Modeling of Blood Flow Velocity into the Main Artery via Left Ventricle of Heart during Steady Condition

Mohd Azrul Hisham Mohd Adib, Nur Hazreen Mohd Hasni

Abstract—A three-dimensional and pulsatile blood flow in the left ventricle of heart model has been studied numerically. The geometry was derived from a simple approximation of the left ventricle model and the numerical simulations were obtained using a formulation of the Navier-Stokes equations. In this study, simulation was used to investigate the pattern of flow velocity in 3D model of heart with consider the left ventricle based on critical parameter of blood under steady condition. Our results demonstrate that flow velocity focused from mitral valve channel and continuous linearly to left ventricle wall but this skewness progresses into outside wall in atrium through aortic valve with random distribution that is irregular due to force subtract from ventricle wall during cardiac cycle. The findings are the prediction of the behavior of the blood flow velocity pattern in steady flow condition which can assist the medical practitioners in their decision on the patients' treatments.

Keywords—Mitral Valve; Aortic Valve; Cardiac Cycle; Leaflet; Biomechanics; Left Ventricle

I. INTRODUCTION

LEFT ventricle is the left lower chamber of the heart that receives blood from the mitral and pumps it out through the aortic to the body. The left ventricle is shorter and more conical in shape than the right and on transverse section its concavity presents an oval or nearly circular outline. It forms a small part of the steno costal surface and a considerable part of the diaphragmatic surface of the heart, it also forms the top of the heart. The left ventricle is thicker and more muscular than the right ventricle because it pumps blood at a higher pressure.

Common problem with left ventricular is LVH. Left ventricular hypertrophy (LVH) is enlargement of the muscle tissue that makes up the wall of our heart main pumping chamber. Left ventricular hypertrophy develops in response to some factor such as high blood pressure that requires the left ventricle to work harder. As the workload increases the walls of the chamber grow thicker, lose elasticity and eventually may fail to pump with as much force as a healthy heart.

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Left ventricular hypertrophy is more common in people who have high blood pressure or other heart problems. Blood flow dynamics inside the left ventricle (LV) contributes significantly to the overall cardiac function by making the efficient transfer of fluid momentum to redirect the blood flow from the LV inflow towards the LV outflow tract during ejection. This transfer is characterized by the storage of kinetic energy in vortices [1].
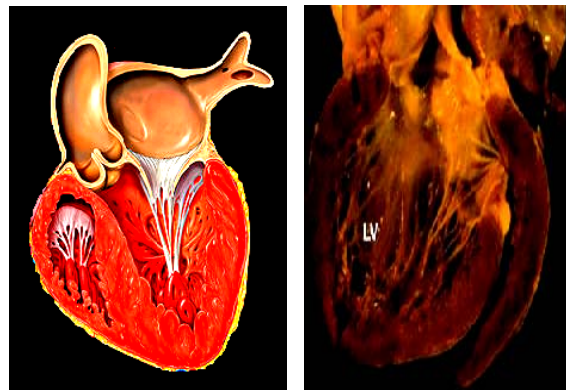

Fig. 1 Pathology portion of the anterior leaflet of the left ventricle of heart

A Computational Fluid Dynamics (CFD) model of the heart has been generated to improve the surgical repair with understanding the pattern flow of blood through the left ventricle of heart model. However, several numerical simulation of the heart has been developed but there are fewer that investigate flow velocity pattern and also not consider with ventricle model [**2; 3**]. The developing CFD model of the heart we are includes the walls of the left ventricle and applied two stage of pressure, systolic and diastolic.

II. METHOD

In this investigation, a three dimensional model is used to mimic the flow passing through the left ventricle of heart model. Blood flow pressure was emulated at cardiac cycle. The wall of the left ventricle is assumed to be rigid. Initially, a simple approximation of the heart was made as being elliptical in shape the major and minor axis were 70 mm and 24 mm respectively. [4,5]. The simplified model was constructed in Solidworks based on the actual but with common simplifications i.e. smooth wall and cross-sectional shape.

It was created with reference to the varied cross-sectional shapes throughout the actual model. The cross-sections are based on average diameters at multiple locations throughout the actual model.

The overset grid method allows for each section of the geometry to be meshed independently and the individual meshes are subsequently coupled together through interpolation methods for the dependent flow variables. This approach has previously been successfully applied by the authors to study flow through a model of the heart [6].

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

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

CFD simulations were performed using a dynamic 3D anatomical LV model [7] as a boundary condition in combination with an analytic description of a typical inflow velocity pattern [8]. The motion of scattering particles within the blood subsequently tracked based on the simulated 3D flow field [1].

TABLE I
CRITICAL PARAMETER OF BLOOD

Characteristics	Value
Diastolic Pressure (mmHg)	82
Systolic Pressure (mmHg)	132
Blood Density (kg/m^3)	1.06×10^3
Blood Viscosity (Pa.s)	2.70×10^{-3}
Reynolds Number	500

In order to start the cardiac cycle calculations, a steady flow condition solution at the maximum flow or Reynolds number is first obtained. Next, this steady flow solution is used as a boundary condition for the steady equations, which are solved with the inlet pulse for cardiac cycles before a time-periodic solution is reached [6]. A commercial finite volume based software Engineering Fluid Dynamics was deployed to solve steady state conservation of mass and momentum equations in all cases. 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 [9].Table 1 shows the inlet boundary conditions that were applied to heart model during steady condition [4,5].
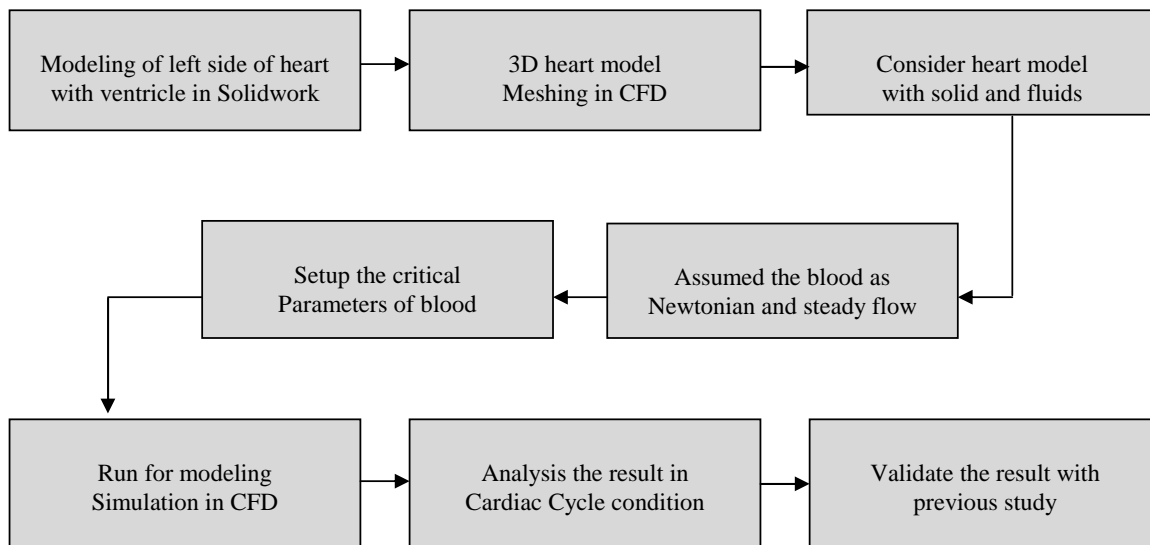

Fig. 2 Process flow of modeling simulation using Computational Fluid Dynamics (CFD) method where applied to investigate the pattern of flow velocity profile though left ventricle of heart mode

III. SIMULATION RESULT

As a theory in the normal heart, inflow decreases during systole. No new blood is coming into the left ventricle so the inflow is blood moving from the base toward the apex as part of the contraction and ejection process. Outflow increases initially and then also decreases, but at a less rapid rate than inflow. Since no blood is being pumped from the heart, the outflow is blood moving from the apex toward the aortic valve in proportion for the next ejection phase. In the case of dilated cardiomyopathy, this same pattern is evident. However, there is a significant increase in the ratio of outflow to inflow during systole. In reduced ejection fraction, this pattern is retained but the volumes are significantly smaller [10].

approximately 0.2sec per plot. Fig. 3(a) and Fig.3(b) shows the left ventricle simulation at the first and second point of initialization. At this beginning, a positive separation of flow velocities indicates in the portion of wall downstream of the ventricle. The same flow velocity fields are reported in Fig. 3(c), Fig. 3(d), Fig. 3(e) and Fig. 3(f). It can be observed that during steady flow condition, the left ventricle chamber is understated with the incoming inflow from the mitral valve pressuring the chamber to dilate and with that the flow is seen to accelerate at a maximum flow velocity throughout the chamber.

| (a). 0.2s | (b). 0.4s | (c). 0.6s |

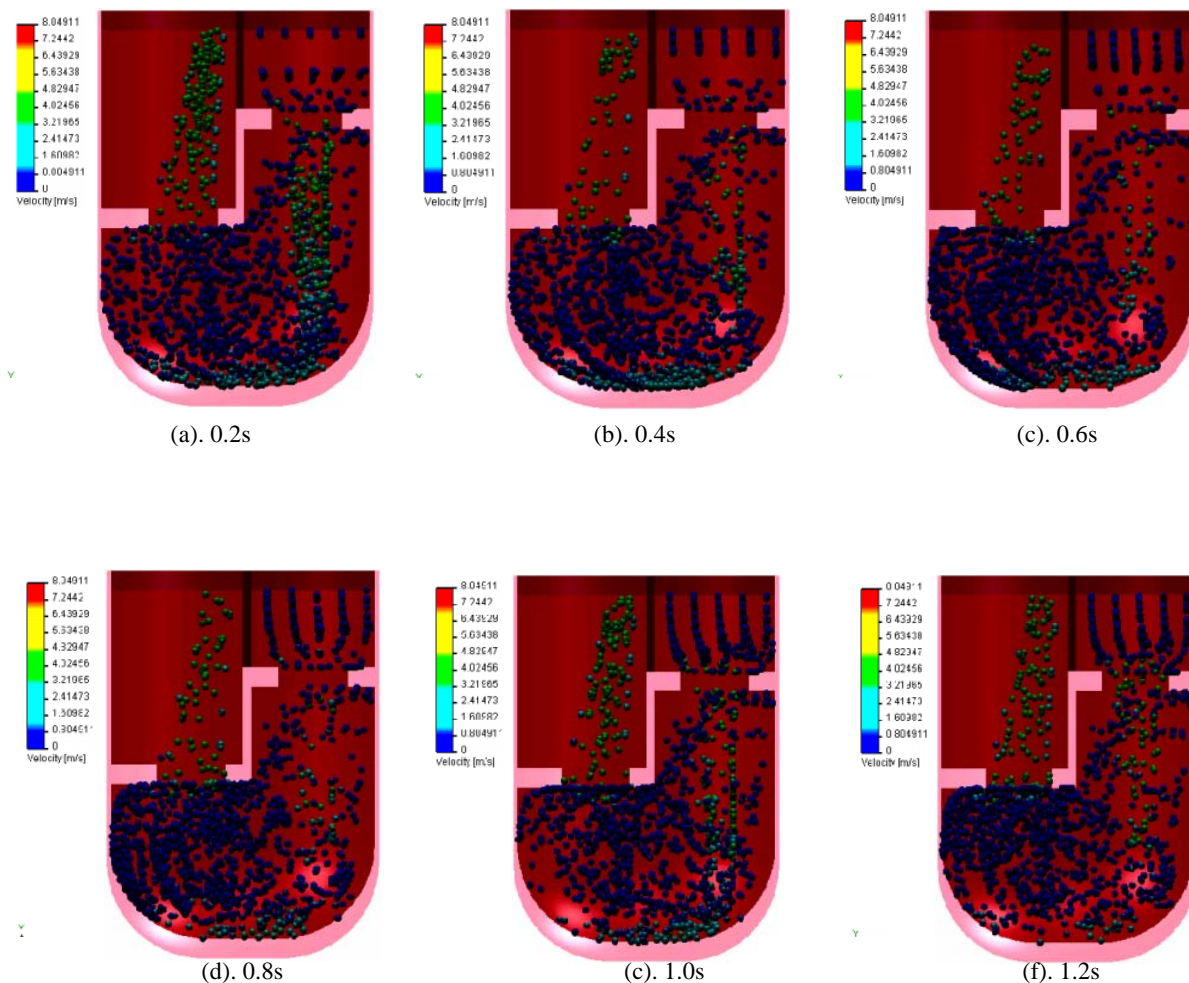| (d). 0.8s | (c). 1.0s | (f). 1.2s |

Fig. 3 Simulation of blood flow velocity into heart model, extract less than 1.2 second under cardiac cycle. Note that the models are for steady flow with considering the left ventricle.

Results of the 3D left ventricle simulation are laid out in graphical representation in Fig. 3. Using different plots the flow velocity in the cardiac cycle phase in the 1.2 second simulation time is observed with the time step separated at

Fig. 4 shows the trend of blood flow velocity during cardiac cycle. In this figure, flow velocity pattern focused from mitral valve channel and continuous linearly to left ventricle wall but this skewness progresses into outside wall in atrium through aortic valve with random distribution that is irregular due to

force subtract from ventricle wall during cardiac cycle and the deformation of the wall leads to a less extended separated region while the contraction of the vessel during the deceleration phase of the imposed diastolic pulse tends to reduce the value of the stress information gained from the flow velocity field is marked at each time step to track the mean velocity at simulation position.

In addition to their value in qualitative assessment, these three-dimensional model offer more complete quantitative medical assessment of blood flow velocity based on statistical values derived from these three-dimensional models of flow as extrapolated from two-dimensional data as is done clinically today [10]. The ability to investigate the blood flow velocity pattern through left ventricle is quite important because changes in flow velocity pattern may prove critical for analysis of patients with heart failure.

(c). 0.6s

(a). 0.2s

(d). 0.8s
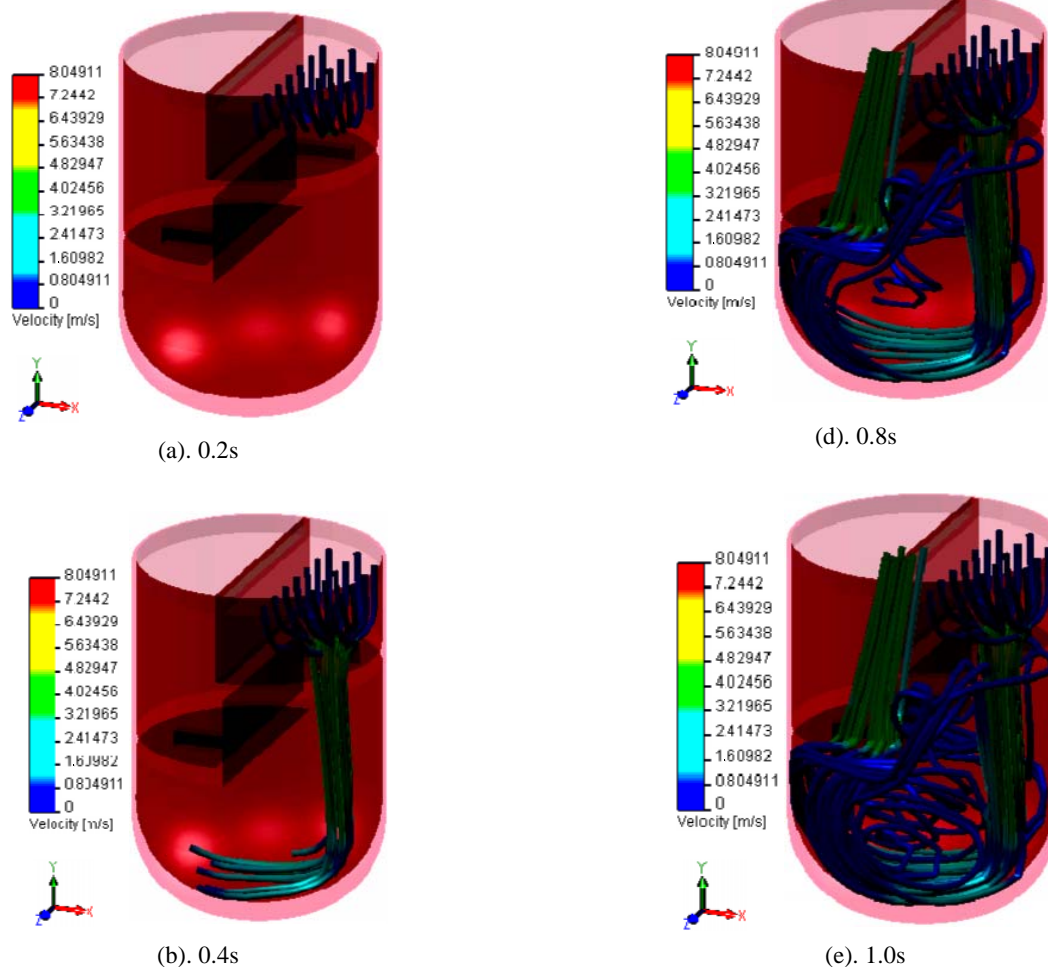

(b). 0.4s

(e). 1.0s

Fig. 4 Trend of blood flow velocity pattern, extract less than 1.0 second under cardiac cycle. Note that the models are for steady flow with considering the left ventricle

IV. DISCUSSION

The result from this 3D left ventricle of heart model allow a medical practitioners to view blood flow velocity in multiple dimensions permitting an immediate observation of the dynamic shape, size and direction of the flow structures and patterns in their true nature without need for the medical practitioners to physically construct 3D views from a limited number of 2D color flow loops. In the model with ventricle the space in the left ventricle after the mitral valves is larger as compared to the space available in the model without ventricle. The situation allows the model with ventricle to confine more blood in the left ventricle hence less pressure development in the system. Due to the relatively less pressure in the model with ventricle [3].The capability to observe left ventricle flow velocity pattern is quite important because changes in flow velocity may prove critical for analysis of patients with heart failure. These investigations are also keys to understanding the ventricular function.

We have defined an approach for creating a three dimensional model of left ventricle blood flow over time. We have shown that in the absence of significant velocity aliasing defects the models obtained by this method conform to the destruction of flow. Finally, we note that this research can be used to differentiate between normal and dilated cardiomyopathy. Further work is needed to establish the accuracy of this method with respect to the standards of medical practice. Future work is also needed to create the medical usefulness of the visualizations and statistics derived from these 3D models. Both of these will lead to conducting a larger biomedical study with a wide range of patients with various heart diseases.

Finally, this method can be applied to other data sets and this idea would be to produce three-dimensional visualizations that include both blood flow and tissue structure. The benefits to the medical practitioners is they can decide better treatments for their patients.

V.CONCLUSION

Computational Fluid Dynamics (CFD) models for this study were developed with considerations of left ventricle model. So during steady flow condition the left ventricle chamber is inflated with the incoming inflow from the mitral valve pressuring the chamber to dilate and with that the flow is seen to accelerate at a maximum flow velocity throughout the chamber and these investigations are also keys to understanding the ventricular function. The findings are actually the prediction of the behavior of the blood flow velocity pattern in steady conditions. These findings are helpful to medical practitioners in making better decisions on the treatments for their patients as they have additional diagnosis on the heart problem based on engineering analysis.

ACKNOWLEDGMENT

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