PREDICTION MODEL FOR DEGENERATION BEHAVIOUR OF MITRAL VALVE

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ABSTRACT

Degenerative mitral valve prolapse without proper monitoring can cause severe mitral valve failure and occasionally lead to sudden death if the surgical correction is not performed on time. In most cases, mitral valve prolapse would cause mitral regurgitation which in a severe case would lead to left ventricle failure due to hemodynamic burden. The aim of this study is to develop a model to predict the degeneration behaviour of mitral valve which will aid the medical practitioner to estimate the mitral valve condition based on the available mitral regurgitation data by echocardiogram assessment. Minimal hemodynamic model has been adopted with modification to obtain mitral regurgitation severity information. The stress-strain behaviour of mitral leaflet has also been studied to model the degeneration of the mitral valve leaflet. Both models were validated with the previously published data generated using Windkessel and Burkhoff methods. The coupling of both models gave the degenerative behaviour of mitral valve leaflet in relation with mitral regurgitation severity. The mitral valve degeneration was assessed by mitral valve leaflet elasticity properties while the severity of mitral regurgitation was measured by the volume of mitral regurgitation into the left atrium. It was found that the reduction of mitral valve leaflet elasticity would cause an increase of the mitral regurgitation volume into the left atrium. Mitral regurgitation severity was found to be less than 10% of left ventricle stroke volume when the mitral valve leaflet degenerates more than 90%. At this point, even with a slight increase of less than 10% in the degeneration of mitral valve leaflet, the regurgitation volume might increase suddenly from 5% up to 95% of the left ventricle stroke volume.

ABSTRAK

Kegelinciran injap *mitral* yang bertambah teruk tanpa sebarang rawatan atau perhatian, boleh menyebabkan kegagalan injap *mitral* dan seterusnya kematian mengejut sekiranya pembedahan koreksi tidak sempat dijalankan. Dalam kebanyakan kes, kerosakan injap *mitral* akan menyebabkan kebocoran yang mana dalam keadaan yang teruk akan menyebabkan kegagalan kepada ventrikel kiri akibat daripada beban hemodinamik. Kajian ini menyasarkan untuk membangunkan sebuah model bagi meramal sifat kemerosotan injap *mitral* yang akan dapat membantu pengamal perubatan untuk menganggarkan keadaan injap *mitral* berdasarkan data kebocoran pada injap *mitral* daripada imej *echocardiogram*. Model hemodinamik minimal telah dipadankan dan diubahsuai untuk mendapatkan maklumat keadaan kebocoran pada injap *mitral*. Sifat tegasan-terikan injap *mitral* juga dikaji untuk menjana model bagi sifat kemerosotan injap *mitral*. Model tersebut disahkan dengan data yang telah diterbitkan dan dijana dengan menggunakan kaedah *Windkessel* dan *Burkhoff*. Penggabungan kedua-dua model tersebut membolehkan maklumat hubungan di antara sifat kemerosotan injap *mitral* terhadap isipadu yang bocor pada injap *mitral* diketahui. Kemerosotan injap *mitral* dinilai berdasarkan tahap kekenyalan injap tersebut manakala tahap kebocoran pula dinilai berdasarkan jumlah isipadu darah yang bocor ke dalam aurikel kiri. Kajian ini telah mendapati bahawa penurunan tahap kekenyalan injap *mitral* telah menyebabkan pertambahan isipadu yang bocor pada injap *mitral* ke dalam aurikel kiri. Keterukan kebocoran injap *mitral* adalah kurang 10% daripada jumlah isipadu strok bagi ventrikel kiri apabila injap *mitral* telah merosot lebih daripada 90%. Pada takat ini, dengan pertambahan kemerosotan injap *mitral* pada kadar yang sedikit sahaja iaitu kurang daripada 10%, akan menyebabkan pertambahan isipadu yang bocor secara mendadak daripada 5% kepada 95% daripada jumlah isipadu strok ventrikel kiri.

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LIST OF SYMBOLS

A	area [m²]
C	coefficient
D	damping factor [rad^{-1}]
E	Young's Modulus [kPa , MPa]
E	elastance [mmHg/ml]
F	force [N]
H	heaviside function
K	gain factor [mmHg^{-1}]
l	length [m]
L	inductance [mmHg s²/ml]
P	pressure [mmHg]
Q	flow rate [ml/s]
R	resistance [mmHg s/ml]
r	radius [m]
t	time [s]
u	velocity [m/s]
V	volume [ml]
z	distance [m]

Greek Symbols

δ	deflection [m]
λ	parameter for EDPVR
θ	angle [rad]
ρ	density [kg/m³]
τ	shear stress [Pa]
ω	eigen frequency [rad/s]

Subscripts

ao	aorta
av	aortic valve
d	discharge
ed	end diastolic
es	end systolic
lv	left ventricle
max	maximum
mt	mitral valve
o	initial
pa	pulmonary artery
pu	pulmonary vein
pul	pulmonary system
pv	pulmonary valve
reg	regurgitation
rv	right ventricle
s	static
tc	tricuspid valve
sys	systemic system

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CHAPTER 1

INTRODUCTION

1.1 Background

Mitral valve prolapse without proper monitoring can cause severe mitral valve failure and occasionally leading to sudden death if the surgical correction is unable to take place in time. A study by Grigioni [1] indicates the sudden death rate due to the mitral valve failure was 1.8% per day . Some of the death occurs after the surgery of the replacement of the mitral valve leaflet. Some of the patients remain with their current condition without undergoing for surgery which indicates the surgery was not accepted widely as the solution at that time [2].

Degenerative mitral valve disease is a common mitral valve disorder affecting approximately 2% of worldwide population [3] and mitral valve prolapse is the common cause of the degenerative mitral valve disease [4]. However, in some cases, mitral valve prolapse did not cause any symptoms or even mitral regurgitation to patients [5].

Unmonitored mitral regurgitation with mitral valves leaflet degeneration always leads to congestive heart failure which is a condition where the heart cannot pump sufficient blood to the body [6]. Approximately 23 million people are diagnosed with congestive heart failure globally. Patients with severe cases of congestive heart failure died within one year from the discovery in majority [7]. Furthermore, heart failure was the most common cause of hospitalization in Asia representing about 24% of the total patients [8]. Due to the above case, many studies

on the mitral valve diseases and failures have been conducted not only by medical practitioners, but also by non-medical practitioners and engineers [9-17].

Although no specific statistics published for mitral valve disease in Malaysia, there are statistics on causes of death in Malaysia with ischemic heart disease was ranked the highest cause of death in Malaysia by statistics for the year of 2005 to 2008 [18-21]. The Statistics on Causes of Death by Department of Statistics, Malaysia for the years from 2005 to 2008 indicated that certified cause of death due to heart disease increased from 11.5% in 2005 to 12.9% in 2008. The percentage of 11.5% in 2005 represents approximately 9,986 deaths and was increased to 10,064 in 2008. On the time of this thesis was completed, the available Statistics on Causes of Death in Malaysia was only up to the year of 2008. Additionally, ischemic heart disease was also major cause of death and disability in developed countries based on a study conducted in 2012 [22].

Debates on timing for surgery by medical practitioners on their patient with mitral valve prolapse and mitral regurgitation is still ongoing [23-26]. Medical specialists have different opinions on the reasons for early surgery and delay in surgery with highlights on advantages for both choices. Differences in opinions on timing for surgery whether early surgery should be encouraged to the patients or otherwise had leaded to the proposal for a tool for medical practitioners to aid their decision on the issue.

It is therefore, this research was aimed to develop a model to aid the medical practitioners in making their decision on the treatment for patients. The model is meant to provide clearer information for the medical practitioners to assess the severity of the mitral valve prolapse. The data obtained in this research then can be used to determine the suitable treatment for the patients such as replacement, repair or reinforcement of the mitral valve leaflet.

This research was focusing on the blood flow into the left ventricle via mitral valve. The study was conducted on the case of mitral valve prolapse which lead to mitral regurgitation. This study was done by simulation and also by experiment.

Experimental data was obtained from the echocardiogram images of patients with mitral regurgitation.

1.2 Research Problem

Mitral valve prolapse in most cases lead to mitral regurgitation [6]. Presently, most medical practitioners utilize echocardiogram to evaluate patients' condition for their decision on patients' treatments [15, 27, 28]. Therefore, it is important to understand the mitral valve leaflet behaviour especially for prolapse mitral valve and to relate this leaflet behaviour to the mitral regurgitation severity.

This study was conducted to analyze the correlation between mitral regurgitation and mitral valve leaflet behaviour for mitral valve with prolapse condition, and to find the representation of mitral regurgitation severity and mitral valve prolapse condition for a development of a model to be utilized by medical practitioners as rapid diagnosis tool.

1.3 Research Objectives

The study was conducted to fulfill the following objectives:

(a) to predict the mitral valve leaflet condition by estimation of mitral valve leaflet elastic behaviour.
(b) to model mitral regurgitation behaviour over a cardiac cycle and under different mitral valve leaflet conditions.
(c) to develop a model which correlates mitral regurgitation volume and mitral valve leaflet degeneration to be utilized as rapid diagnosis tool for medical practitioners.

1.4 Research Questions

The research questions for this study were:

a) What is the relation between mitral regurgitation orifice area and mitral regurgitation flow rate?
b) How mitral regurgitation volume does correlates with mitral regurgitation orifice area?
c) How mitral regurgitation severity does correlates with mitral valve leaflet condition?
d) How does the degenerative behaviour of mitral valve leaflet affect the mitral regurgitation severity?

1.5 Research Methodology

The research was conducted by two methods; experimental and numerical simulation. Echocardiogram images analysis was taken as the experimental aspect for this research and was being complemented by program code developed in MATLAB for the numerical simulation.

Echocardiogram images of patients with mitral valve prolapse and mitral regurgitation were analyzed visually for the extraction of mitral regurgitation and mitral leaflet deflection information. Mitral leaflet Young's modulus and mitral regurgitation severity were calculated by employing beam deflection principle for mitral leaflet Young's modulus and by grid independent technique for mitral regurgitation severity. Degenerative behaviour of mitral valve leaflet was estimated in relation to mitral regurgitation.

On the numerical simulation, established Cardiovascular System (CVS) Model was employed. The model was upgraded to capture the mitral regurgitation and mitral valve prolapse. Mitral valve leaflet degeneration was simulated in relation to mitral regurgitation volume to complement the same parameters evaluated by experimental method.

Mitral valve leaflet elastic behaviour in relation to the first objective of this study was estimated by determination of mitral valve leaflet Young's modulus. The Young's modulus values were estimated based on the deflection of mitral valve leaflet with respect to the pressure differential between left atrium and left ventricle.

Next, mitral regurgitation behaviour was estimated based on the mitral regurgitation volume calculated with relation to pressure differential between left atrium and left ventricle, and the deflection of the mitral valve leaflet. The deflection of mitral valve leaflet determines mitral regurgitation orifice area which was utilized to calculate the volume of mitral regurgitation.

Finally, the behaviour mitral leaflet Young's modulus and mitral regurgitation volume were coupled to create a model of correlation between the two behaviours. Additionally, the worsening condition of mitral valve leaflet which is also known as degenerative mitral valve leaflet condition was included in the model and also simulated against mitral regurgitation behaviour. The model can be utilized as rapid diagnostic tools to estimate mitral valve leaflet conditions with input information of mitral regurgitation volume or orifice area from echocardiogram images.

1.6 Chapters Overview

This thesis consists of six chapters discussing on the prediction of mitral valve behaviour by fluid and structure interaction approach inclusive of this chapter of introduction as Chapter 1.

Chapter 2 covers the literature review on topics related to this study ranging from the basic of mitral valve to the previous studies conducted by several researchers which are being value added by this study.

In the next chapter, the determination of mitral valve leaflet Young's modulus with relation to mitral regurgitation volume is discussed. The related study appeared in a conference proceedings [29]. Determination of correlation between

Young’s modulus of mitral valve leaflet and mitral regurgitation volume was conducted by utilizing 2D echocardiogram images.

Next, the numerical model on cardiovascular system is discussed in Chapter 4. The methodology of this study on modeling of mitral valve behaviour is inclusive of overall cardiovascular system modeling to capture the accurate situation of mitral valve leaflet under the cardiac cycles. Additionally, the structure of the mitral valve leaflet was modeled based on deformation caused by the prolapsed mitral leaflet which allow the mitral regurgitation. The mitral regurgitation volume and mitral valve leaflet degeneration behaviour was coupled to establish correlation between them by mitral regurgitation orifice area and pressure differences which were utilized to calculate both mitral regurgitation volume and mitral valve leaflet degeneration.

Chapter 5 discussed mainly on the simulation results to verify the model proposed in this study. All elements of output outlined in Chapter 4 are being discussed in this chapter. Most important is the findings on correlation between mitral valve leaflet Young’s modulus and mitral regurgitation volume also capturing the element of degenerative mitral valve leaflet.

Finally, Chapter 6 outlined the conclusions of this study and some recommendations have been made for further investigation on mitral valve behaviour with extension of current model employed in this study.

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