

**SIMULATION OF BLOOD FLOW IN BI-LEAFLET
MECHANICAL HEART VALVE**

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**SIMULATION OF BLOOD FLOW IN BI-LEAFLET MECHANICAL HEART
VALVE**

by

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LIST OF SYMBOLS

$f(x, c, t)$	Number of molecules at time t
c	Microscopic velocity
x	Position of lattice node
Ω	Complex collision term
f	Distribution function
f_{eq}	Maxwell Boltzmann equilibrium distribution function
ω	Collision frequency
τ	Relaxation factor
ρ	Density
w	Weighting function
ρ_0	Constant
$\delta\rho$	Small change
w_α	Weighting Factor
c_s	Speed of sound
C	Lattice constant
e_i	Discrete velocity set
f_i	Particle distribution function
t	Time
u	Macroscopic velocity
v	Fluid velocity
\dot{V}	Volume flow rate
D	Inlet diameter
π	Pi

δt	Discrete time step
δx	Discrete space interval
N	Reference resolution
V	Velocity
Δx	Displacement
Δt	Time
dX	Particle displacement
I_i	Interrogation areas
t_{lower}	Lower velocity threshold
t_{upper}	Upper velocity threshold
\bar{u}	Velocity
σ_u	Standard deviation of velocity
C	Correlation
V_{jet}	Velocity Jet
V_{LVO}	Velocity Left Ventricular Outflow
V_{inlet}	Velocity Inlet
V_{outlet}	Velocity Outlet

LIST OF ABBREVIATIONS

AC	Alternating Current
ALE	Arbitrary Lagrangean–Eulerian
ATS	ATS Heart Valve
AV	Atrioventricular
AVR	Aortic Valve Replacement
BGK	Bhatnagar-Groos-Krook
BHMV	Bi-leaflet Heart Mechanical Valve
CAD	Computer-Aided Design
CCD	Charge-Coupled Device
CFD	Computer Fluid Dynamic
CNC	Computer Numerical Control
CPU	Central Processing Unit
DVI	Doppler Velocity Index
DVR	Double Valve Replacement
EOA	Effective Orifice Area
FDM	Finite Difference Method
FEM	Finite Element Method
FSI	Fluid- Structure Interaction
FVM	Fluid Volume Method
IA	Interrogation Area
JEPERM	Jawatankuasa Etika Penyelidikan Manusia
LB	Lattice Boltzmann
LBGK	Lattice Boltzmann Bhatnagar–Gross–Krook
LBM	Lattice Boltzmann Method

LVO	Left Ventricular Outflow
MCRI	ON-XR mechanical valves
MH	Medtronic
MHV	Mechanical Heart Valve
MPI	Message Passing Interface
MRT	Multiple Relaxation Time
MVR	Mitral Valve Replacement
PIV	Particle Image Velocimetry
PSP	Polyamide Seeding Particles
RLBM	Regularized Bhatnagar–Gross–Krook
RT	Relaxation Time
SJM	St Jude Medical
SL	Semilunar
STL	Stereolithography
WSS	Wall Shear Stress

SIMULASI ALIRAN DARAH DALAM DUA INJAP MEKANIKAL JANTUNG

ABSTRAK

Jantung manusia boleh dijangkiti oleh beberapa penyakit yang boleh menyebabkan injap jantung tidak berfungsi. Oleh itu, injap jantung mekanikal dua injap (BMHV) digunakan sebagai pengganti yang terdiri daripada dua injap separa bulat dan selongsong luar injap. Dalam kajian ini, reka bentuk BMHV akan dioptimumkan untuk menghasilkan injap yang sesuai untuk menggantikan injap mitral yang tidak berfungsi. Simulasi kaedah Lattice Boltzmann (LBM) yang digunakan dan disahkan menggunakan eksperimen (PIV). Simulasi LBM telah menunjukkan jarak antara dua injap yang lebih jauh mempunyai aliran hemodinamik yang lebih baik. Selain itu, kelengkungan injap yang berbeza akan dibandingkan dengan mengoptimumkan dinamik aliran darah. Berdasarkan kriteria indeks halaju (DVI), kesemua enam reka bentuk yang berbeza berjaya merekodkan nilai DVI dalam had yang dibenarkan dengan nilai kurang daripada 2.2. Kontur halaju dan vortek menunjukkan persamaan dalam aliran darah antara simulasi dan eksperimen. Peratusan perbezaan profil halaju pada DVI antara data simulasi dan eksperimen ditunjukkan kurang daripada 15%. Dalam pembentukan vortek, 0.6mm lengkungan dalam didapati mempunyai nilai vorteks terkecil berbanding dengan lima reka bentuk yang lain. Dari segi profil tekanan dan tegasan ricih dinding yang dikira, semua keputusan menunjukkan nilai yang sama untuk semua reka bentuk yang digunakan. Tekanan ricih dinding maksimum yang dikira dari kajian ini adalah kira-kira 26.46 Pa. Dari semua kes yang dikaji, dengan 0.6mm lengkungan dalam menunjukkan tekanan geseran dinding terendah yang bermanfaat kerana ia mengurangkan darah beku.

SIMULATION OF BLOOD FLOW IN BI-LEAFLET MECHANICAL HEART VALVE

ABSTRACT

Our heart can be affected by several diseases during its lifetime that consequently result to heart valve malfunctioned. For this reason, bi-leaflet mechanical heart valve (BMHV) is used as a replacement that consist of two semi-circular leaflets and a valve housing. In this research, the design of the BMHV will be optimized in providing suitable replacement for the malfunctioned mitral valve. Simulation results from Lattice Boltzmann method (LBM) code will be used and validated using particle image velocimetry (PIV) experiment. LBM simulations have shown that the leaflet with higher gap distance between leaflets have an improved hemodynamic flow. Additionally, different leaflet curvatures will be compared to further optimize the blood flow dynamics. Based on the Doppler velocity index (DVI) criteria, all six different designs managed to record DVI values within the allowable limit with values of less than 2.2. The result of the velocity contour and vorticity revealed great similarity in the leaflet motion and flow fields between both simulation and experiment. The percentage difference of velocity profile on DVI between both simulation and experiment data is shown to be less than 15%. With regards to the vortex formation, 0.6mm curved inward is found to have the smallest vortex value compared to five other leaflet designs. In terms of the pressure profile and computed wall shear stress, all of the computed pressure results show approximately similar value for all designs used. The maximum wall shear stress computed from this study is about 26.46 Pa. Of all the cases studied, the leaflet with the 0.6mm inward curvature shows the lowest wall shear stress which is beneficial since it reduces thrombosis.

CHAPTER ONE

INTRODUCTION

1.1 Overview

Chapter 1.2 and 1.3 will discuss the heart valve and common type of heart valve diseases in the human body. The objective, problem statements and the research scope are presented in 1.5 till 1.6. Thesis outline will be explained more in 1.8.

1.2 Research Background

1.2.1 Heart Valve Diseases

Heart valve disease occurs when one of the valves does not function correctly due to damaged valve that is unable to open or close properly. It will disturb the flow of the blood through the heart. There are several diseases that can cause the heart to be malfunction such as stenosis, regurgitation, atresia, rheumatic valve disease, infective endocarditis and congenital heart valve (Olsen L.J., Subramanian R., 1984).

All the heart valve disease that could lead to thrombus formation especially for infective endocarditis is normally generated by micro-organisms such as bacteria or fungi leading to possible inflammatory reaction. The complications could be developing due to the infection like thrombotic vegetation development on the surfaces of the valve leading to irregular heartbeat and destruction of the valve. The big lump of mass will bring serious complications as it will impede the flow of the blood through the circulatory system.

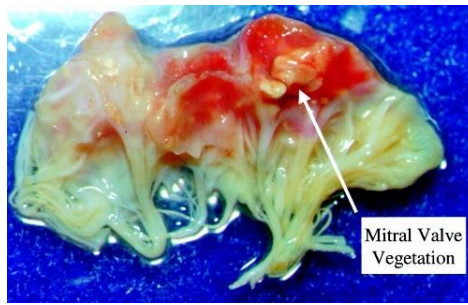


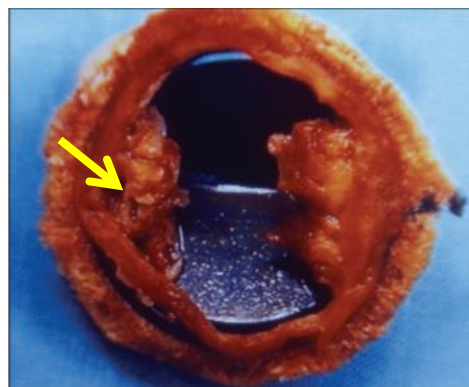
Figure 1.1. Mitral valve vegetation (Cabell, Abrutyn, & Karchmer, 2003)

Moreover, floppy heart valves could cause heart valve weakening and subsequently loss of elasticity. This condition leads to ballooning or prolapsing of the valves thereby increasing the risk of regurgitation, chordal rupture and thrombosis (van Loon, 2005).

Generally, thrombosis is the formation of a blood clot inside a blood vessel that obstructs the flow of blood through the circulatory system. Thrombosis on prosthetic valve could be non-obstructive or obstructive that can cause clinical thromboembolic event. Thrombosis of a prosthesis heart valve is potentially life threatening, resulting in hemodynamically severe stenosis or regurgitation. Thrombotic risk is related to the type of valve, position of the valve and adequacy of anticoagulation (Nkomo & Pislaru, 2015)



(a)



(b)

Figure 1.2. Thrombosis on (a) mitral valve prosthesis (Elmer, Wilke, Wende, Horst, & Steverding, 2011) (b) aortic valve prosthesis (Tirilomis, 2012)

Hemolysis which is the rupturing of red blood cells is one of the potentially serious complications of prosthetic heart valves. It is usually associated with either structural deterioration or paravalvular leak. Therefore, the damaged threshold of blood components by fluid shear stress must be considered in the design of a prosthetic heart valve.

1.2.2 Artificial Heart Valve

Malfunction of a native valve will impair its efficient fluid mechanic and hemodynamic performance. Artificial heart valves have been used since 1960 to replace diseased native valves and have managed to save millions of lives. Unfortunately, despite five decades of use, these devices are still less than ideal and can lead to many complications such as thrombosis, vegetation and hemolysis. Artificial heart valve has already been discussed for the past few decades. There are a lot researcher involved in the design and development of the artificial heart valve that act as mechanical or a bio-prosthetic heart valve. Many successful surgeries have been conducted to replace the actual heart valve with artificial heart valve. Mechanical valve has two implantation which are percutaneous implantation (stent frame and not frame) and sternotomy or thoracotomy implantation (ball and cage, tilting disk, bi-leaflet, and tri-leaflet). The commonly used mechanical valve are caged ball valve, tilting-disc valves and bi-leaflet valve. Generally, existing mechanical heart valve consists of a ring outer body, inner ring, leaflets, orifice and hinges. Most mechanical heart valves are made of titanium, graphite, pyrolytic carbon, and polyester. The titanium is used for the housing or outer ring, graphite coated with pyrolytic carbon is used for the leaflet and 100% pyrolytic carbon is used for the inner ring.

1.2.3 Heart Valve

The heart is a vital muscular organ which pumps blood throughout the body. Heart has four main valves which are mitral valve and tricuspid valve located at the lower chamber controlling the blood flow from atria to the ventricles, while aortic valve and pulmonary valve located at the upper chamber controls the blood flow out from ventricles. The atria consist of left or right atrium that act as a receiving chamber of heart by receiving blood flowing back to the heart. The ventricles that consist of left or right ventricles will pump the blood out from the heart. The four valves of the human heart as shown in Figure 1.1 are the aortic, mitral, pulmonary and tricuspid valves.

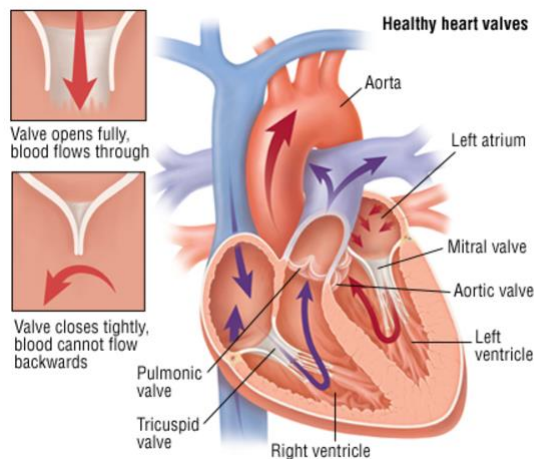


Figure 1.3. The position of valve in heart (NHLBI, 2013)

Heart valve functions when blood returns back from the body and the lung causing it to fill up the atria (left atrium or right atrium). As the blood fulfil the atria, these valves (mitral valve or tricuspid valve) will open allowing blood to flow into the ventricles. The most common heart valve disease are aortic and mitral valve diseases based on the findings by researcher in the field of cardiology (Maganti, Rigolin, Sarano, & Bonow, 2010; Roberts & Ko, 2008). In this research, the mitral valve which contributed to high mortality rate will be the prime focus in this research study.

1.2.4 Computational Method for Clinical Study

To simulate this type of study, the measure of pressure, shear and strain are important to determine the damaged or ruptured cause that occurs on the valve. Fluid dynamic knowledge can be used to determine the shear of fluid flow also that is the basis of this study. The computational method is very useful to solve problem involving complex and irregular three-dimensional geometries and high resolution. There are many approaches to computational method that include finite element and lattice Boltzmann. Currently, most of the researchers relating to artificial heart valve study utilizes computational method but it is limited only to the finite element method or finite volume method. It should be noted that researchers have shown that lattice Boltzmann method can provide an alternative method with various advantages as compared to its predecessors. Additionally, studies have also shown the capability of LBM in solving problems relating to blood flow.

1.2.5 Fluid-structure Interaction (FSI)

Fluid–structure interaction (FSI) is known as interaction of some movable or deformable structure with an internal or surrounding fluid flow. It is interactions that can be stable or oscillatory. The past 10 years have seen significant growth in computational fluid dynamics (CFD) based formulation to tackle FSI based problems. These studies have played an important role in solving problems relating to airflow along an aircraft, particle flow, and deformation of artery, heart and also heart valve. FSI method is mostly applied for use with computational method that involved coupling of finite element and finite volume as well as some initial work involving particle-based LBM. The use of LBM is still at the starting and this research study will attempt to solve FSI based problems using LBM in solving the artificial heart valve problems.

1.3 Problem Statement

Nowadays, many people live long and healthy lives without realizing they have a mild valve problem. This valve disease can seriously increase a person's risk of sudden death or cause rapid development of problems in and around the heart that can become fatal without treatment. The creation of mechanical heart valve has made an incredible impact in the biomedical field due to its lifetime durability. However, there are still problems in mechanical valves such as thrombosis, vegetation, and many more. Hence, a better valve shape design has to be developed to maximize the survival rate of patients suffering such diseases.

Development of highly accurate and detail simulation code for micro and nano simulation to assist in heart valve design are also getting wider. Most of the research are conducted the simulation based on finite element and finite volume method. The solution analysis from both of the methods are highly accurate and reliable. There exist some problem in trying to solve simulation problem following the same degree of reliability as the micro and nano- scale. The LB model is based on streaming and collision of each particles. In this scale, inter-particle forces or microscopic interactions are used to describe the interaction forces between particles in the simulation which requires identification of the location, velocity and trajectory of individual particles. These interaction forces will influence the results of the stresses and deformation of the simulation solution. Additionally, these inter-particle forces cannot be solved using conventional mesh-based method. Therefore, the use of LBM based software that is capable of incorporating these interactions, would help to aggravate this issue to give the ability to solve the solution for both macro and micro scale level. It is noteworthy to mention that there are limited amount of researches that have been conducted to tackle the FSI problem using LBM for biomedical