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PREDICTION OF BLOOD FLOW VELOCITY AND LEAFLET DEFORMATION VIA 2D MITRAL VALVE MODEL

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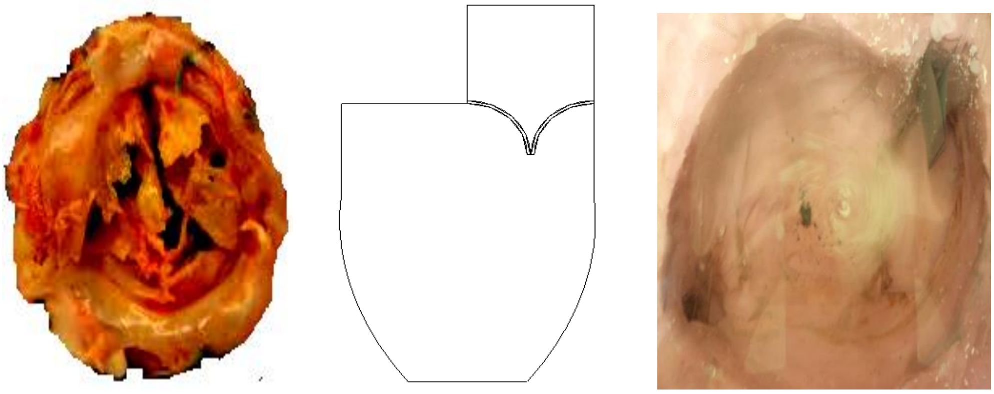
ABSTRACT

In the mitral valve, regional variations in structure and material properties combine to affect the biomechanics of the entire valve. From previous studies, we know that the mitral valve leaflet tissue is highly extensible. A two-dimensional model of the mitral valve was generated using an Arbitrary Lagrangian-Eulerian (ALE) mesh. A simple approximation of the heart geometry was used and the valve dimensions were based on actual measurements made. Valve opening and closure was simulated using contact equations. The objective of this study was to investigate and predict flow and leaflet phenomena via a simple 2D mitral valve model based on the critical parameter of blood. Two stages of mitral valves analysis were investigated: the systolic and diastolic stages. The results show a linear correlation between the mitral valve leaflet rigidity and the volume of backflow. Additionally, the simulation predicted mitral valve leaflet displacement during closure, which agreed with the results of our previous data analysis and the results for blood flow velocity during systole condition through the mitral valve outlet, as reported in the medical literature. In conclusion, these computational techniques are very useful in the study of both degenerative valve disease and failure of prostheses and will be further developed to investigate heart valve failure and subsequent surgical repair.

Keywords: Biomechanics, heart, systolic, diastolic, fluid structure interaction (FSI)

INTRODUCTION

In recent years, there has been a change in attitude towards mitral valve surgery. A trend has developed towards simplified and streamlined reconstruction techniques allowing for successful repairs of the mitral valve, rather than replacement with artificial prostheses. To repair the mitral valve is now considered the procedure of choice over valve replacement. Numerical simulation is one method that can be applied to simulate mitral valve function and evaluate any proposed surgical repair. Therefore, a fluid structure interaction model of the mitral valve has been generated to improve surgical repairs through developing an understanding of the correlation between backflow and mitral valve rigidity. Several numerical models of mitral valves have been developed but there are few that investigate backflow and the rigidity of the mitral valve, or that consider it with a ventricle model (Baccani, Domenichini, & Pedrizzetti, 2002). Figure 1 shows the model of mitral valve.



(a). (b). (c).

Figure 1**.** Model of Mitral Valve: a) Dissected specimen of the mitral valve with part of the heart muscle dissected; b) 2D elliptical model of mitral valve leaflet; c) Model of left ventricle heart through experiment.

Successful mitral valve repair is dependent upon a full understanding of the normal and abnormal mitral valve anatomy and function. The mitral 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 of the left ventricle around the body. In doing so, it prevents the back-circulation of fluid. Several Finite Element (FE) models of the mitral valve have been developed; however, there are few that account for the effect of fluid flow through the valve (Van Loon, Anderson, & Van De Vosse, 2006; Watton, Luo, Wang, Bernacca, Molloy, & Wheatley, 2006). Only one fluid structure interaction (FSI) model of an actual mitral valve with two leaflets has been developed (Einstein, Kunzelman, Reinhall, Nicosia, & Cochran, 2005). The developed FSI model of the mitral valve includes the walls of the left ventricle of the heart, both anterior and posterior leaflets of the valve and the outflow tract of the aorta. The main objective of this study is to investigate and predict flow and leaflet phenomena via a simple 2D mitral valve model based on the critical parameter of blood.

METHODS

Models of the mitral valve leaflet were created in ADINA-FSI for computational fluid dynamic analysis. 2D geometries of the mitral valve leaflet were created in ADINA with mesh. In ADINA, we will consider both a fluid and a structure model. In the fluid model, blood is not strictly a fluid but rather a suspension of particles. The blood viscosity increases when the deformation rate decreases because the red blood cells tend to aggregate (Watton et al., 2006). 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 (Einstein et al., 2005). In this study, we only consider large vessels and the fluid is assumed to exhibit Newtonian flow, shown in Eq. (1), where: μ is the dynamic viscosity, p is the pressure and v is the velocity.

$$p_{ij} = -p\partial_{ij} + \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\partial_{ij}\nabla.v\right) \quad (1)$$

In the structure model, a 2D FSI model of the mitral valve leaflet was generated using ADINA-FSI. Lagrange multipliers were 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 (De Hart, Peters, Schreurs, & Baaijens, 2003). Structural deformation and fluid dynamics are determined simultaneously. An Arbitrary Lagrangian-Eulerian (ALE) mesh was used to allow FSI simulations to be performed. The ALE formulation of an incompressible viscous fluid is shown as Eq. (2) (Chen, McCulloch, & May-Newman, 2004).

$$\rho\frac{d_m u}{dt} + \rho\left(u - \hat{u}\right)\nabla u = \nabla.T + f \quad (2)$$

where: μ is the dynamic viscosity, p is the pressure, T is the stress, $\hat{u}$ is the mesh velocity and u is the velocity. The properties of the blood and mitral valve leaflets are shown in Table 1 (Reul, Talukder, & Müller, 1980; Espino, Shepherd, Hukins, & Buchan, 2005).

Table 1. Parameters of blood and mitral valve.

Parameter	Value
Blood density, kg/m^3	1.06×10^3
Blood viscosity, Pa.s	2.70×10^{-3}
Diastolic Pressure, mmHg	82
Systolic Pressure, mmHg	132
Anterior leaflet Young's Modulus, MPa	2.0×10^6
Posterior leaflet Young's Modulus, MPa	1.0×10^6
Normal Mitral valve area, cm^2	4.0 – 5.0
Normal Mitral Valve Thickness, mm	3.5 +/- 0.8
Mitral Valve Leaflet density, kg/m^3	1.06×10^3
Leaflet Poisson's ratio	0.49

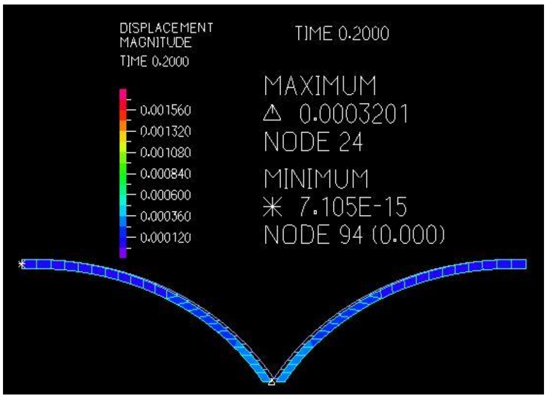
Boundary Conditions

The preliminary setup in the simulation was to determine the parameters of the blood and valve leaflets. During application of the diastolic and systolic condition to the mitral valve leaflets, a normal traction was enforced at the atrium side to create a pressure difference between the left ventricle and the atrium across the mitral valve. This will cause the condition of fluid flowing through the mitral valve to occur. In this paper, an Arbitrary Lagrangian-Eulerian (ALE) mesh was used during the setup in the simulation**.** De Hart et al. (2003) stated that to solve multidimensional problems, such as two-dimensional numerical simulation problems that involve fluid dynamics and nonlinear solid mechanics, it is always necessary to contend with strong distortions of the continuum under consideration, while allowing for a clear delineation of fluid-fluid, solid-solid, or fluid-structure interfaces. In the ALE explanation, the nodes in the computational mesh could be moved either with the continuum in normal Lagrangian fashion, or be held fixed in the Eulerian method. In the Lagrangian method, it can defined that each individual node in the computational mesh follows the associated material particle during movement, which usually apply in the structural mechanism. The disadvantage of the Lagrangian method is that it is unable to be applied during large distortions of the computational domain without redoing the meshing operations. Furthermore, the Eulerian method is widely applied in fluid dynamics where the mesh is fixed and the continuum moves with respect to the grid. It is different to the Lagrangian method in that it can handle large distortions in the continuum motion.

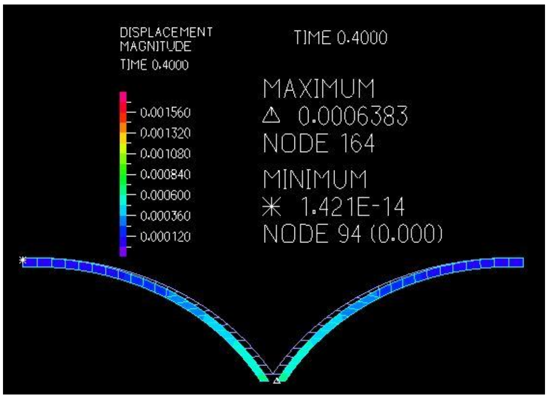
RESULTS AND DISCUSSION

Figure 2 represents the displacement changes of the mitral valve leaflet under deformation during the time period of 1 second. At the time instant of 0.2 seconds, which is shown in Figure 2(a), the displacement change is 0.5322 mm. In Figure 2(c), at the time instant of 0.6 seconds, the displacement change has increased to 1.452 mm. At 1.0 second, which is shown in Figure 2(e), the change of displacement has reached the maximum value of 2.346 mm. The displacement changes are illustrated through the changes in colours. The flow of blood causes the valve leaflets to deform in turn altering the flow of blood. Measurements were taken from specific points for a quantitative comparison with the results of published data (Reul et al., 1980). Reasonable agreement was obtained and the simulation predicted mitral valve leaflet deformations during closure, which agreed with results from experiments in the literature (Reul et al., 1980).

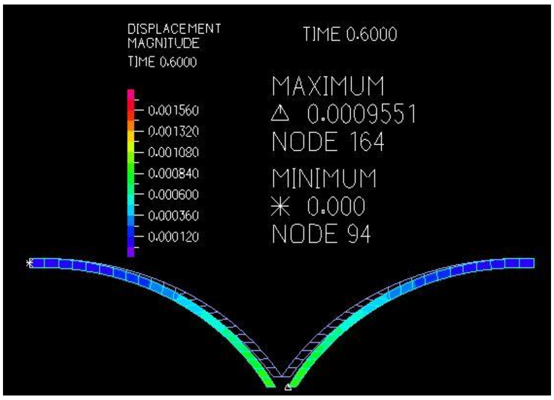
Figure 3 represents the change of blood velocity when flowing through the mitral valve leaflets for the duration of 1.0 second. From Figure 3(a), where the time instant is 0.2 seconds, the blood flow velocity is 13.8 mm/s. At the time instant of 0.6 seconds, shown in Figure 3(c), the velocity of blood flow is 59.78 mm/s. Figure 3(e) shows the highest velocity of the blood flow at 94.46 mm/s at the time instant of 1.0 second. The pressure applied to generate the blood flows can be determined from the background colour in the image. Different colours mean that the pressure between the left atrium and left ventricle is different. In the normal case, a smaller opening produces a higher fluid flow velocity because a higher pressure is applied. There are pressure changes on the fluid but no change in valve displacement during flow in the normal case. Therefore, it is not a normal case, where for a constant pressure, the obtained result shows that the value of velocity is dependent on time. Thus, the velocity results shown could be explained by using Newton's third law, where force is equal to the mass times the velocity of the motion. From this, the change of motion of the body is directly proportional to the motive force impressed upon it. In the fundamental pressure law, pressure is equal to the force divided by the surface area. The section area mentioned here is the cross sectional area of the blood flow during valve opening. A higher cross sectional area is related to behaviour that causes a greater change in leaflet displacement. Blood flow cross sectional area is directional proportional to the displacement changes of the leaflets. Higher displacement changes will lead a higher cross sectional surface area of blood flow. Given the condition of constant pressure and mass, we could make the conclusion that the change of blood velocity is related to the change of leaflet displacement. Hence, a wider leaflet opening will cause the fluid to flow with a higher velocity.



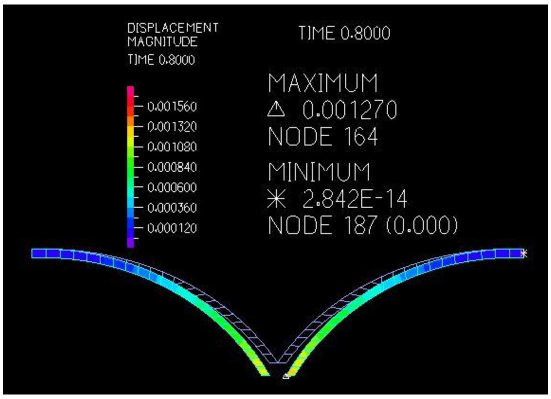
(a). 0.2 s



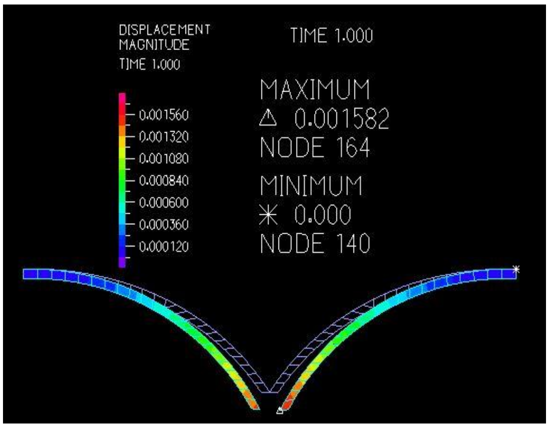
(b). 0.4 s



(c). 0.6 s



(d). 0.8 s



(e). 1.0 s

Figure 2. Simulated closure of mitral valve leaflet with application of pressure. Extract of a 1.0 second simulation showing the displacement magnitude.

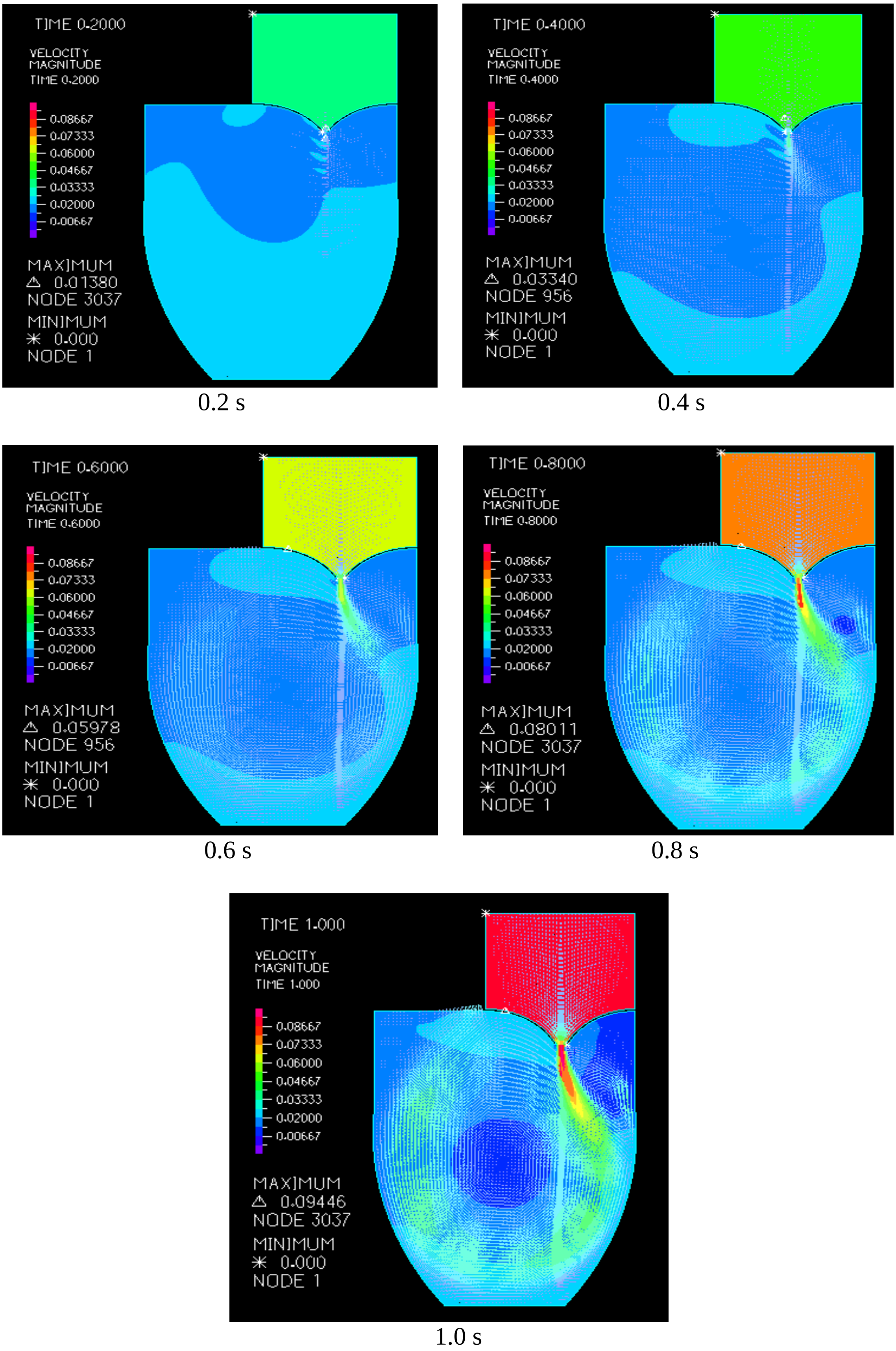
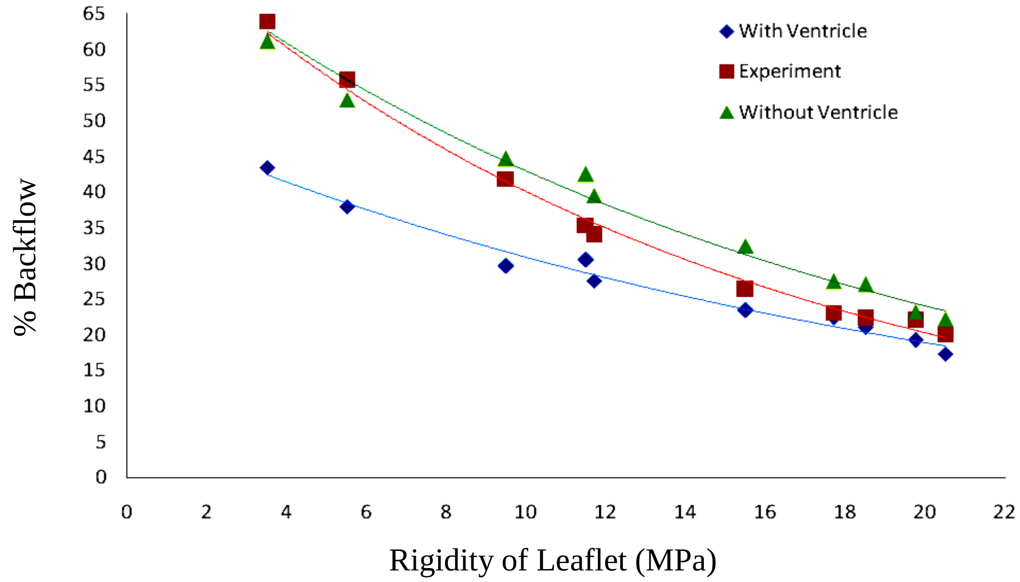
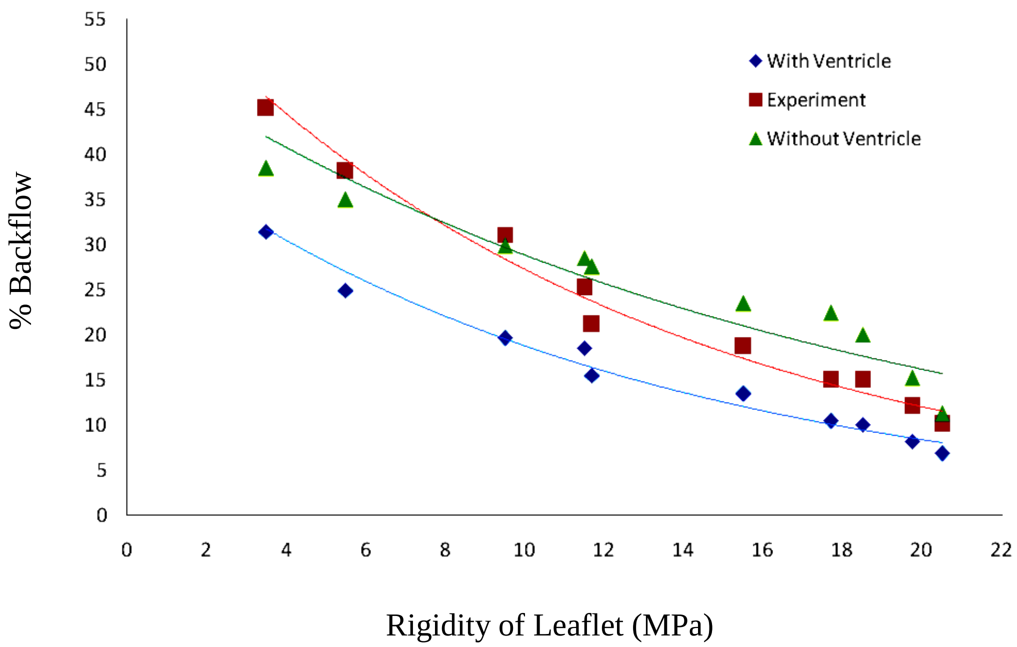


Figure 3. Simulated blood flow through mitral valve during systole condition. Extract of a 1.0 second simulation showing the velocity magnitude.

Figure 4 shows the variation of mitral valves rigidity. The graph shows bigger backflow volume for models without a ventricle. In general, the results show a linear relationship between the rigidity of the mitral valve leaflet and volume of backflow (Adib, Hasni, & Makson, 2011a). The plots for the systolic and diastolic states push the level of backflow volume to the higher limit, approximately 65% and 45%. The model with ventricle exhibits a smaller backflow volume compared with the model without a ventricle.



(a)



(b)

Figure 4. Variation of backflow against rigidity of mitral valve leaflet: (a) During systolic state and (b) During diastolic state.

There is more turbulence in the model with a ventricle than in the model without a ventricle. This is due to the curves in the model with ventricle, which do not exist in the model without a ventricle. In the simulation, the results of the percentage of backflow represent the severity of the mitral valve prolapse. This is demonstrated by the increase in the percentage of backflow as the condition of the mitral valves worsens (Adib, Osman, & Jong, 2011b). The predicted results assist medical practitioners in finding the approximation of the condition of the mitral valves, based on the backflow data obtained through an echocardiogram.

CONCLUSIONS

Two-dimensional model of a mitral valve with and without a ventricle wall were developed. Correlations between the backflow and heart valve condition were found to be linear between the two parameters. The backflow increases as the condition of the mitral valve deteriorates. On average, the difference in backflow is less than 10% between the two models for both systolic and diastolic states and various conditions of the mitral valve. The findings are actually predictions of the behaviour of the mitral valve leaflet in deformation stage and blood flow velocity under various conditions. This model will be used in the future to determine the rigidity of the mitral valve, in order to aid medical practitioners to make better decisions on the treatment for their patients, through additional diagnosis on the mitral valve problem based on an engineering analysis.

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