Computational Simulation of Heart Valve Leaflet under Systole Condition using Fluid Structure Interaction Model

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Abstract. Recorded about two million people worldwide have heart problems everyday. One was due to heart valve disease. The objectives of this study are to simulate the stress distribution and analyze the rigidity of heart valve leaflet during systole condition. Two-dimensional model of the heart valve were created in ADINA-Fluid Structure Interaction for computational simulations. The result shows rigidity of heart valve leaflet always opposite to degeneration and the simulated show stress distribution in this model corresponded to normal distribution in physical heart valve in systole condition. The conclusion is modeling simulation techniques are very useful in the study of degenerative valve disease and the findings would allow us to optimize feature and geometries to reduced stresses and rigidity of heart valve failure.

Keywords: Heart Valve Leaflet, Fluid Structure Interaction, Systole, Degeneration.

1. Introduction

Heart valve is one of the most important organ in the operation of the movement of blood flow and oxygen in the heart but there are some problems in the heart valve and can only are restored by the replacement and repair techniques. Successful heart valve repair is dependent upon a full understanding of normal and abnormal heart valve anatomy and function. Computational simulation is one such method that can be applied to simulate heart valve function in order to analyze the roles of individual components and evaluate proposed surgical repair. The real prolapsed portion of the anterior heart valve leaflet show in Fig. 1. Therefore, a fluid-structure interaction (FSI) model of the heart valve has been generated. The heart valve is present in the left side of the heart and functions normally to allow blood to flow into the left ventricle of the heart when it is filling. This valve then closes when blood is pumped out from the heart towards the body. In doing so, it prevents the regurgitation of fluid. Several Finite Element (FE) models of the heart valve have been developed however there are fewer that account for the effect of fluid flow through the valve [5;1]. Before this, only one FSI model of an actual heart valve with two leaflets has been developed [2]. The FSI model of the heart valve we are developing includes the walls of the left ventricle of the heart, both anterior and posterior leaflets of the valve.

2. Method

Using ADINA-FSI, a two-dimensional model of heart valve within the heart was generated shown in Fig. 2. Fluid dynamics and structural deformation are determined simultaneously. In fluid model, blood is not strictly a fluid but rather a suspension of particles. The red blood cells which constitute almost half of the volume of the total blood are the main responsible for a complex mechanical behavior. The blood viscosity increases when the deformation rate decreases because the red blood cells tend to aggregate. In the small vessels, the blood viscosity decreases when the vessel radius decreases because red blood cells move to the central part of the vessel. The elasticity of the red blood cells is also responsible for viscoelastic effects in the blood and these effects are important in small vessels or at low deformation rates. In this study, we only consider large vessels. The fluid will be therefore assumed to be Newtonian. Blood pressure will give the effect to deformation of heart valve structure. Lagrange multipliers have been used to apply the pressure exerted on the deforming structure due to the flow of fluid as has been done for other heart valve FSI simulations. To allow FSI simulations to be performed, ALE mesh was used.

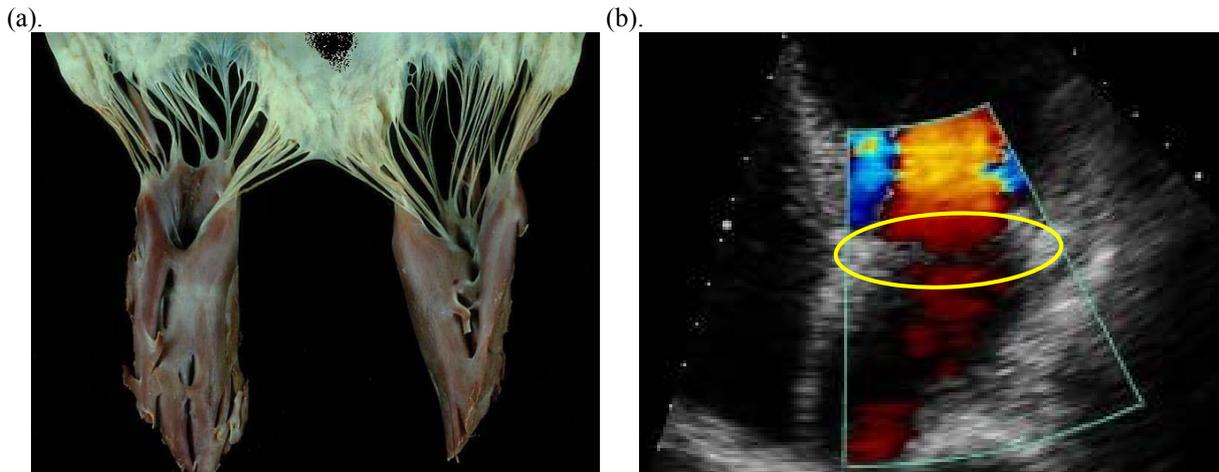(a).   (b).

Fig. 1 : a). Prolapsed portion of the anterior heart valve leaflet ;

b). Image of heart valve leaflet in echocardiogram collected by a transthoracic transducer.

2.1. Geometry and Parameters

To produce the best geometry to model heart valve, the method of measurement has been identified. The viscosity of blood and the elastic properties of the valve leaflets were obtained from the literature [3] show in Table 1. A simple approximation of the heart was made as being elliptical in shape. The dimensions of the valve leaflets were based on measurements made and approximately. A geometrically more accurate model has also been generated that matches a study in which measurements of pressure, flow and flow patterns were used to quantitatively validate the prediction of the model for inflow during valve opening.

Table 1: Parameters of heart valve

Parameter	Value
Diastolic Pressure, *mmHg*	82
Systolic Pressure, *mmHg*	132
Normal Heart Valve Thickness, *mm*	3.5 +/- 0.8
Heart Valve Leaflet density, *kg/m³*	1.06×10^3
Anterior leaflet Young's modulus, *MPa*	2.0×10^6
Blood density, *kg/m³*	1.06×10^3
Blood viscosity, *Pa.s*	2.70×10^{-3}
Posterior leaflet Young's modulus, *MPa*	1.0×10^6
Leaflet Poisson's ratio	0.49

2.2. Boundary Condition

In identifying the boundary condition in blood flow, the composition of the normal blood pressure in the cardiovascular system is very important because the stability measurement of the rigidity of the heart valves leaflet depends on the pressure exerted at a certain time. Blood inflow boundary conditions through heart valve were applied to simulate valve opening and closure during systole. During systole, ventricular pressure was applied from the apex of the heart and outflow boundary conditions were applied at the valve outlet.
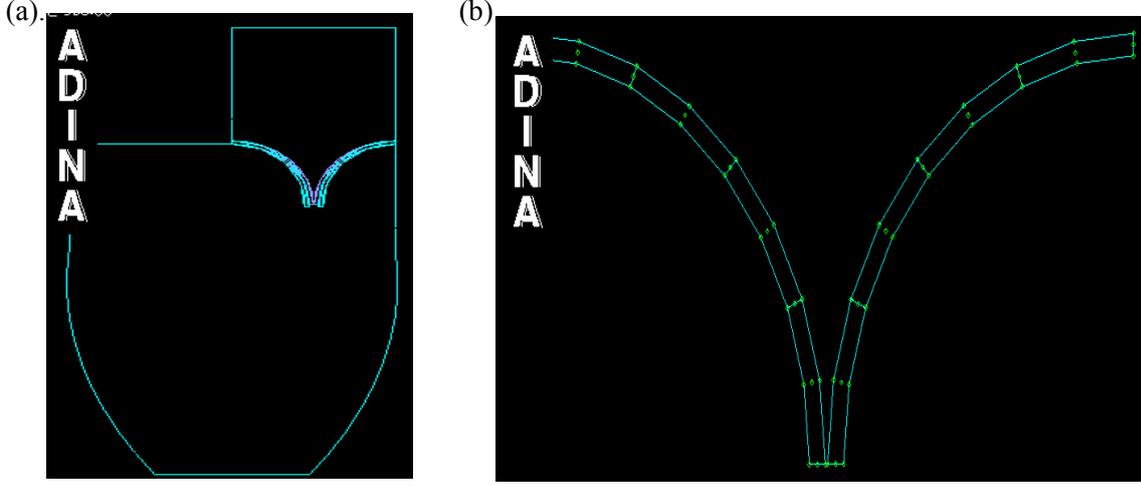
(a).   (b)

Fig. 2 : Model of left ventricle geometry used. a). Modelling of 2D elliptical heart valve model ;

b). 2D model of two heart valve leaflet

2.3. Contact Simulation

It is generally admitted that turbulence is not present in the cardiovascular system in physiological situations. In this work for simplicity, we will suppose that the flows are laminar. In conclusion, the fluid will be governed by the classical incompressible Navier-Stokes equations show in equation 1. Where u is the fluid velocity, ρ the fluid density and fluid domain Ω_F is a priori time dependent because of the movement of the vessel walls and the valves.

$$\left\{\rho\left(\frac{\partial u}{\partial t}+u.\nabla u\right)-div(\sigma)=0\right\} \quad \text{for } x \in \Omega_F(t)$$

$$\left\{\rho\left(\frac{\partial u}{\partial t}+u.\nabla u\right)-div(u)=0\right\} \quad \text{for } x \in \Omega_F(t) \tag{1}$$

In FSI, the relationship between fluid and structure is relevant because there are elements that allow continuous interactions between blood pressure and the rigidity of heart valve leaflet. Between the boundaries of the two heart valve leaflets, the valve closure was simulated using contact equations. Integration coupling variables were used to allow information regarding the position of the contacting boundaries available to each other all along the boundary of the leaflets. The distance between nodes of one boundary on one leaflet and the whole boundary on the other leaflet was applied to equation 2.

$$F=\begin{cases} Pe^{-gk/P} & g>0 \\ P-gk & g \leq 0 \end{cases} \tag{2}$$

The two contacting boundaries were separated into small segments with nodes at the end of each small segment. These contact forces were calculated at each node for both leaflet boundaries that came into contact. The force acting along the whole boundary was then determined by interpolation between the two nodes at the end of each boundary. It was assumed that the force in between two nodes would be continuous. In the sequel, force will typically be the hydrodynamic force and also take into account contact forces. In the rigid case, the fluid-structure interface is assumed to coincide with the structure domain.

3. Result and Discussion

Results from the models of heart valve leaflet using the contact equation are shown in Fig. 3. Reasonable agreement was obtained and the simulation predicted heart valve leaflet deformations during opening and closure in systole condition agreed with results from experiments in the literature [4] which stress distribution in this model corresponded to normal distribution in physical heart valve leaflet.

(a).
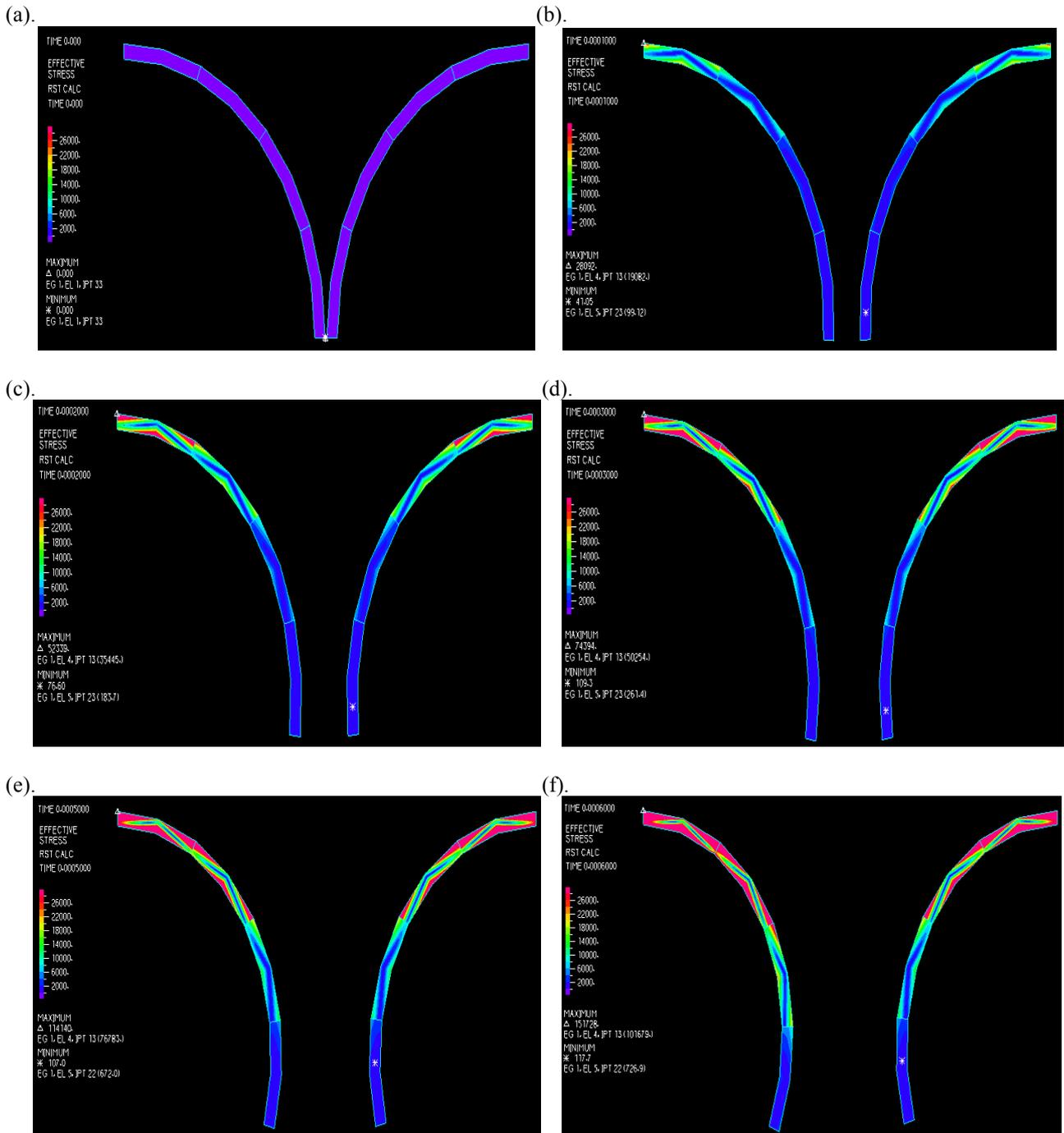
(b).

(c).

(d).

(e).

(f).

Fig. 3 : Simulated the stress distribution of heart valve leaflet during opening and closure, extract less than 10 second simulations under systolic pressure.

Fig. 4 shows the overall results for different cardiac cycle in systole and diastole condition. In general the graph shows opposite relationship between percentage of degeneration and rigidity of heart valve leaflet which the degeneration increasing, rigidity of the heart valve leaflet will be decreased. The plots for diastolic states push the level of degeneration to the higher limit, approximately 85 percent and the model during systolic states shows smaller degeneration as compared to the model during diastolic states. It could be

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caused by the pressure effect which the situation allows the model to confine more blood in the left ventricle hence less pressure development in the system and also caused by differences rigidity of heart valve leaflet. Then the results obtained from analysis by modeling simulation technique, it is a bit much to help doctors make decisions about how to treat patients suffering from HVP. Besides that, it can study the behavior of mitral valve leaflet when the output rate of degenerative through specific estimations.
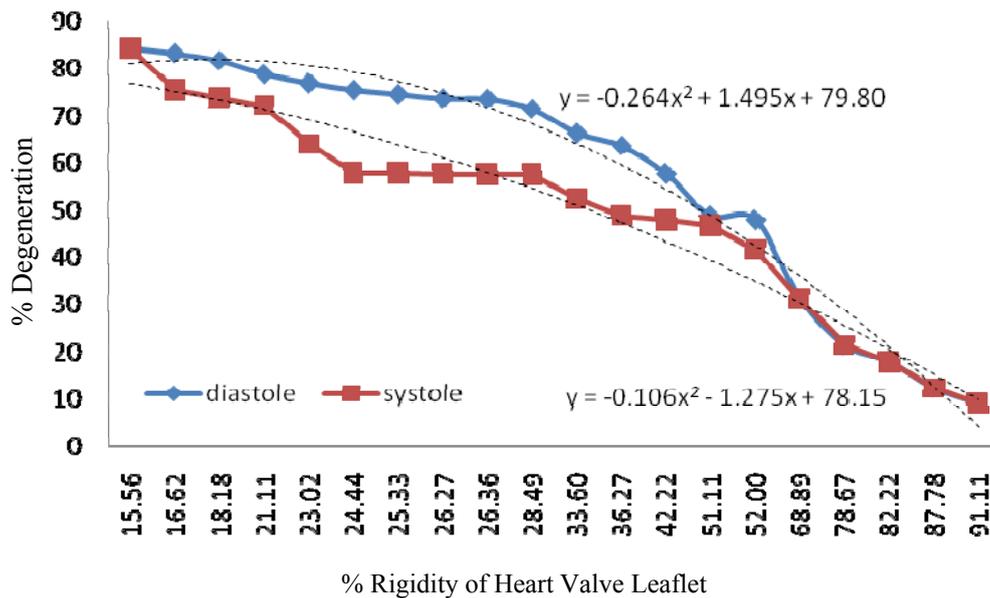

Fig. 4 : Validation result between persentage of degeneration vs. persentage of rigidity in systole and diastole condition.

4. Conclusion

Overall, the results from computational simulations agree with observations in the medical literature. The result shows rigidity of heart valve leaflet always opposite to degeneration and the simulated show stress distribution in this model corresponded to normal distribution in physical heart valve in systole condition and well with observation on previous literature. This model will be used in future to determine the rigidity of heart valve for helpful to medical practitioners in making better decisions on the treatments for their patients as they have additional diagnosis on the heart valves problem based on engineering analysis.

5. Acknowledgements

6. References

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