. We define the degree of calcification γ as

$$\gamma = \log\left(\frac{k}{k_H}\right) \tag{1}$$

Some important parameters like flow velocity, volume flow rate as well as stress can be used to ascertain the level of calcification of the valves. Figure 3 shows how the flow velocity in the valve is affected by calcification.

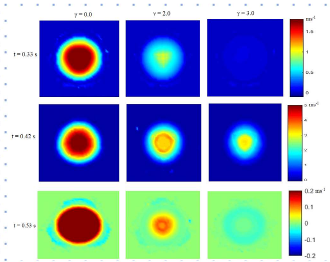

Figure 3. Velocity profile at different time steps

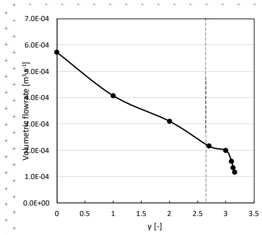

Figure 4. Volumetric blood flow with respect to γ.

- It shows that, as calcification progresses, spots of high mechanical stress appear. Firstly, they concentrate in the regions connecting two leaflets; when severe calcification is reached, then they extend to the area at the basis of the valve.

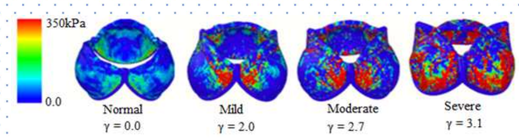

Figure 7. Mechanical stress on the valve leaflets at maximal opening

Conclusion

- The effect of calcification in a 3D aortic valve is simulated with Discrete Multi-physics. The model accounts for both hemodynamics and leaflet deformation, and it can be considered an improvement over a previous 2D model (Ariane et al., 2017). The results show that the mean transvalvular flow could be used to assess valve calcification, and severe calcification occurs when the flow rate is lower than 200 mL s^{-1}.
- The results also show that, as calcification progresses, spots of high mechanical stress appear. Firstly, they concentrate in the regions connecting two leaflets; when severe calcification is reached, they extend to the area at the basis of the valve. This suggests that the model could be improved by accounting for local changes in stiffness, which depends on the local stress distribution.

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References

- Fioretta et al. **(2018).** The Future of Heart Valve Replacement: Recent Developments and Translational Challenges for Heart Valve Tissue Engineering: The Future of Heart Valve Replacement. *Journal of Tissue Engineering and Regenerative Medicine*, 12 (1), e323–e335. https://doi.org/10.1002/term.2326.
- Amindari et al. **(2017).** Assessment of Calcified Aortic Valve Leaflet Deformations and Blood Flow Dynamics Using Fluid-Structure Interaction Modeling. *Informatics in Medicine Unlocked*, 9, 191–199. https://doi.org/10.1016/j.imu.2017.09.001.
- Otto and Prendergast **(2014).** Aortic-Valve Stenosis — From Patients at Risk to Severe Valve Obstruction. *New England Journal of Medicine*. https://doi.org/10.1056/NEJMra1313875.
- Ariane et al.**(2017).** Discrete Multi-Physics: A Mesh-Free Model of Blood Flow in Flexible Biological Valve Including Solid Aggregate Formation. *PLoS ONE*, 12 (4), e0174795. https://doi.org/10.1371/journal.pone.0174795.

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