

Simulation of Blood flow in Different Configurations Design of Bi-leaflet Mechanical Heart Valve

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Abstract. In this work, two different designs of artificial heart valve were devised and then compared by considering the thrombosis, wear and valve orifice to anatomical orifice ratio of each mechanical heart valve. These different design configurations of bi-leaflet mechanical heart valves model are created through the use of Computer-aided design (CAD) modelling and simulated using Computational fluid dynamic (CFD) software. Design 1 is based on existing conventional bi-leaflet valve and design 2 based on modified bi-leaflet respectively. The flow pattern, velocity, vorticity and stress analysis have been done to justify the best design. Based on results, both of the designs show a Doppler velocity index of less than the allowable standard of 2.2 which is safe to be used as replacement of the human heart valve. However, design 2 shows that it has a lower possibility of cavitation issue which will lead to lower thrombosis and provide good central flow area of blood as compared to design 1.

1. Introduction

Heart is the one most important muscular organ that pumps blood throughout the whole body. Heart contains 4 chambers which are right atrium, right ventricle, left atrium and left ventricles. The heart valves are the key components that prevent backflow of blood. Four heart valves, two on either side of the heart, make sure blood produces unidirectional flow during muscle contraction and pass through the heart valve [1]. Circulation of blood begin at the right hand side of heart, the tricuspid and pulmonic valve control the flow of blood which is returned from body to the lung to received oxygen. For the left hand side of heart, the mitral and aortic valves regulate the oxygenated blood from the lung to receive oxygen and flow to body [2]. Today, many people live long and healthy lives and never realize they have a mild valve problem. However, valve disease can seriously increase a persons' risk for sudden death or cause rapid development of problems in and around the heart that can become fatal without treatment. The introduction of artificial heart valve definitely has made an incredible impact in biomedical field due to its lifetime durability. However, there are still problems in artificial valves such as thrombosis, vegetation, cavitation and many more. Hence, a better valve design has to be created to eradicate the problems encountered.

This happened when the patient with heart valve disease that involves one or more of the four valves of the heart malfunction. Commonly, heart valve diseases are involved in the left heart valve that consist of aortic valve and mitral valve. There are two types of heart valve malfunction that include the valve did not close (regurgitation) or open (stenosis) properly causing valve insufficiency. This may cause disturbing flow of blood throughout the human body. An artificial heart valve is a



device implanted in the heart to replace the natural valve with an artificial valve [3]. There are several types for artificial heart valve that are commonly used as replacement namely tissue heart valve and mechanical heart valve [4-5]. In this project, two bi-leaflet mechanical heart valve models are designed to analyze a blood flow system through the left heart. The conceptual design on artificial mitral valve will be created using CAD software and then simulated using computational fluid dynamic (CFD) software to select the best heart valve design that meet forward and backward flow shear, reduced blood clotting, minimal leakages and carry out vorticity study of heart valve simulation

2. Methodology

2.1. Establishment of CAD Model

The CAD model of the bi-leaflet mechanical heart valve in this project is constructed using Solidworks software. There are two types of the bi-leaflet model 1) normal bi-leaflet 2) modified bi-leaflet. Normal bi-leaflet is flat and straight surface while modified bi-leaflet is little curvature on the leaflet as shown in Figure 1 (a) and Figure 1 (b). The model consists of housing and two leaflet. The diameter of the mechanical heart valve is 28mm. The length of the model mechanical heart valve is 14mm.

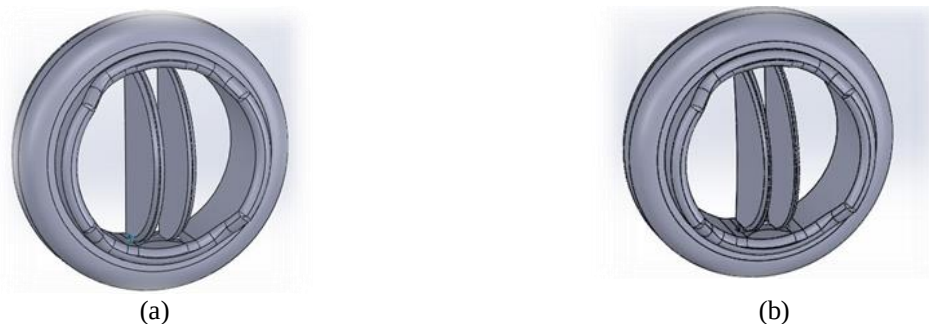


Figure 1. Geometry of (a) the conventional bi-leaflet (b) modified bi-leaflet

2.2. Simulation Using CFD Software

In computational fluid simulation, ANSYS software is used to simulate the two different configurations of bi-leaflet mechanical heart valve.

2.2.1. Stress Analysis. As the heart valve operates under the blood pressure conditions, it might be damaged or impaired. We aimed to modify of bi-leaflet mechanical heart valve and compare with a normal mechanical heart valve using mechanical analysis. Stress and strain on mechanical mitral heart valve, during opening and closing, were determined with a finite element analysis including deformation. Support at the outer ring body is fixed with 120mmHg pressure is applied in Y-direction [6]. All the materials involved in this work is define as pyrolytic carbon which has a tensile yield strength of 120 MPa as shown in Figure 2.

Properties of Outline Row 3: Pyrolytic carbon				
	A	B	C	D E
1	Property	Value	Unit	
2	Density	2240	kg m ⁻³	
3	Isotropic Elasticity			
4	Derive from	Young's Mod...		
5	Young's Modulus	4800	MPa	
6	Poisson's Ratio	0.28		
7	Bulk Modulus	3.636E+09	Pa	
8	Shear Modulus	1.875E+09	Pa	
9	Tensile Yield Strength	1.2059E+08	Pa	

Figure 2. Material property of pyrolytic carbon in CFD Software

2.2.2. Flow Analysis. The flow of blood through the valves will be simulated for different angles of leaflets and the flow pattern will be observed. Assume the flow is laminar and steady state. The density and dynamic viscosity of the blood is 1060 kg/m^3 and 0.0035 Pa s respectively [7].

3. Result And Discussion

3.1. Stress Analysis Result.

From this paper, deformation analysis for conventional and modified bi-leaflet is conducted when bi-leaflet heart valve is closed and open. The result of deformation analysis for both bi-leaflet mechanical heart valve as shown in Figure 3 and Figure 4.

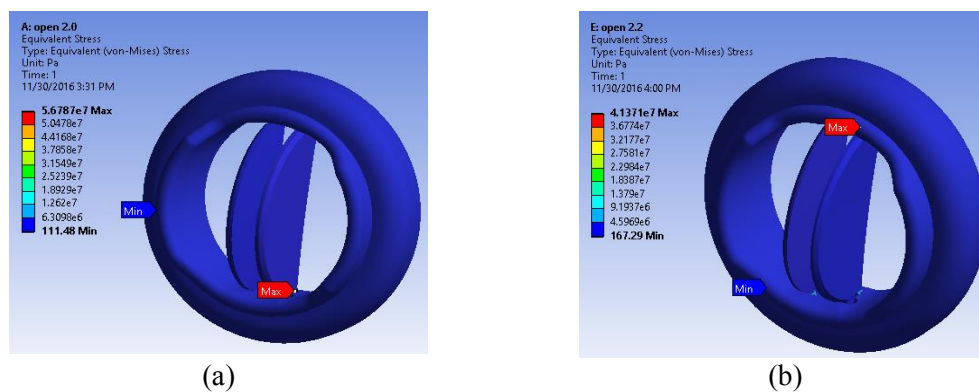


Figure 3. Stress analysis for fully opening of bi-leaflet mechanical heart valve. a) Conventional bi-leaflet (b) Modified bi-leaflet

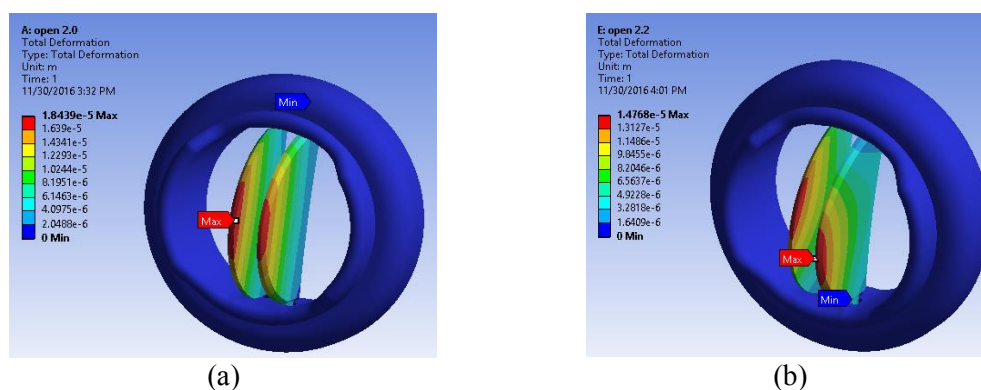


Figure 4. Deformation analysis for fully opening of bi-leaflet mechanical heart valve. (a) Conventional bi-leaflet (b) Modified bi-leaflet

Table 1. Stress and deformation of convectional and modified bi-leaflet heart valve

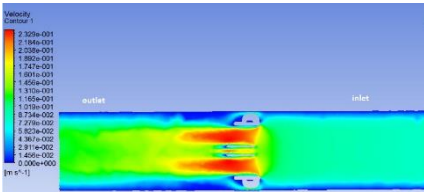
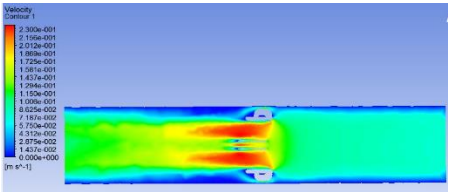
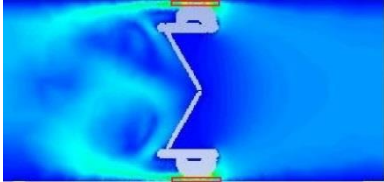
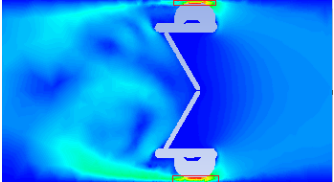
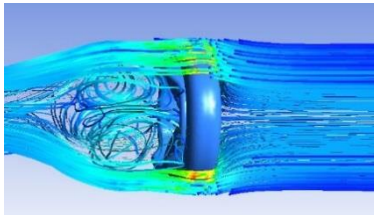
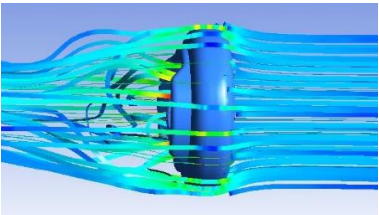
Valve Type	Fully Opening			
	Stress (Pa)		Deformation (m)	
	Min	Max	Min	Max
Normal bi-leaflet	111.48	5.679×10^7	0	1.844×10^{-5}
Modified bi-leaflet	167.29	4.137×10^7	0	1.477×10^{-5}

From Figure 3 and Figure 4, the distribution of stress is different from tips of leaflet to the hinge of leaflet. Simulation results showed that the maximum of stress when valve is fully opened, occurred at the hinge joint of leaflet in both bi-leaflet valves. Between conventional bi-leaflet and modified bi-leaflet, stress concentration on the hinge joint in the modified bi-leaflet valve was less than that in the conventional bi-leaflet valve which is 4.137×10^7 Pa. While, for leaflet deformation in modified bi-leaflet valve was also lower compared to conventional bi-leaflet valve as shown in Table 2. This is because increasing in deformation and stress may lead to damage of mechanical heart valve [8-9]. Thus, modified bi-leaflet has shown the best structural rigidity.

3.2. Flow Analysis of conventional and modified bi-leaflet.

From Table 2, simulation of fully opened and closed for both bi-leaflet mechanical heart valve are done to analyse flow analysis, leaking area and vortex formation between both bi-leaflet mechanical heart valves.

Table 2. Analysis of the flow pattern of conventional and modified bi-leaflet mechanical heart valves.

Features	Conventional bi-leaflet	Modified bi-leaflet
Velocity contour (valve fully open)		
Peak velocity	0.2329 ms ⁻¹	0.23 ms ⁻¹
Leaking area (red rectangle)		
Vortex formation		

Based on the velocity contour in Table 2, we can observe modified bi-leaflet valve observe a better central flow whereas conventional of bi-leaflet valve undergo flow separation in the middle area. In addition, the maximum velocity when blood flow through is the lowest and which is ideal as the flow velocity before and after passing the mechanical valve should be close to each other. In addition, the leaking area of both bi-leaflet valves are almost similar provided the mechanical valve is still in good condition. Besides, the larger comparison between both bi-leaflet heart valves is the vortex formation during opening. The vortex formation in conventional bi-leaflet valve is greatest compared to modified bi-leaflet valve as shown in Table 2. This is because the curvature on modified bi-leaflet affects the middle section of the blood flow that reduces the vorticity during opening operation. For an artificial heart valve, vortex formation should be considered to avoid thrombosis and cavitation formation.

While, the larger vortices forms at the middle area of conventional bi-leaflet valve might induce cavitation to happen and reduce blood flow drastically. On the contrary, the vortices formed in modified bi-leaflet is less accumulated in the middle section and thus lower chance of cavitation. Smaller vortex, lesser area affected and better flow dynamic for an artificial heart valve [10-12].

3.3. Detection and Quantification of Left heart valve Stenosis.

One of the criteria to determine the mitral stenosis is through the Doppler velocity index (DVI). From Figure 5, the normal DVI value for mitral valve should be less than 2.2.

	Normal		Possible stenosis		Significant stenosis	
	Aortic	Mitral	Aortic	Mitral	Aortic	Mitral
Valve structure and motion						
Mechanical or bioprosthesis	Normal	Normal	Often abnormal**	Often abnormal**	Abnormal**	Abnormal**
Doppler quantitative parameters						
Peak velocity (m/s)* †	<3	<1.9	3–4	1.9–2.5	>4	>2.5
Mean gradient (mm Hg)* †	<20	≤5	20–35	6–10	>35	>10
Doppler velocity index* ¶	≥0.30	<2.2	0.25–0.29	2.2–2.5	<0.25	>2.5
Effective orifice area (cm ²)* §	>1.2	≥2	0.8–1.2	1–2	<0.8	<1
Effective orifice area versus normal reference value* §	Reference±1SD	Reference±1SD	<Reference–1SD	<Reference–1SD	<Reference–2SD	<Reference–2SD
Contour of the transprosthetic jet‡	Triangular, early peaking	—	Triangular to intermediate	—	Rounded, symmetrical	—
Acceleration time (ms)‡	<80	—	80–100	—	>100	—
Pressure half time (ms)‡ 1	—	<130	—	130–200	—	>200

Figure 5. Allowable DVI in mitral valve[13]

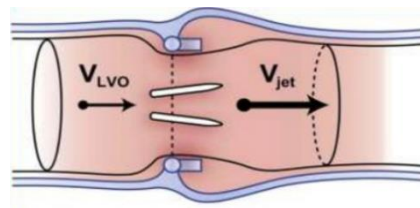


Figure 6. Parameters involved to calculate DVI

For mitral valve: Doppler Velocity Index (DVI) = $\frac{V_{jet}}{V_{LVO}}$

Table 3. Average velocity of blood flow depicted from computational simulation when the valve is fully open.

Valve type	Inlet velocity (m/s)						Outlet velocity (m/s)					
	1	2	3	4	5	Average	1	2	3	4	5	Average
Conventional Bileaflet	0.11	0.13	0.12	0.14	0.12	0.126	0.201	0.16	0.23	0.17	0.215	0.1952
Modified Bileaflet	0.11	0.13	0.12	0.14	0.12	0.126	0.2	0.201	0.17	0.16	0.22	0.190

Table 4. Doppler velocity index between both bi-leaflet mechanical heart valves.

Valve type	Doppler Velocity Index
Conventional bi-leaflet	1.55
Modified bi-leaflet	1.51

From Table 4, DVI value of modified bi-leaflet is the lowest compared to the others. Although conventional bi-leaflet valve has a DVI value of 1.55 but it is still within the allowable range which is less than 2.2. Hence, all the both valves are within the permissible limit and safe to be used. However, as time goes by, the mechanical valve will consistently undergo expansion and contraction so if the valve was to subjected to sudden changes, modified bi-leaflet valve might be a better choice as it can allow at least a double increased of current peak velocity.

4. Conclusion

Two different designs for the mechanical heart valve to replace defective mitral valve have been presented and discussed in this work. Design 1 is a conventional bi-leaflet valve and Design 2 is modified bi-leaflet respectively. The stress at each hinge is much lower than conventional bi-leaflet heart valve. Both designs have a Doppler velocity index of less than the allowable 2.2 which is safe to be used as replacement of the human heart valve. However, design 2 is clearly the best design as it has lowest cavitation issue which will lead to lower thrombosis and provide good central flow area of blood.

5. Acknowledgement

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