EXPERIMENTAL ANALYSIS INTO THE MAIN ARTERY OF 2 CHAMBER HEART MODEL DURING CARDIAC CYCLE

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ABSTRACT

Regarding to the report from World Health Organization (WHO), the most killer disease throughout the world is cardiovascular disease. There are millions of people deaths because of this disease every year. So, it is important to study the blood pumping mechanism in human body and what is the reason causing this device damage or fail to operate normally in detail. The objective of this study is to develop a heart model for investigating the patterns of fluid flow, and blood velocity diastolic. This heart model is able to observe the fluid flow pattern in left and right ventricle in a pressurized pulsate flow. A detail on fabrication, limitation, future improvement, and problem faced of heart model are discussed in this study. The whole system will be conduct in a close system which operated by using the combination of motor, and syringe. The results showed a relationship between heart beat, velocity, and blood vessel diameter especially for inferior, and superior vena cava can be establish. The result also proved that the relationship between heart beat and the velocity, and the difference of pressure between atrium and ventricle are directly proportional. Additionally, the relationship between vortex formation and septum in the heart chamber can be established at the end of this study. In conclusion, this study had succeeded to produce an equation relates to the velocity, diameter and heart beat in inferior, and superior vena cava. This result can contribute to future heart study as well as application in medical field.

ABSTRAK

Menurut laporan World Health Organization (WHO), penyakit jantung merupakan pembunuh utama di dunia. Berjuta-juta manusia maut akibat penyakit ini setiap tahun. Jadi, kajian secara teliti pada jantung manusia untuk mengenal pasti kerosakan, dan tidak berfungsi secara nomal adalah amat penting. Objektif kajian ini adalah untuk membina model jantung dan menyiasat corak aliran bendalir, dan halaju darah semasa diastolik. Model jantung ini dapat menyiasat corak aliran cecair dalam ventrikel kiri, dan kanan di bawah tekanan dan aliran berirama. Prebincangan secara terperinci mengenai fabrikasi, had, penambahbaikan dan masalah yang dihadapi model jantung juga akan dibincangkan dalam kajian ini. Seluruh sistem bagi kajian ini akan berada dalam keadaan tertutup dan konsep untuk model jantung ini adalah berasas kan kombinasi antara picagari dan motor. Hubungan antara degupan jantung, halaju dan diameter saluran darah terutamanya bagi inferior dan superior vena cava telah dijumpai. Selain itu, keputusan juga membuktikan bahawa hubungan antara halaju dan perbezaan tekanan antara atrium dan ventrikel adalah berkadar terus dengan kadar denyutan jantung. Hubungan antara pembentukan vorteks dan septum dalam jantung juga dapat dikaji pada akhir kajian ini. Kesimpulannya, kajian ini telah berjaya untuk mendapatkan persamaan yang berkaitan dengan halaju, diameter dan denyutan jantung di inferior dan superior vena cava. Keputusan ini berkemungkinan besar akan menyumbang kepada kajian jantung pada masa hadapan dan juga dapat aplikasi dalam bidang perubatan.

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LIST OF SYMBOLS

ρ	Density of fluid
v	Velocity of fluid
L	Characteristic linear dimension
μ	Dynamic viscosity of fluid
V_{lv}	Left ventricle volume
P_{lv}	Left ventricle inner pressure
P_a	Arterial blood pressure
R_{lv_a}	Resistance between left ventricle and aorta
P_{a0}	Left ventricle inner pressure before time *dt*
V_{lv0}	Left ventricle volume before time *dt*
R	Resistance vessel
C	Compliance
ρ_g	Density of glycerin

ρ_w	Density of water
ρ_b	Density of blood
V_g	Volume of glycerin
V_w	Volume of water
g	Gravitational acceleration
$P_{\max}$	Maximum pressure
I	Second moment of inertia
N	Rotational speed
r_s	Length of the rotational shaft
V_p	Velocity of syringe piston
V_1	Velocity of fluid at position 1
V_2	Velocity of fluid at position 2
r_1	Pipe radius at position 1
r_2	Pipe radius at position 2
Θ	Angle of rotational shaft from horizontal plane
B	Heart beat rate

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Heart is a myogenic muscular organ to provide a rhythmic blood flow to the blood vessels throughout whole body. The average of normal human heart beat rate is about 72 beats per minute under the rest condition. Other than the cardiac muscle, a human heart also consists of heart valve which is to prevent back flow of the blood in the heart. Most of the mammal's hearts consist of 4 heart valves. These valves ensure unidirectional blood flow during cardiac cycle. Atrium and ventricle are the upper and lower chambers where atria act as receiving chamber and ventricles act as discharging chamber. Left and right hearts are separate by a thick wall of muscle call septum. Heart valves are passive tissues which its opening and closing are depending on the difference in blood pressure across the valves. Any failures of heart valve to perform will cause heart disease. Heart valve disease can be group into two categories which are Stenosis and Mitral Incompetence. Stenosis happen when the heart valve failed to open fully due to stiffened valve tissue. Mitral Incompetence happens when the heart valve failed to perform well and cause backflow of blood in the heart (Gonazalez, 2003).

Fluid flow structure in a cavity will be influence by the fluid velocity, flow rate, pressure, continuity and also the physical properties of the cavity. The fluid flow pattern is directly influenced by the properties of the blood and the structure of heart. This phenomenon can be describe by studying the Reynolds number (Re) as in Eq.(1.1). In this equation, it shows the flow pattern is inversely proportional to the dynamic viscosity of fluid and directly proportional to the fluid density, velocity, and the dimension of the flow. Fluid flow pattern can be generally categorized into 3 types which are Laminar, Transitional and Turbulent flow on the bonds of Reynard Number. Blood flow in human heart and arteries will have a high pressure and velocity during contraction. Hence the Reynolds Number will be relatively high, and can be classify into Turbulent flow.

$$\mathrm{Re} = \frac{\rho v L}{\mu} \tag{1.1}$$

1.2 PROBLEM STATEMENT

Analysis on the heart is a wide field of study. Generally, study on heart can be dividing to three categories which are analysis on structure, fluid flow, and valves. Most of the previous studies had given more attention to the deformation of ventricle wall and fluid flow pattern in left ventricleby numerical method. However, it is important to have a modeling experiment to validate the results from the numerical study (Kanyanta, 2009). Details of the actual geometry will influence the flow dynamics (Domenichini, 2006, Hart, 2000). Besides, pressure variation throughout the left ventricle cavity shows the importance to the fluid flow effect in the heart chamber (Doyle, 2011). Unfortunately, how does the heart structure, and blood pressure influence the flow at the heart and vortex formation in the heart chamber during cardiac cycle is still under investigation.

1.3 OBJECTIVE

The aim of this research are to develop a heart model and to predict the correlation between fluid flow patterns, diastolic blood velocity heart beat and vein diameter in a pressurized rhythmic flow by applying different pressure and heart beat.

1.4 SCOPE OF STUDY

The scope of study will be organizes from:

1) This modeling experiment will only conduct in a close system.
2) The pipe diameter and flow rate ratio will be taken similar to actual human body condition where the heart model is 2 times smaller than the actual human heart.
3) Heart valve rigidity will be fixed at 2GPa to obtain more accurate result.
4) The flow-structure interaction will be analyzed in two dimensional conditions.
5) Obtain a relationship between blood velocities, heart beat and vein diameter during diastolic condition.

1.5 ORGANIZATION OF THE THESIS

This thesis is organized from:

1) Chapter 1- Introduce to the problem statements and scope for this study.
2) Chapter 2- Review of papers and discuss the limitation and similarities among the journals.
3) Chapter 3- Heart model design and materials used.
4) Chapter 4- Result and discussion of the calculation and images.
5) Chapter 5- Conclusion and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Studies of the heart valve are divided into few categories which are the modeling experiment, mathematical modeling, computational analysis, and simulation. The modeling experiment of heart structure will give a better understanding on the function of heart, and pattern of fluid flow thus, enhance the development in the heart structure study. Additionally, the numerical study on the heart structure and fluid flow also play a significant role on the development of artificial heart study.

2.2 RELATIONSHIP BETWEEN LEAFLET BEHAVIOUR AND FLUID FLOW PATTERN

Hart (2000) is focusing on influence of aortic heart valve structure to the pattern of fluid flow. The author studied the vortex formation after aortic valve during diastole using numerical and modeling experiment. This modeling experiment applied different aortic valve leaflet thickness and the flow is supplied periodically so the movement of the leaflet can be established. Additionally, the finite element method was applied in this experiment for fluid and structural computation. The aim of the author to employing computational analysis is to validate the result on the structure of fluid flow from simulation with the experimental model as shown in Figure 2.1. In the numerical study, the author had involved two dimensionless parameters which are Reynolds and Strouhal number are around 800 and 0.19 respectively.

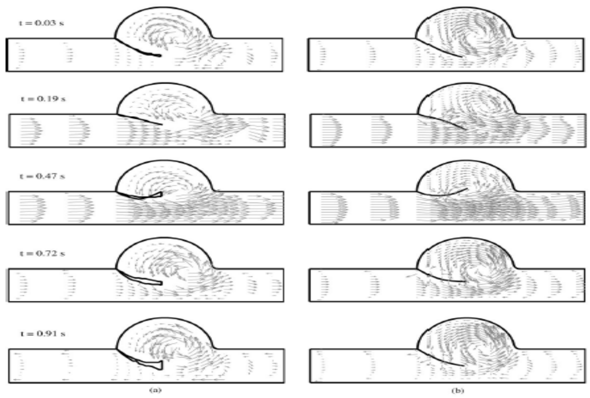

Figure 2.1: Comparison of fluid flow vector after the valve from experiment (a) and numerical (b) for leaflet thickness 0.16mm

Source: Hart 2000

2.3 BLOOD FLOW IN LEFT VENTRICLE

Left ventricle is the heart chamber which receives and delivers oxygenated blood to the entire body. Domenichini et.al (2007) analyzed the structure of fluid dynamics in left ventricle using the combination of numerical and experimental models. In the experiment model, movement of blood throughout the heart chamber is caused by the dynamic ventricle wall controlled by a computerized piston device. In this experiment, heart valves does not included into the study. Two check valves are installed at mitral and aortic tubes to avoid back flow. After the experiment, the result showed a strong agreement on the vortex formation between numerical and experimental modeling. Vortex ring formation in the numerical study (see Figure 2.2) had shown a clearer result compare to the modeling experiment. Additionally, these results also agree that the fluid flow in the heart chamber is more complex during diastolic phase (Domenichini, 2007).

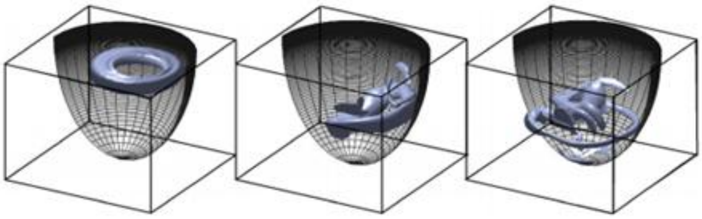

Figure 2.2: 3D vortex ring formation shown in simulation

Source: Domenichini 2007

2.4 CONTINUOUS BLOOD FLOW THROUGH MITRAL VALVE

Mitral valve is also known as bicuspid valve which separate left ventricle and atrium. Mushtak et. al (2010) used a continuous fluid flow in an open system through the mitral valve and recored the flow by using digital camera. However, it is different with the actual fluid flow in human heart valve because the blood flow in the heart is conduct in a close system with pulsate flow. On the other hand, the numerical study by using Fluid Structure Interaction (FSI) on the same heart design also had been carried out. The result proved that the flows from both experiments are similar (see Figure 2.3). However, in the FSI simulation, the authors used two parameters; the blood density and viscosity. However the parameters used in the flow model are unknown (Al-Atabi 2010).

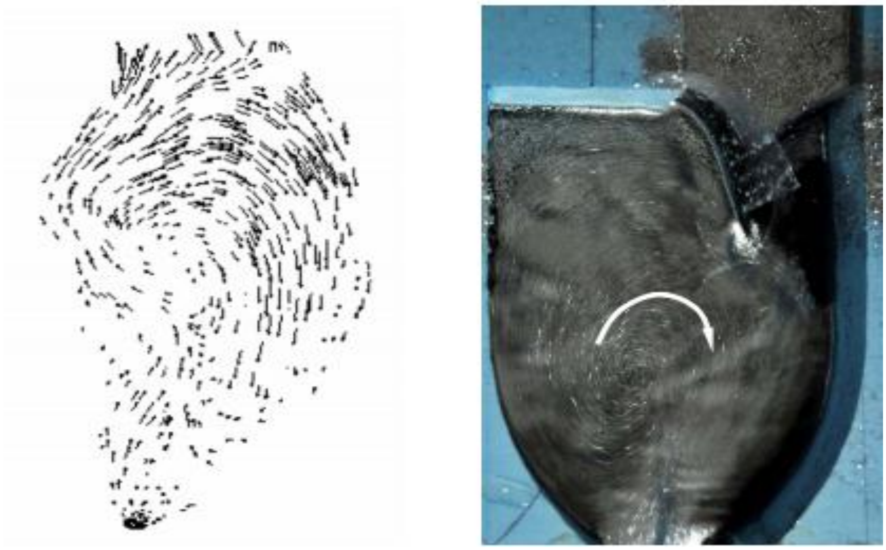

Figure 2.3: Comparison of the result from MRI scans and modeling experiment on the vortex formation in left ventricle

Source: Al-Atabi 2010

2.5 LEFT VENTRICULAR DEFORMATION

Movement of the ventricle wall also is one of the factors which affect the pattern of fluid flow in the heart chamber. Hence, a study of movement of the human heart contraction by the help of the Magnetic Resonance Imaging (MRI) and been developed by Bistoquet(2007). At the beginning of the study, the author used two assumptions:

1) Incompressibility of the myocardium muscle, and
2) Any point on the left ventricular wall will only move at the normal direction to the original point.

These assumptions are made because the MRI cine does not contain enough information to estimate both criteria during cardiac cycle. To observe the 3-D contraction of the heart muscle, the author divided the heart into a few segments and use pseudo thin plate to interpolate the nodes on that segment. These nodes are used to be a reference point for the motion of the ventricle wall (see Figure 2.4 (b)). All the movements of the nodes are represented in a vector form (see Figure 2.4 (c)). To validate this result, the study on the patient that have heart disease and repetition of the MRI scanning had been carried out on the same subject after four months and the result of the ventricle wall deformation before and after four months are agreed well (Bistoquet, 2007).

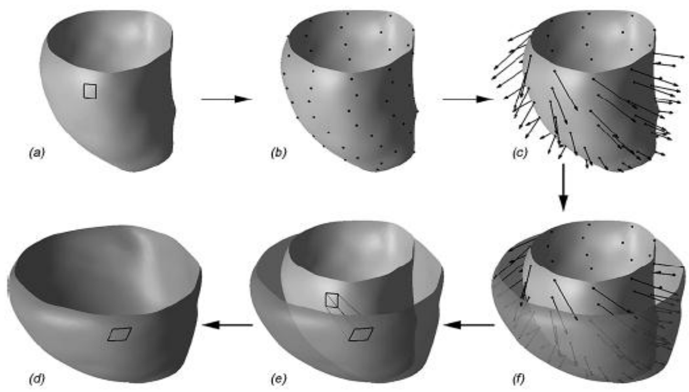

Figure 2.4: The sample of nodes, vector and deformation of the left ventricle

Source: Bistoquet 2007

2.6 CARDIAC MOVEMENT DETECTION

Heart disease can be classified into structure and motion abnormalities. Both types of disease can be detected by the echocardiogram. So, it is possible to carry out automatic disease detection by using echocardiogram. One of the common methods used is scale invariant features on edge-filtered motion magnitude mapping on the echocardiogram (Kumar, 2010). The sources of this method are coming from the Echocardiogram videos. The interest point on the feature will be selected from the edge-filtered features and the motion will be detected in two dimensional (see Figure 2.5).

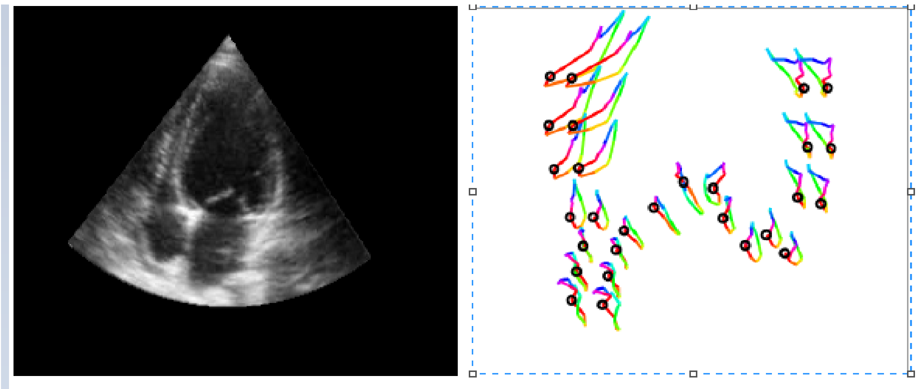

Figure 2.5: The picture of a normal person echocardiogram and the velocity movement profile of left ventricle

Source: Kumar 2010

2.7 SIMULATION OF CARDIAC MOTION BY USING FEM

In order to obtain a similar shape as human left ventricular shape, using a set of MR images to extract a 2-D feature of heart is required. However, to obtain a more accurate data 3-D feature is needed for the simulation. So as to generate 3-D image data, 3-D smoothing filter is one of the method used (Amano 2007). Beside the 3-D images, cell orientation and material properties of left ventricular tissue are also important criterions which affect the heart muscle movement. Figure 2.6 illustrated the shape of the left ventricle deformation model during end of diastole and systole by using FEM. The result showed that the contracting force is varying depends on the cell orientation. (Amano 2007).

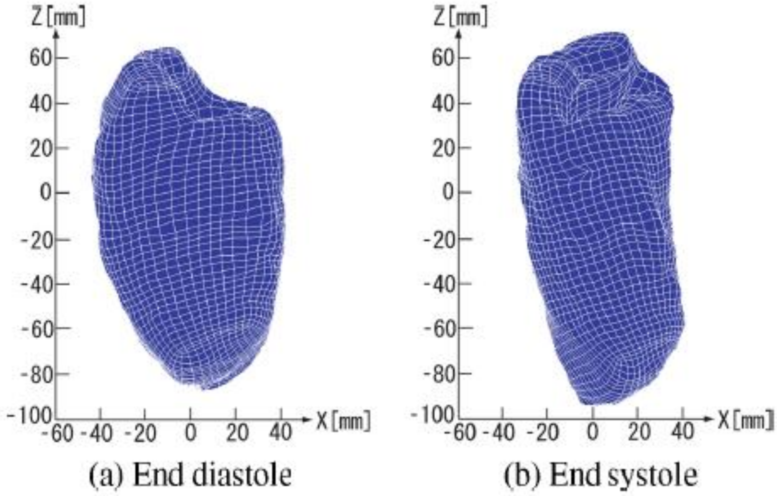

Figure 2.6: Left ventricle deformation of simple cell orientation

Source: Amano 2007

2.8 COUPLING SIMULATION

Nobuaki (2005) combined the simulation result from the mechanical and circulation model to obtain a high accuracy result regarding to the volume, pressure, and contraction force respect to time. The convergence calculation will be the coupling method use in this experiment. The basic concept of this coupling method is shown in Figure 2.7. There are two main equations used in this experiment:

$$\frac{dV_{lv}}{dt} = \frac{P_{lv} - P_a}{R_{lv\_a}} \tag{2.1}$$

$$c(P_a - P_{a0}) + (V_{lv} - V_{lv0}) + \frac{P_a}{R}.dt = 0 \tag{2.2}$$

The FEM solver and circulation simulator (windkessel model) are used to obtain the coefficients in the calculation model. In order to solve the Equation 2.1 and 2.2, the author had also fixed the boundary condition during isovolumic contraction, ejection, isovolumic relaxation, and filling phase.

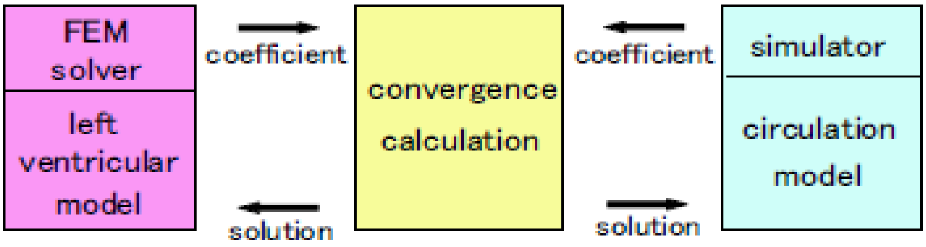

Figure 2.7: Simple system configuration

Source: Nobuaki 2005

2.9 HEART CAVITY PROFILE MOVEMENT

Similar to Kumar (2010), Riyadi (2009) also used the images from echocardiogram to detect the cardiac movement of healthy left ventricle. The methodology involved several tasks such as the collection of echocardiogram images, the computation of optical flow field and the extraction of the movement profile. The optical flow field is computed regarding to the intensity of the image which is similar to the method for analyzing the echocardiogram images. The author separates the left ventricular images into few segments. The result showed the displacement and direction (angle) profile regarding to different segments (see Figure 2.8). This result can contribute to the medical field to detect the abnormality of the human heart.