Hemodynamics of a bileaflet mechanical heart valve with different levels of dysfunction

Abstract

Heart disease is one of the leading causes of death. Treatment of certain types of heart disease involves surgically implanting mechanical heart valves. Bileaflet mechanical heart valves (BMHVs) are commonly used for valve replacement because their design can minimize flow disturbances. However, the rate of artificial valve dysfunction is 0.2-6% patient/year. Analysis of blood flow characteristics such as velocity, pressure drop, wall shear stress and vorticity profiles was performed. Results suggested that leaflet dysfunction caused increased local velocities, separation regions and wall shear stresses. For example, the maximum velocity increased from 2.53 m/s to 4.9 m/s when dysfunction increased from 0% to 100%. The pressure drop increased (by up to 300%) with dysfunctionality. Results suggested that leaflet dysfunction also caused increased wall shear stresses on the valve frame where higher stresses developed around the hinges (at 75% and 100% dysfunctions). Analysis also showed that increased dysfunctionality of one leaflet led to higher net shear forces on both the healthy and dysfunctional leaflets (by up to 200% and 600%, respectively).

Keywords: pulsatile blood flow, dysfunctional leaflet, cardiovascular modeling, shear forces, cd-adapco

Introduction

Heart disease is one of the leading causes of death. Treatment of certain types of heart disease involves surgically implanting mechanical heart valves. Bileaflet mechanical heart valves (BMHVs) are commonly used for valve replacement because their design can minimize flow disturbances. However, the rate of artificial valve dysfunction is 0.2-6% patient/year. Analysis of blood flow characteristics such as velocity, vortex formation and turbulent stresses are of importance to identify potential blood cell damage, especially due to complex and unsteady flow in the valve hinges. Increased wall shear stresses are of importance to detect as it can contribute thrombus formation. Moreover, a leaflet dysfunction can cause backflow. Several different techniques to study blood flow in BMHV were implemented in previous studies. This included CFD (Computational Fluid Dynamics) and experimental methods such as PIV (Particle Image Velocimetry), Video Analysis, LDA (Laser Doppler Anemometry). In the current study, CFD is used to model the valves and blood flow as the software allows relatively easy and economical conduction of parametric studies. The objective of this study is to investigate the flow around BMHV at different levels of leaflet dysfunction by:

a) Documenting the relevant flow structures using streamlines and vorticity information
b) Quantifying the changes in pressure drop
c) Calculating wall shear stresses on the valve frame and shear forces on the leaflets
d) Comparing the results of Newtonian and non-Newtonian fluids.

Previous studies of BMHV have shown that the blood flow moves through three orifices and creates three jets that cause stronger shear stresses than the case of natural valves. Furthermore, studies suggested that vortices become more prominent and wall shear stresses increase with leaflet dysfunction. Increased wall shear stresses are important to detect as it can contribute thrombus formation. Moreover, a leaflet dysfunction can cause backflow. Several different techniques to study blood flow in BMHV were implemented in previous studies. This included CFD (Computational Fluid Dynamics) and experimental methods such as PIV (Particle Image Velocimetry), Video Analysis, LDA (Laser Doppler Anemometry). In the current study, CFD is used to model the valves and blood flow as the software allows relatively easy and economical conduction of parametric studies. The objective of this study is to investigate the flow around BMHV at different levels of leaflet dysfunction by:

a) Documenting the relevant flow structures using streamlines and vorticity information
b) Quantifying the changes in pressure drop
c) Calculating wall shear stresses on the valve frame and shear forces on the leaflets
d) Comparing the results of Newtonian and non-Newtonian fluids.

This study may provide data that can enhance our understanding of the implications dysfunctional leaflets, which can lead to improved design of BMHV.
Models and methods

In this study, the computational domain was divided into four regions sequentially in the flow direction: upstream, heart valve, aortic root sinuses and downstream. The heart valve geometry (Figure 1A) investigated was chosen to be similar to previous studies.2,16–20 Figure 1B shows the asymmetric aortic root sinuses geometry (with inlet diameter of 0.023m), which was generated using information extracted from a previous experimental study21 and was represented as an epitrochoid. Creating a realistic geometry of the aortic sinuses is important for appropriate internal flow field analysis.13,22 In the current study, the top (functional) leaflet was assumed to be fixed in the fully open position while the bottom leaflet was fixed at different levels of dysfunctions. Since the dynamics of the leaflet opening and closure were not simulated, the data presented in the results section will focus on the fully opening period. Figure 1C shows the side cross section of the BMHV at different levels of leaflet dysfunction of 0, 25, 50, 75 and 100%. The positive direction of the shear forces was chosen to be in the flow direction from inlet to outlet. In this study, a commercial CFD software (STAR-CCM+, CD-adapco, Siemens, Germany) was utilized to perform the unsteady simulation for one complete cardiac cycle (simulation time, T=0.866s) with a time step=0.5 ms and 25 iterations per time step. The in vitro CFD analyses were performed for a pulsatile flow through a three-dimensional BMHV with fixed leaflets. The inlet velocity corresponding to cardiac output of 5L/min and heart rate of 70bpm with systolic phase duration of 0.3s as illustrated in19 The peak inflow velocity was ~1.2m/s and the density of blood was set to ρ=1080kg/m³. The blood also was considered to be both Newtonian with the viscosity of 0.0035kg/(m.s) and non-Newtonian based on generalized Carreau-Yasuda model.14 This lead to an inlet peak Reynolds number \(Re_{peak}=\frac{\rho U_{peak}d_{inlet}}{\mu}\) of 8516 and a \(W_0\) is Womersley number, \(W_0=\frac{d}{2}\sqrt{\frac{\rho}{\mu}}\); \(\omega=\frac{2\Pi}{T}\) is the frequency of pulsatile flow equals to 17.21. Moreover, high quality polyhedral mesh was generated in the flow domain, especially in the heart valve and aortic sinuses regions, close to the wall and the leaflet surfaces, Figure 2 in order to maintain \(y+\ll1(y+=0.46\) at the peak flow).

Validation

The normalized velocity profile along a line located 7 mm downstream of the healthy (0% dysfunction) valve is shown in Figure 3. The velocity profiles obtained in previous experimental study that considered a valve with similar geometry and flow conditions23 are also shown in the same figure. The results from the current study are in good agreement with the previous experimental and computational data. To quantify the difference between our computational and the experimental results, the root-mean-square (RMS) of the difference in velocity was calculated. The RMS of the velocity difference was 6.58% of the maximum velocity, suggesting agreement between the results of the current study and the measured values.
**Results and discussion**

Figures 4A2–4A5 shows the streamlines at the peak systolic time of 90ms, where the color represents the velocity magnitude. For 0% dysfunction (Figure 4A1), the blood flow seemed to have a narrower velocity range (i.e. more uniform velocity) compared to the higher levels of dysfunction (Figures 4A2–4A5). Figure 3A1 also shows relatively smaller flow separation in the wake region downstream of the leaflets as would be expected. The flow reattachment also happened closer to the exit of the aortic sinuses. The velocity magnitude in the orifices increased, especially in the bottom orifice, as leaflet dysfunction increased. Figure 4 also suggests that an increased leaflet dysfunction may increase the potential for development of higher levels of disturbances in the flow and possibly increased turbulence. This data also suggested that more intense vortical structures start to appear in the valve and sinus regions during the acceleration phase (e.g., 60 to 90ms). Figure 4B1–4B5 shows vorticity at different levels of dysfunction. Vorticity increased with dysfunctions and spread downstream of the leaflets. Conversely, lower levels of vorticity occurred in the sinus downstream of the dysfunction leaflet at 100% dysfunctions, which can be because the obstruction caused by the dysfunction created a low velocity region behind that leaflet. While Figure 4 shows information for t=90ms, flow structures were also examined for all times between 60 to 250ms and were found similar to those shown in Figure 4.

![Figure 4](image1)

**Figure 4 Flow field around the valve**

A. Streamlines  
B. Vorticity.

The maximum velocity in the flow domain was determined and was found to occur at the time of the peak systolic velocity. Results suggested that the maximum flow velocity increased with dysfunction. For instance, as dysfunctionality increased from 0% to 100%, the maximum velocity increased from 1.63 to 3.3m/s and from 1.52 to 3.65m/s in the middle and top orifices, respectively. In addition, the maximum flow velocity increased from 2.52m/s to 4.89m/s. Higher velocities and flow separation at the leaflet surfaces were accompanied by growing eddies and vorticity downstream of the valve (Figure 4). Figure 5 shows the pressure drop (during the cardiac cycle) for different levels of dysfunction. The figure shows that the pressure drop tended to increase with dysfunctionality. The maximum pressure drop (around t=0.06s in Figure 5) increased from 20mmHg to 63mmHg (~2300Pa to ~8500Pa). Note that since leaflets are fixed in the current study, the pressure drop in the fully open period is most relevant.

![Figure 5](image2)

**Figure 5 Pressure drop from inlet to outlet at different levels of dysfunction.**


described the pressure drop from inlet to outlet at different levels of dysfunction. The maximum pressure drop (around t=0.06s) increased from 20mmHg to 63mmHg (~2300Pa to ~8500Pa). The data suggest that the pressure drop was higher with higher levels of dysfunction.

Table 1 illustrates the maximum values of the averaged wall shear stress applied on the heart valve frame which occurred at the peak systole. The averaged and maximum wall shear stresses on the valve frame at the peak systole increased with dysfunction. The information regarding the location of the highest WSSs in the flow domain is presented in this table. The data indicate that the helicity increased with dysfunction and peaked around peak systolic velocity time. Shear forces on the top and
bottom leaflets were also studied for Newtonian and non-Newtonian flows. Figure 7 shows the shear forces on the top and bottom leaflets at 50% dysfunction. The results indicate that the shear forces on top and bottom leaflets for Newtonian flow is similar to non-Newtonian flow. The maximum difference between the two flow conditions was less than 1%. While Figure 7 shows shear forces for 50% dysfunction, similar trends were seen at different levels of dysfunction.

### Table 1
Averaged and maximum wall shear-stresses (WSSs) on the valve frame, location of the highest WSSs in the flow domain and the maximum helicity in the aortic sinuses

| Dysfunction (%) | Averaged WSS at peak systole (Pa) | Maximum WSS at peak systole (Pa) | Location of the highest WSSs | Maximum helicity in aortic sinuses (m/s²) |
|-----------------|-----------------------------------|----------------------------------|-----------------------------|------------------------------------------|
| 0               | 27.86                             | 241.67                           | Leading edge of the leaflets| 2088.01                                  |
| 25              | 38.71                             | 326.77                           | Leading edge of the leaflets| 5209.04                                  |
| 50              | 48.08                             | 448.96                           | Leading edge of the leaflets, trailing edge of the dysfunctional leaflet and top leaflet hinges | 5936.48                                  |
| 75              | 65.34                             | 666.61                           | Inner surface of the valve frame close to the trailing edge of the dysfunctional leaflet, bottom surface of the top leaflet and top leaflet hinges | 8328.39                                  |
| 100             | 50.24                             | 952.78                           | Upper half of the valve frame, top leaflet top and bottom surfaces and top leaflet hinges | 9794.89                                  |

### Conclusion

In this study, blood flow through a bileaflet mechanical heart valve was analyzed at different levels of leaflet dysfunction. Results suggested increased vortical structures and velocities with dysfunction. For instance, as dysfunctionality increased, the maximum velocity increased from 1.63 to 3.3 m/s and from 1.52 to 3.65 m/s in the middle and top orifices, respectively. Higher velocities and flow separation at the leaflet surfaces were accompanied by growing eddies and vorticity downstream of the valve. The pressure drop was found to increase with dysfunctionality (from 20 mmHg to 63 mmHg). Results

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Figure 6: Wall shear stresses on valve frame
A. Newtonian flow
B. Non-Newtonian flow (1: 0%; 2: 25%; 3: 50%; 4: 75% and 5: 100% dysfunction).

Figure 7: Shear forces on top and bottom leaflet at 50% dysfunction for Newtonian and non-Newtonian flows.

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suggested that leaflet dysfunction caused increased wall shear stresses on the valve frame. Higher stresses developed around the hinges (at 75% and 100% dysfunctions) and some part of the valve surfaces at the bottom orifice (at 25% and 50% dysfunctions). Identification of regions of elevated shear stress is important since this can increase thrombus risk. Analysis also showed that increased dysfunctional forces of one leaflet led to higher net shear forces on both the healthy and dysfunctional leaflet (by up to 200% and 600%, respectively). These results were similar for both Newtonian and non-Newtonian flow suggesting that the assumption of Newtonian flow, which can reduce computational cost, would be valid.

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**Conflict of interest**

The author declares no conflict of interest.

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