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

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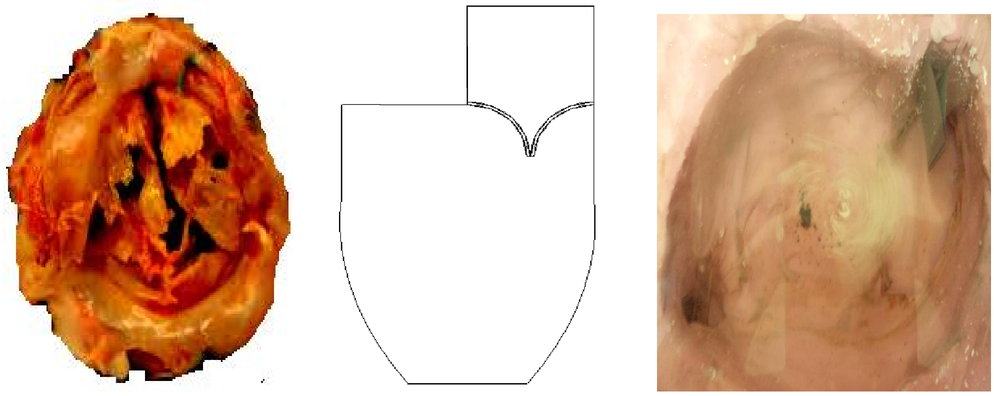
ABSTRACT

In the mitral valve, regional variations in structure and material properties combine to affect the biomechanics of the entire valve. Previous study, we know that 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 measurements made. Valve open and closure was simulated using contact equations. So, the objective of this study was to investigate and predict flow and leaflet phenomena via simple 2D mitral valve model based on critical parameter of blood. Two stages of mitral valves analysis systolic and diastolic stages were investigated. The results show linear correlation between rigidity of the mitral valves leaflet and volume of backflow. Also the simulation predicted mitral valve leaflet displacement during closure agreed with our previous data analysis results and the results for blood flow velocity during systole condition through the mitral valve outlet as reported in the medical literature. In conclusions, these computational techniques are very useful in the study of both degenerative valve disease and failure of prostheses and will be continue developed to investigate heart valve failure and subsequent with surgical repair.

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

INTRODUCTION

The experience of the last few years shows a change in concepts for mitral valve surgery. A trend toward simplified and streamlined reconstruction techniques allowing more often the successful repair of the mitral valve and not replacement with artificial prostheses observed. To repair the mitral valve is considered choice of procedure and it seems to be generally accepted to valve replacement. Numerical simulation is one of method that can be applied to simulate mitral valve function and evaluate proposed surgical repair. Therefore a fluid structure interaction model of the mitral valve has been generated to improve the surgical repair with understanding the correlation between backflow and mitral valve rigidity. However, several numerical modeling of the mitral valve have been developed but there are fewer that investigate backflow and rigidity of mitral valve and also not consider with ventricle model (Baccani et al., 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 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 from the heart towards the body. In doing so, it prevents the regurgitation of fluid. Several Finite Element (FE) models of the mitral valve have been developed however there are fewer that account for the effect of fluid flow through the valve (Van Loon et al., 2006; Watton et al., 2006). Before this, only one FSI model of an actual mitral valve with two leaflets has been developed (Einstein et al., 2005). The FSI model of the mitral valve was developed 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 simple 2D mitral valve model based on critical parameter of blood.

METHODS

Models of the mitral valve leaflet were created in ADINA-FSI for computational fluid dynamic analysis. 2D geometries of mitral valve leaflet were created in ADINA with meshed. In ADINA, we will consider fluid and structure model. In 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 will be assumed as Newtonian flow shows in Eq. (1), where, μ is the dynamic viscosity, p is the pressure and v is the velocity.

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

In structure model, a 2D FSI model of the mitral valve leaflet was generated using ADINA-FSI. 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 (De Hart et al., 2003). Structural deformation and fluid dynamics are determined simultaneously. An Arbitrary Lagrange Euler (ALE) mesh was used to allow FSI simulations to be performed. The ALE formulation of incompressible viscous shown as Eq (2) (Chen et al., 2004).

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

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 blood and properties of the mitral valve leaflets is shown as Table 1 (Reul et al., 1980; Espino et al., 2005).

Table 1. Parameter 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

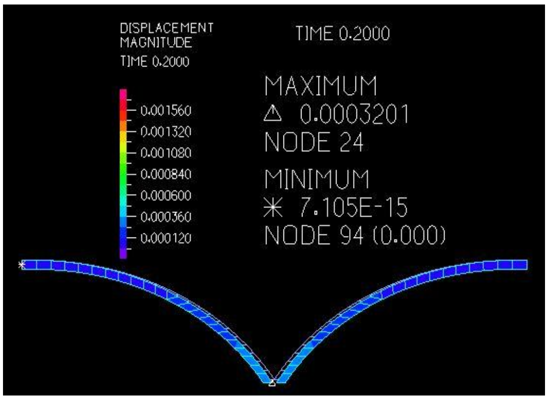
Boundary Conditions

The preliminary setup in the simulation was determined the parameters of blood and valve leaflets. During applying the diastolic and systolic condition to the mitral valve leaflets, a normal traction was enforce at the atrium side to make a pressure difference between the left ventricle and the atrium for mitral valve. This will cause the condition of fluid flowing through the mitral valve occurred. In this paper, Arbitrary Lagrange Euler (ALE) mesh was used during the setup in simulation**.** (De Hart et al., 2003) stated that to solve the multidimensional such as two-dimensional numerical simulation problems which involved fluid dynamics and nonlinear solid mechanics, it always required coping 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 Eulerian method. In Lagrangian method, it can define as each individual node in the computational mesh follows the associated material particle during movements, which usually apply in the structural mechanism. The disadvantage for Lagrangian method is it unable to apply during large distortions of the computational domain without depends on redo meshing operations. Furthermore, Eulerian method is widely applied in fluid dynamics where the mesh is fixed and continuum moves with respect to the grid. It is different with Lagrangian method where it could handle with large distortions in the continuum motion.

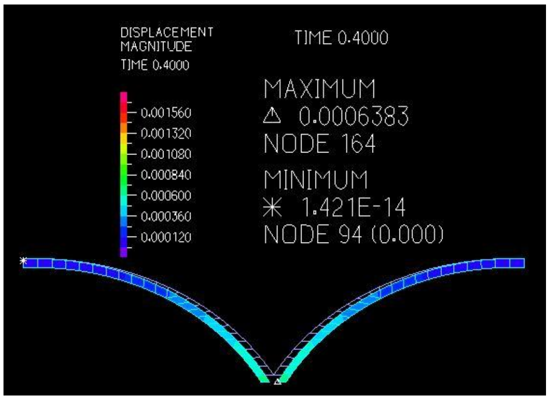
RESULTS AND DISCUSSION

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

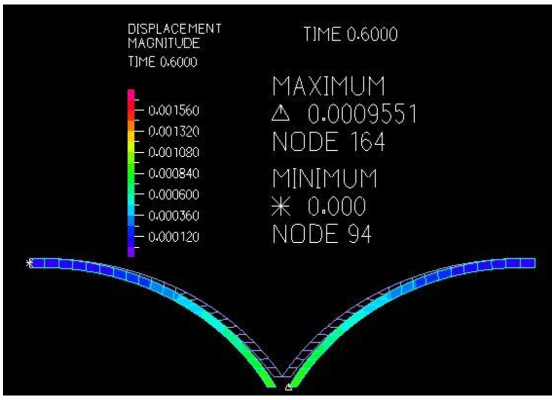
Figure 3 represents the changes of blood velocity when flowing through the mitral valve leaflets in 1.0 second of duration. From the Figure 3(a) where the time instant is 0.2 second, the blood is flow in a velocity value of 13.8 mm/s. Then at the time instant is 0.6 second shown in Figure 3(c), velocity of blood is 59.78 mm/s. At Figure 3(e), the highest velocity of the blood is achieved at a value of 94.46 mm/s at the time instant of 1.0 second. The pressure used to apply to push the blood flows can be determined from the background colour in the image. Different colour means the pressure condition between the left atrium and left ventricle is different. In the normal case, the smaller the opening produces a higher fluid flow velocity since the higher pressure applied. There is having pressure changes on the fluid and no changes in valve displacement during flowing in normal case. Therefore, it is different with normal cases where the velocity result obtained shows the value of velocity for a constant pressure applying depend on the time. Thus, the velocity results shown could be explained by using Newton’s third law and where force is equal to the mass times velocity of the motion. From this, the change of motion of the body is directly proportional to the motive force impressed on it. In the fundamental pressure law, pressure is equals to the force divided with the surface area. The section area mentioned here is pointed to the cross section area of the blood flow during the valve opening. For getting a higher cross section area, it related to a behavior which is having higher change in leaflets displacement. Blood flow cross section area is directional proportional to the displacements changes of leaflets. Higher displacements changes will lead a higher crossing surface area of blood flow. At the condition of constant pressure and mass applied, we could make a conclusion that the changes of blood velocity is related with the changes is leaflets displacement. Hence, more in leaflets opening will result the fluid to flow is higher velocity.



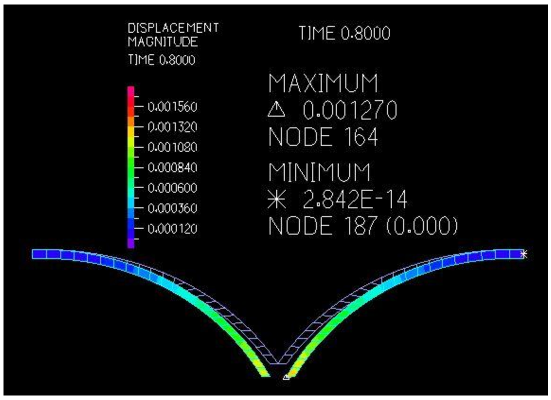
(a). 0.2 s



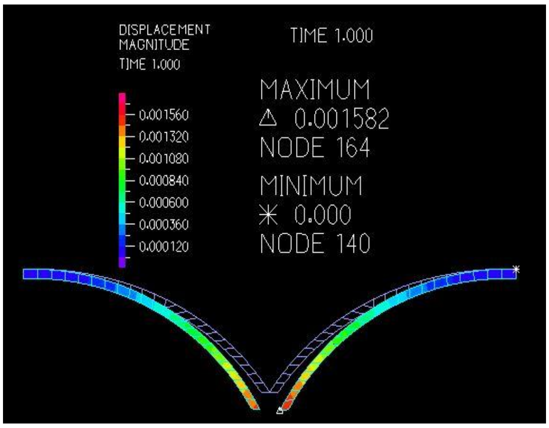
(b). 0.4 s



(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 with showing the displacement magnitude.

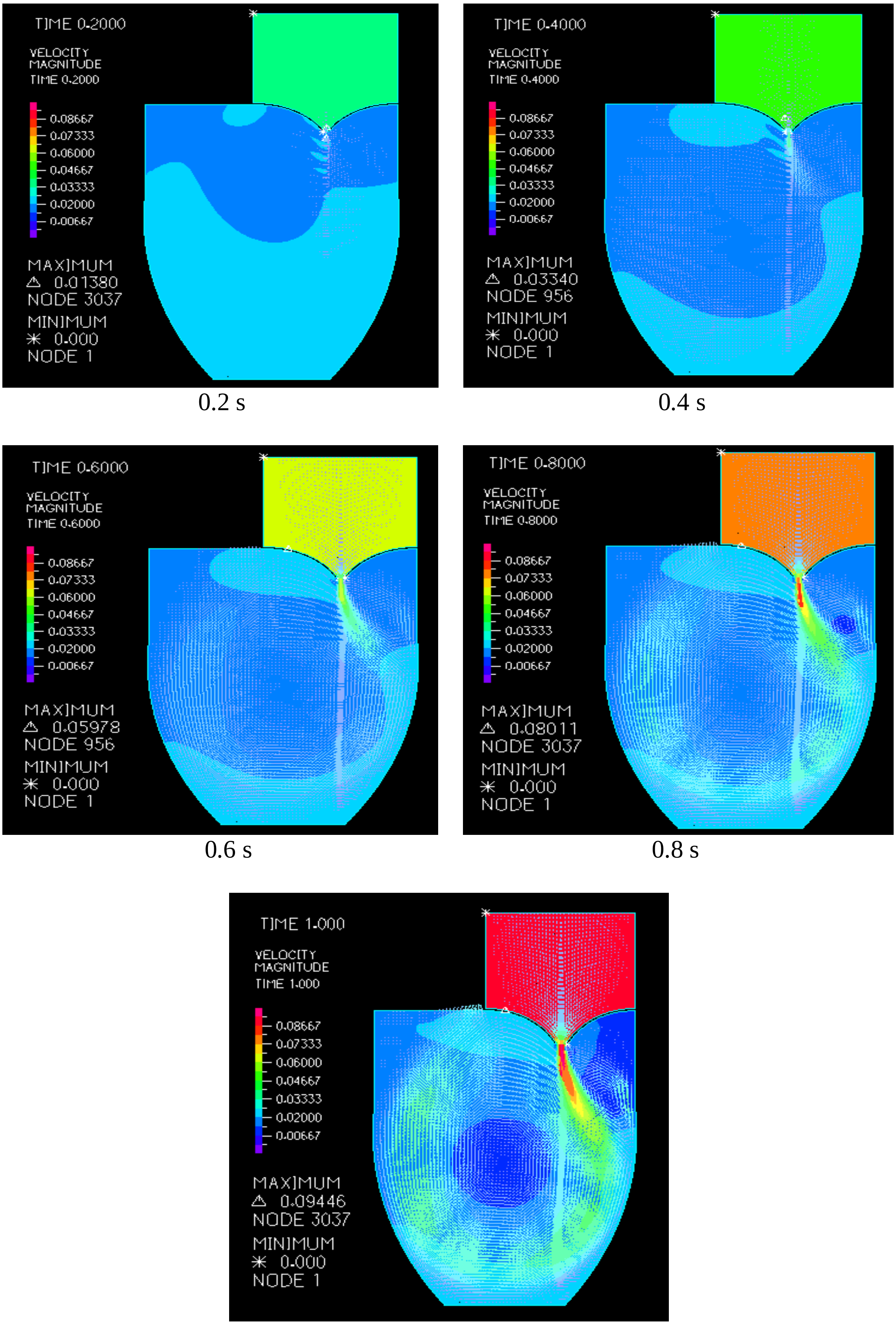


Figure 3: Simulated blood flow through mitral valve during systole condition. Extract of a 1.0 second simulation with showing the velocity magnitude.

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

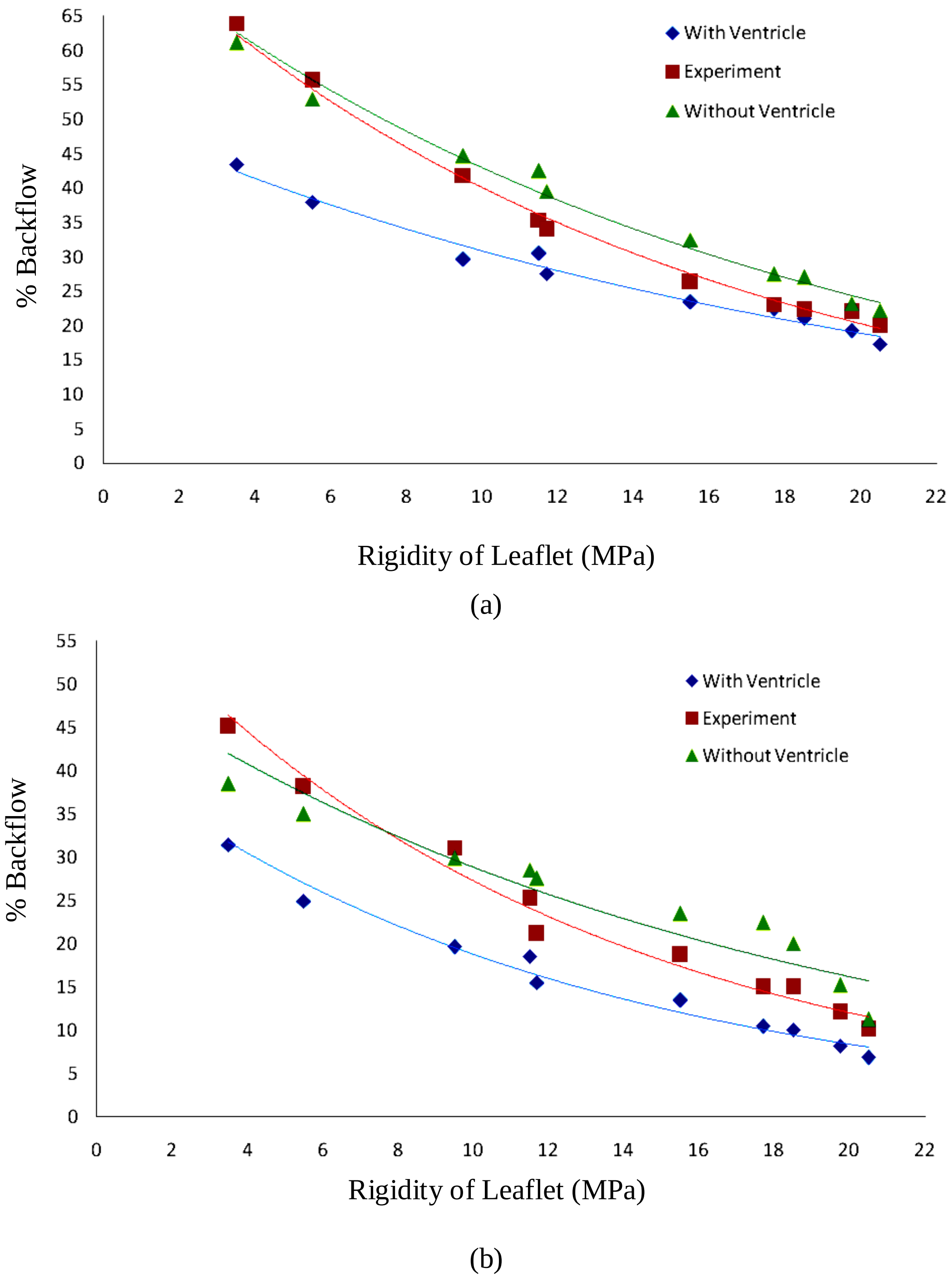


Figure 4: Variation of backflow againts rigidity of mitral valve leaflet (a). During systolic state and (b). During diastolic state.

There is more turbulence in the model with ventricle than in the model without ventricle. This is due to curves in the model with ventricle which did not exist in the model without ventricle. In the simulation, the results of the percentage of backflow are representing the severity of the mitral valves prolapse. This is demonstrated by the increase of the percentage of backflow as the condition of the mitral valves worsens (Adib et al., 2011). The predicted results assist the medical practitioner to find the approximation of the condition of the mitral valves based on the backflow data obtained through echocardiogram.

CONCLUSIONS

The 2D models mitral valve with and without ventricle wall were developed. Correlations between backflow and heart valve conditions were found to be linear between the two parameters. The backflow increases as the mitral valves condition worsen. It can be seen that the differences less than 10 percent of backflow on average between the two models for both systolic and diastolic states with various conditions of mitral valves. The findings are actually the prediction of the behavior of the mitral valves leaflet in deformation stage and blood flow velocity in various conditions. This model will be used in future to determine the rigidity of mitral valve for helpful to medical practitioners in making better decisions on the treatments for their patients as they have additional diagnosis on the mitral valves problem based on engineering analysis.

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