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Fluid Structure Interaction Analysis of a Calcified Aortic Valve

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Abstract

The aim of this paper is to investigate the effect of calcification of the aortic-valve leaflets on the flow pattern and hemodynamic parameters such as transvalvular pressure gradient and valve orifice area based on fluid structure interaction modelling methodology using ANSYS. The geometry has been developed in ANSYS Workbench based on echocardiography images available in the literature. A pulsatile inlet velocity extracted from Doppler velocity measurement data in the literature has been used as an inlet boundary condition. For modelling the turbulent flow downstream of the leaflets, the k-ω SST turbulence model was used. For comparison, both healthy and calcified aortic valves were modelled and analysed. Results show that the transvalvular pressure gradient increases from 769 Pa for the healthy aortic valve to 2356 Pa for the calcified one. Furthermore, there is a significant decrease in the valve orifice diameter, from 13.5 mm for the healthy aortic valve leaflets to 9.21 mm for the calcified one. It was also shown that the wall shear stress on fibrosa and ventricular layers of the leaflets are significantly changed as a result of change in the thickness and material properties of the leaflets. Averaged wall shear stress on the ventricular surface increases from 16.3 Pa for the healthy case to 23.8 Pa for the calcified aortic valve. For the fibrosa surface, it decreases from 3.42 Pa for the healthy leaflets to 1.53 Pa for the calcified one.

Introduction

The aortic valve is a unidirectional valve located between the left ventricle and aorta. It opens during the ventricular systole allowing the oxygenated blood to be pumped from the heart to pass through the aortic valve and enter the aorta. At the ventricular diastole, when the valve closes it prevents blood from flowing back to the heart. The calcification of the aortic-valve leaflets is one the most prevalent diseases particularly among adults over 65 years old [2]. The calcification prevents the aortic valve leaflets from opening and closing appropriately, resulting in aortic valve stenosis. The stenotic aortic valve increases the velocity of the blood in the valve orifice and results in an increased transvalvular pressure gradient and accordingly higher heart attack risk [1].

Doppler echocardiography is the most common diagnostic method for detection of aortic valve stenosis via measuring the jet velocity, effective orifice area (EOA) and transvalvular pressure gradient (TPG). However, determining the TPG and EOA via echocardiography has associated significant errors due to the assumed constant axial velocity along the jet orifice area [2]. Computational fluid dynamic (CFD) models generated from medical images are an alternative, and can provide detailed information on the fluid flow parameters. Using this information enables engineers to calculate the hemodynamic parameters such as TPG and valve orifice area (VOA) and accordingly diagnose aortic valve stenosis. Various studies have investigated the blood flow pattern and determined the hemodynamic forces on the valve leaflets during the systolic phase [4-5]. The effect of fluid flow on dynamical motion of the leaflets has also received attention, recently. A 3D aortic valve model has been presented by Weinberg et al. [4]. They have investigated the influence of the calcification on the dynamical motion of the aortic-valve leaflet using LS-Dyna. According to their results, there is a relation between the valve calcification and aging. Halevi et al. [5] studied the effect of calcification on valve orifice area via CFD. They used individual patient MRI images to generate 3D models of the aortic valve. They utilised ABAQUS to analyse the dynamical motion of the leaflets. They showed that the valve orifice area decreases with calcium deposits present on the leaflets. The effect of leaflet movement on the fluid flow has been neglected in these studies.

To investigate the complex dynamic motion of the aortic valve leaflets, taking into account the interaction between the blood flow and the movement of the leaflets, the fluid structure interaction (FSI) approach was applied by De Hart et al [6]. In a more recent study by Halevi et al. [7], the influence of calcification on the hemodynamics of the aortic valve using 3D FSI models was reported. They used ABAQUS for modelling the structural part and Flow Vision for simulating the fluid part. Fedele et al. [3] implemented an analytical FSI modelling approach using moving resistive immersed implicit surfaces. The same FSI approach was used to investigate the aortic valve dynamics. In another work, Vahidkhah et al. [8] investigated the formation of blood stasis on prosthetic aortic valves using a 3D FSI mathematical model. As an alternative approach to mathematical modelling, Amindari et al. [9] utilised ANSYS for modelling a 2D aortic valve. They demonstrated the effect of calcification on TPG and VOA due to changing material properties of the valve leaflets.

Studies show that, in addition to changes in properties, calcification increases the thickness of the leaflets. Although the effect of changes in material properties has been investigated in the aforementioned studies, to the best knowledge of the authors, the effect of change in thickness has not been well studied. In this study, the effect of calcification on the hemodynamic parameters of the aortic valve has been investigated taking into account both changes in the thickness and material properties of the leaflets. Using echocardiography images available in the literature [9], a 2D model of the aortic valve has been generated in ANSYS Workbench 18.2. ANSYS FLUENT and ANSYS MECHANICAL APDL were selected to solve the fluid and structural part, respectively. The System Coupling FSI Module in ANSYS Workbench was used to link the fluid and structure fields. The combined effect of the changes in the thickness and material properties of the aortic valve leaflets due to the calcium deposition on the hemodynamic parameters has been investigated.

Numerical Modelling

Figure 1 shows a two-dimensional model of the aortic valve, aortic root, sinuses, and leaflets implemented in ANSYS Workbench 18.2 from echocardiography images available in the literature [9]. To apply FSI in the simulation, the model is divided into three sections: fluid domain, structure domain, and FSI surfaces. In the fluid domain (Figure 1) the blood is assumed incompressible and Newtonian with a constant density and viscosity of 1060 kg/m^3 and 0.0035578 J/s, respectively [9-10]. A velocity inlet boundary condition is defined at the inlet of the aortic valve. The velocity inlet has a pulsatile profile as measured by LaDisa et al. [10] using

Doppler technique (Figure 2). The outlet boundary condition is considered as a pressure outlet. An unstructured mesh was used in the fluid domain based on sweep method, with 9952 prism elements and maximum skewness of 0.52 (as shown in Figure. 3).

The structure domain comprises flexible valve leaflets and aortic walls. The aortic walls (as shown in Figure 1) are considered rigid for simplicity. The joint between the flexible valve leaflets and aortic wall is defined as a fixed support.

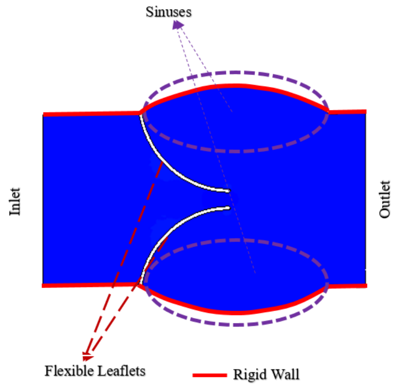

Figure 1. Schematic view of the aortic root with flexible leaflets, inlet, outlet and sinuses, and aortic wall

The material properties of the leaflets are assumed to be isotropic and elastic with a density of l050 kg/m^3 and a Young modulus of E=2 MPa for the healthy aortic valve leaflets and E=10 MPa for the calcified one [11-12]. The Poisson's ratio of the leaflet is assumed as 0.3 [9]. For the structure domain a total of 120 tetrahedral elements with a maximum skewness of 0.43 are used. The blood forces the leaflets to move inside the fluid domain. The surfaces between the blood and leaflets are hence defined as fluid structure interaction surfaces.

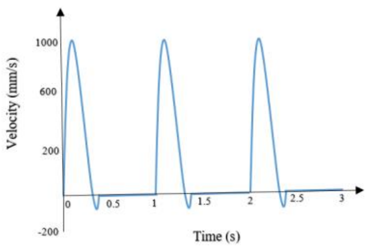

Figure 2 Inlet transient velocity profile applied to the inlet surface of the model (only a single cycle is considered in this paper)

Due to the application of the pulsatile velocity profile at the inlet of the aortic valve it is expected to exhibit turbulent flow downstream of the leaflets at peak systole at the maximum Reynolds number of around 4766. Hence, to obtain reliable results taking into account the separation and circulatory flow behind the leaflets, the k-ω SST turbulence model was utilised. Due to the limitation of the 1-way uncoupled approach in FSI simulation of highly coupled fluid and structure domains, in particular when it is applied to flexible biological tissues [13], a 2-way coupled implicit approach is used to analyse the fluid structure interaction simulation of the aortic-valve leaflets.

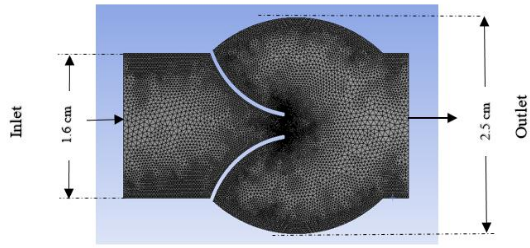

Figure 3 Schematic view of the fluid domain mesh and accompanying boundary conditions

Validation of the Model

To validate the model, the maximum jet velocity, transvalvular pressure gradient, and valve orifice area at peak systole of healthy and calcified leaflets are compared with the published data of Amindari et al. [9].

Table.1 Maximum jet velocity, valve orifice area, transvalvular pressure gradient for healthy and calcified models

Aortic valve	TPG (Pa)	VOA (mm)	MJV (m/s)
Healthy (thickness=0.6mm, E=2 MPa)	769 (633[9])	13.5 (14[9])	1.59 (1.57[9])
Calcified (thickness=1mm, E=2MPa)	1854	10.8	1.92
Calcified (thickness=1mm, E=10MPa)	2356	9.21	2.32

Results and Discussion

The velocity contours for a healthy aortic valve during the systolic phase are shown in Figure 4. As shown in Figure 4, for the healthy aortic valve, the velocity reaches the maximum velocity jet flow (V=1.59 m/s) at the valve orifice during the systole. Near the ventricularis surface of the aortic valve leaflets at peak systole, the velocity profile is significantly increased (shown with arrows in Figure 5) while inside the jet orifice area the velocity contours do not change significantly. As a result, the velocity gradient near the ventricularis surface causes the high wall shear stress (WSS) on these surfaces. The WSS difference between the ventricularis and fibrosa layers of leaflets is one of the main reason for calcification of the aortic valve leaflets [9].

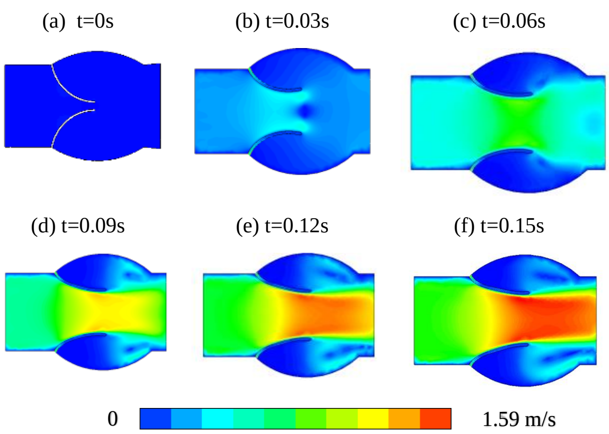

Figure 4 Velocity contours of the healthy aortic valve during cardiac cycle

Moreover, the circulatory flow is created behind the sinuses because of the complex geometry and flow separation on the leaflet tips. The generated vortices in the upper sinuses rotate clock wise whilst the one in the lower sinuses rotates in the opposite direction.

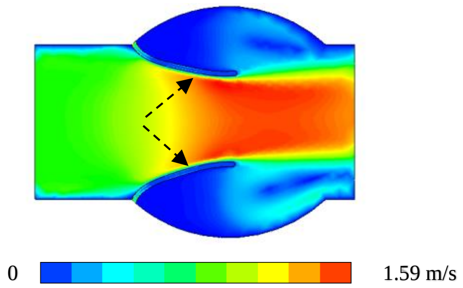

Figure 5 Velocity contour of the healthy aortic valve at t= 0.15s; arrows show a significant increase in the velocity near ventricularies layer

The velocity streamlines of the healthy aortic valve with Youngs modulus E=2MPa is depicted in Figure 6 during the cardiac cycle. The vortices are created behind the sinuses because of the flow separation at the tip of the leaflets. As seen, the vortices move from behind the sinuses at peak systole toward the end of sinuses at the end of systole and grow during the systolic phase. Moreover, the shape and location of the vortices are affected by the opening angle of the leaflets and the parameters of the flow during the cardiac cycle.

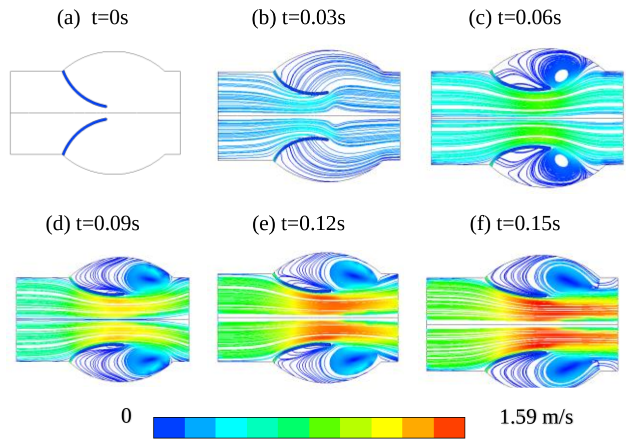

Figure 6 Velocity streamlines of the model of the healthy aortic valve during systole phase

Figure 7 shows the velocity streamlines of the model during the diastole phases. As seen, the vortices become larger downstream of the leaflets (shown with black arrows) and start disappearing during the diastole phases. The flexible leaflets start oscillating during the diastole phases because of the pressure difference between the left ventricle and aorta. At the same time, because of the oscillation of the leaflets, two other vortices are created and become larger on the rear of the sinuses (shown with red arrows). At the end of diastole at t= 0.27 and t= 0.35, two different vortices, one with smaller size behind the leaflets (in ventricularis surfaces) and another with larger size (near the outlet) are created, respectively (shown with blue arrows).

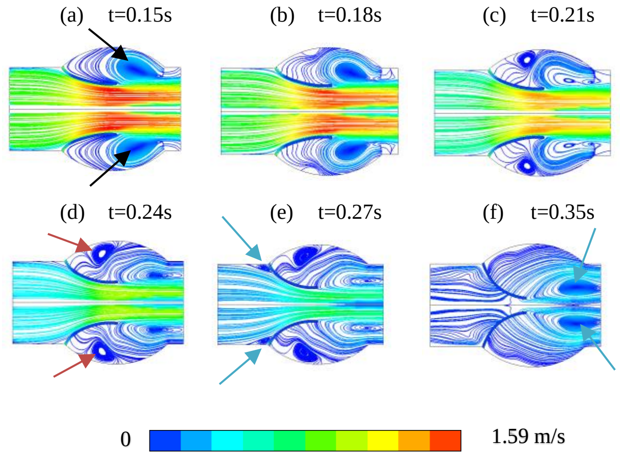

Figure 7 Velocity streamlines of the model during diastole phase

Figure 8 depicts the velocity streamlines for healthy (Figure 8a) and calcified (Figure 8b and 8c) aortic valve leaflets. As explained, because of calcium deposition on the leaflets over time, they thicken and stiffen. The effect of the calcification on the valve orifice diameter is represented in Figures 8 (b) and (c). As seen, the thickened leaflets (Figure 8 (b)) have smaller valve orifice diameter (10.8 mm) in comparison with the healthy one 13.5 mm. Calcium deposition not only changes the thickness of the aortic valve leaflets, but also increases the elastic modulus of the leaflets. For the calcified aortic valve with higher thickness and Youngs modulus (thickness=1mm, E=10MPa), the valve orifice diameter is the smallest one at 9.21 mm. Furthermore, the shape, location, and strength of the vortices for the calcified leaflets differ to the healthy one.

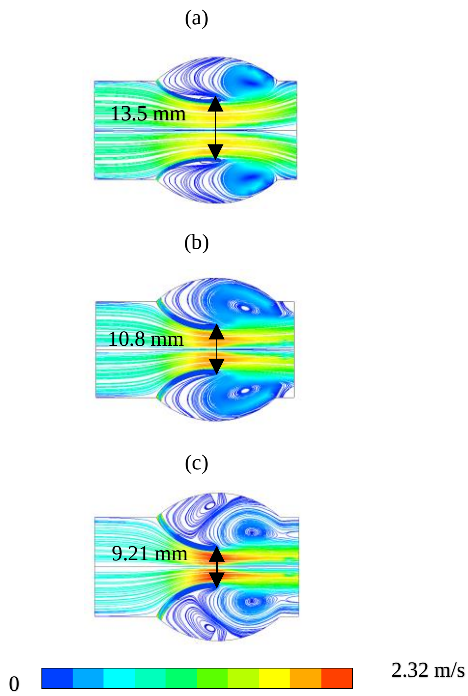

Figure 8 Velocity streamlines at peak systole for **(a)** healthy (E=2MPa, thickness=0.6mm), **(b)** calcified (E=2MPa, thickness= 1mm), **(c)** (E=10MPa, thikness=1mm)

As shown in Figure 8, the size of the vortices for the calcified aortic valve are bigger than those of the healthy one. The fluid flow for the healthy aortic valve near the annulus and behind the sinuses are stronger than calcified ones. This shows that calcification changes the shape of the flow behind the sinuses particularly along the base of the leaflets. Furthermore, the calcification changes the transvalvular pressure gradient. As shown in Figure 9, the TPG for the healthy valve is around 769 Pa, while for the calcified aortic valve with higher thickness is around 1854 Pa, and for the stiffened one is 2356 Pa, respectively.

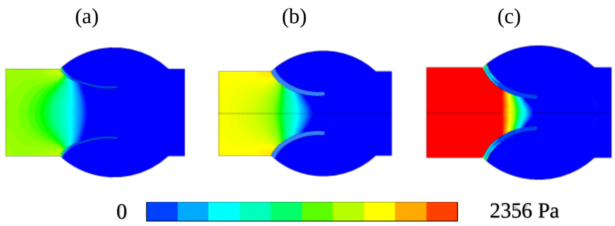

Figure 9 Pressure contours of the healthy and calcified models of the aortic valve at peak systole

Conclusion

In this study the influence of calcification of the aortic-valve leaflets on the hemodynamic parameters such as TPG, VOA, and flow pattern have been investigated via FSI simulation.

The velocity contours and streamlines for healthy and calcified aortic valves have been demonstrated during cardiac cycle. Simulation results reveal that valve orifice diameter decreases from 13.5 mm (opening ratio of 84%) for the healthy valve to 9.21 mm (opening ratio of 48%) for the calcified one because of the calcification. The TPG at the peak systole increases from 769 Pa for the healthy aortic valve to 2356 Pa for the calcified one. Furthermore, the size and location of the vortices have changed in the calcified aortic valve. The size of the vortices of the calcified valve are observed to be bigger compared to the healthy one.

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