Modeling and Mechanobiology of the Mitral Valve

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Abstract. In this study, we have used a fluid structure interaction to model the blood flow in the mitral valve and its leaflets. Using CT images, we have made a real geometry of the mitral valve, and SolidWorks was used to make the model. The real boundary conditions were used, and the diastolic phase of the heart was modeled for 0.5 seconds. The hyper elastic material properties were used both for the left ventricle and the mitral. ANSYS software was used to perform numerical simulations. The hemodynamic parameters, including blood velocity, pressure, and shear stresses, were analyzed. The results obtained were compared to the existing literature. The displacements and strain of the left ventricle tissue were also studied.

Keywords: Mitral; simulation; mechanobiology; velocity; pressure; stress; strain

1. INTRODUCTION

The heart has four valves, including the mitral valve. This valve is between the left atrium and ventricle. The low-pressure blood flows from the left atrium to the left ventricle, and there is no backflow when the pressure of the left ventricle increases during the pumping of blood in the cardiovascular system. The valve has an annulus, two asymmetrical leaflets, and a chordal rope that connects the leaflets to the left ventricular wall. There are many numerical simulations for modeling the function of the mitral valve, as stated below:

Collia et al., 2022 used a computational fluid dynamics study to investigate mitral regurgitation. They also introduced a simplified model for mitral valve modeling to investigate the clinical relevance of left ventricular function using fluid dynamics [Collia et. al. 2019]. Meschinie et al., investigated the effects of natural and prosthetic mitral valves on the flow structure in healthy and abnormal left ventricles. In another attempt, Miller et al [4] studied prolapse of the mitral valve with mild mitral regurgitation. Finally, Meschini et al., investigated the effects of mitral muscles on the flow in the left heart ventricle. In this study, we have used the fluid-structure interaction method (FSI) to obtain the hemodynamic parameters of blood flow during mitral valve opening and closure by ANSYS software and a patient-specific model.

2. MATERIALS AND METHODS

The mitral geometry is patient-specific, where the CT scans of ten adults with a normal mitral valve geometry were extracted. The sample was a 45-year-old male. The model of the valve was shown in Fig.1. Different dimensional indices were calculated for each leaflet, including leaflet length, width, thickness, and curvature radius. The final dimensions were chosen by consulting a cardiologist, thus, all the dimensions needed to create the finite element model are mentioned in the table. The mitral valve has two identical leaflets, and the model was built using CATIA V5R21. Tissues were assumed hyper elastic and anisotropic with large deformations, as the alignment of the collagen fibres in the leaflet tissue showed an anisotropic response to stress-strain. Simulations were performed by the software ANSYS using a staggered Cartesian grid as shown in Fig.2. We have simulated the model for cardiac cycles at 0.8 s. The fluid density and viscosity were assumed to be 1050 kg/m3 and 0.04 Poise, respectively [Prot V et. al.]. The tissue module of elasticity was assumed to be 1.5 MPa with a

Poisson's ratio of 0.4 [Prot V et. al.]. The meshing was conducted using shell elements. We applied a time-dependent physiologic pressure curve to the leaflets over the whole cardiac cycle. The contraction of the annulus was modelled using nodal displacements applied to the nodes belonging to the annulus from the maximum area to the minimum. Moreover, the motion of the papillary muscles was fixed and not considered, and the edge of each leaflet was free for displacement. The friction coefficient between the leaflets was assumed equal to 0.05. Our aims were to develop a 3D model of the mitral valve using fluid–structure interactions to study the normal function of the valve by noting the relation between the leaflets and blood flow. We used ANSYS for all numerical simulations to show the outcomes of the presented complex model.

3. RESULTS AND DISCUSSIONS

Fig.3 shows the velocity streamlines of the blood flow, and Fig.4 shows the pressure distribution contour at t=0.8s. The maximum velocity occurs at 0.8 s in diastole when the maximum flow rate passes from the mitral. The difference between the inlet of the mitral and its outlet (entering to aorta) is shown in Fig.5. The pressure of the inlet flow to the mitral is greater than that of the outlet to allow blood flow to the aortic valve. Ejection fraction is one of the important parameters that presents the performance of the myocardium. It also demonstrates the efficiency of the heart. It refers to the volume of blood that has been ejected to the left ventricle at the end of diastole. The difference between the end of systolic and diastolic volumes refers to stroke volume. We have calculated the ejection fraction from our model using the following relation:

$$E_f = \frac{SV}{EDV} = \frac{EDV - ESV}{EDV} \times 100 \quad (1)$$

Where EDV refers to end diastolic volume, ESV to end systolic volume, and SV to stroke volume. We obtained the following values:

$$EDV = 138.68\, ml$$
$$ESV = 62.19\, ml$$
$$SV = 76.49\, ml$$
$$EF = 55.53\%\, ml$$

The normal physiological range of ejection fraction is 55-70 % [Cheng et. al.]. Another calculated factor is the cardiac output. The cardiac output is the total volume of blood that is ejected to the aorta by the left ventricle in each heart cycle. The normal range of the cardiac output is between 4 to 8 liters/min. We used the following relation to calculate the cardiac output:

Cardiac output=Stroke volume * heart rate

For a normal person whose heart rate is 75 beats per minute for 0.8 s, the cardiac output is 5.74 liters/min. We have also calculated the maximum stress in mitral leaflets equal to 1.6 MPa at the end of the time. Furthermore, we found out that the strain ranges are in good agreement with Morganti *et al*., who employed a nonlinear hyperplastic material to present the mechanical properties of the mitral leaflet. Our predicted results should be discussed as well as there are many factors that are considered for applying these findings to clinical applications. In our model, we have considered a linear elastic material property for the leaflets and their muscles. But experiments have shown that mitral leaflets are not linear. We will consider this limitation in our future studies.

4. CONCLUSIONS

In this study, we introduced a three-dimensional model to study the hemodynamic parameters of blood passing through the mitral. We made a geometry and applied the inlet pressure variation to it during a cardiac cycle. The results can be used by the medical and biomechanical experts regarding the variation of velocity and pressure in the mitral valve leaflets during the function of the mitral valve.

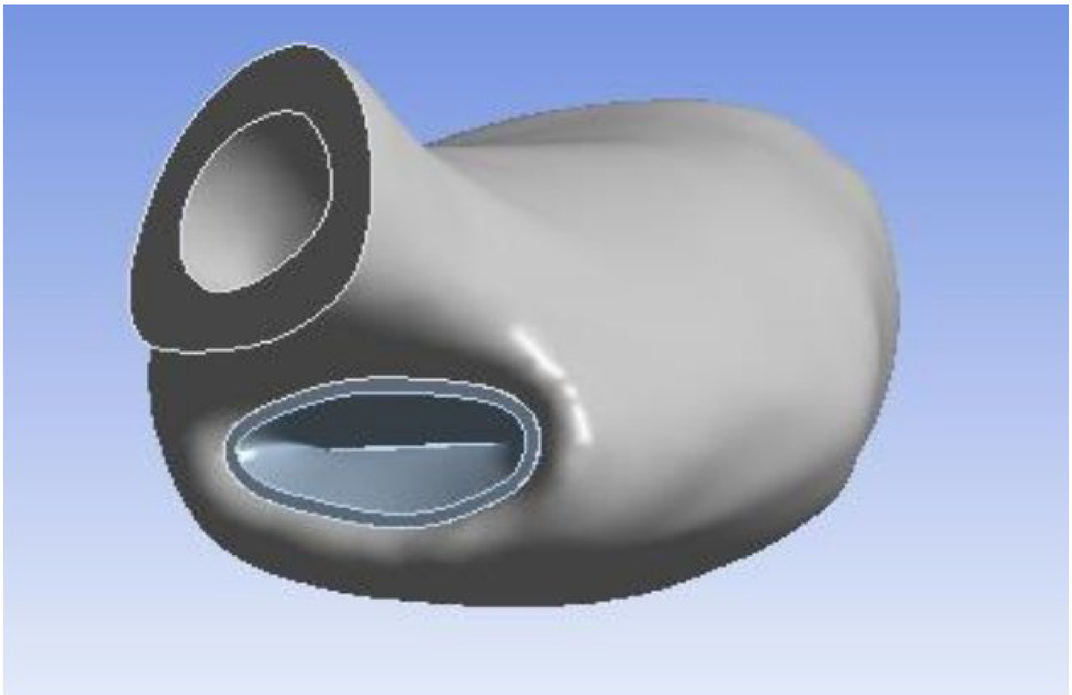

Fig.1 The geometry of mitral valve and left ventricle.

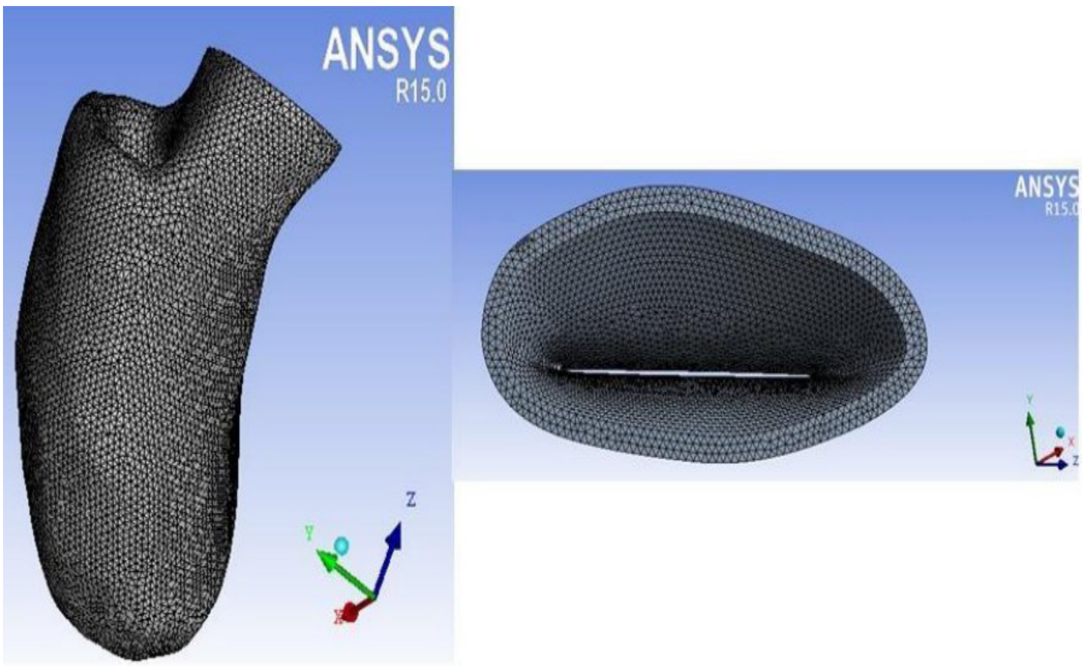

Fig.2 The mesh of the model.

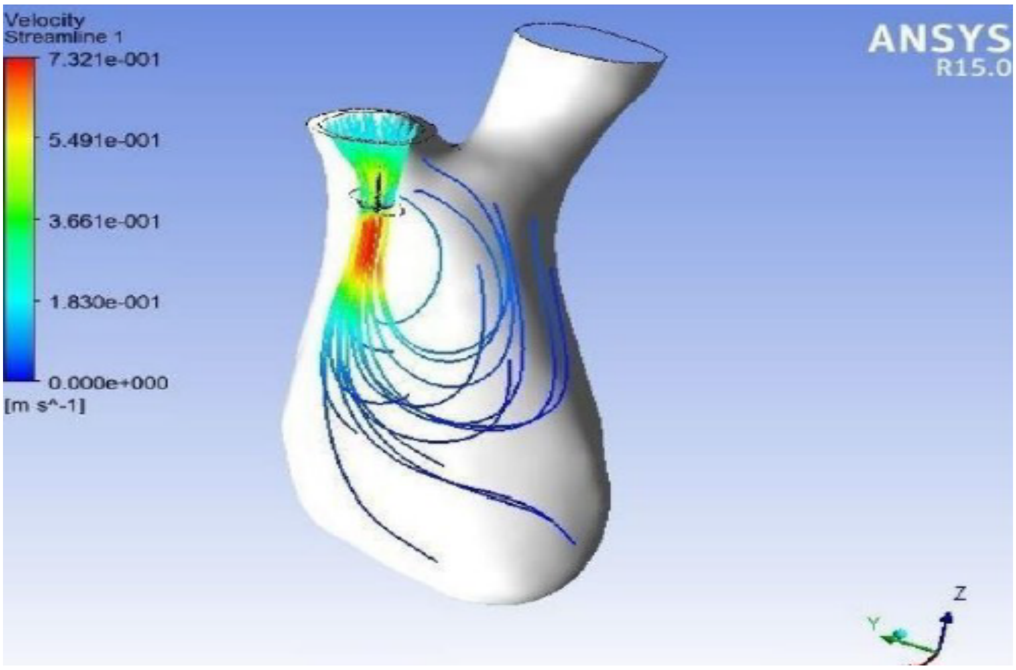

Fig.3 The velocity streamlines

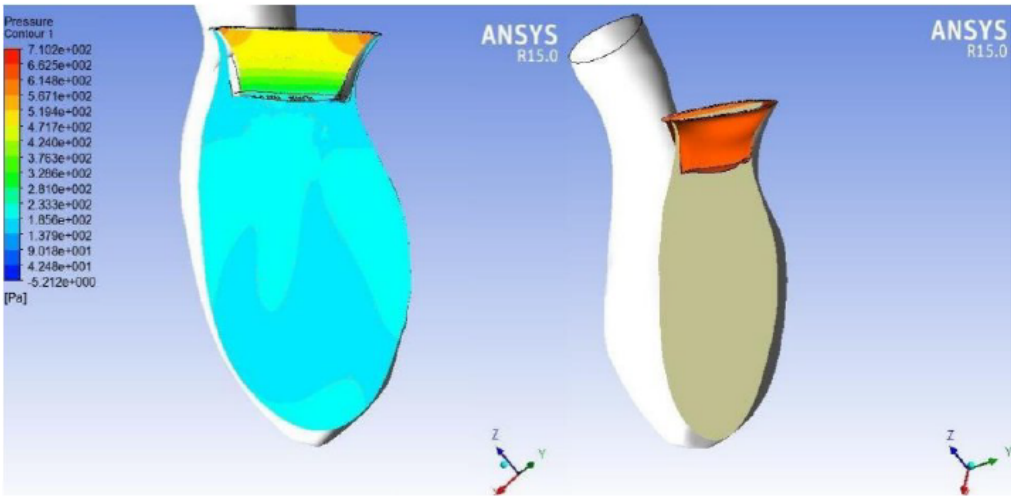

Fig.4 The pressure distribution in mitral and left ventricle.

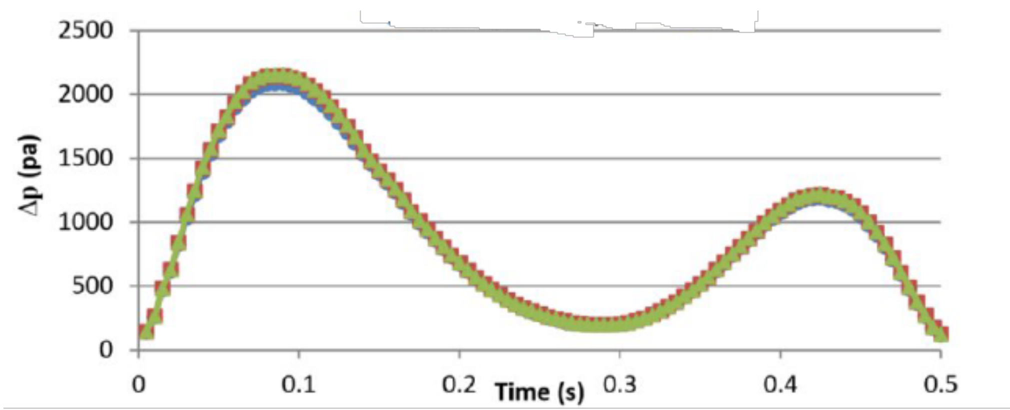

Fig.5 The difference in pressure between the inlet and outlet of the mitral.

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