Borneo International Journal eISSN 2636-9826; Vol. 2 (2); 2019; 1-15
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Estimation of mitral valve degenerative behavior with mitral regurgitation

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Received: 25 November 2019
Accepted: 12 December 2019
Online Published: 12 December 2019

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.

Keywords: Mitral degeneration, Estimation model, Mitral regurgitation

Nomenclature

A	area [m²]
C	coefficient
D	damping factor [rad-1]
E	Young's Modulus [kPa , MPa]
E	elastance [mmHg/ml]
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]

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

1. INTRODUCTION

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].

Debates on timing for surgery by medical practitioners on their patient with mitral valve prolapse and mitral regurgitation is still ongoing [18-21]. 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.

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, 22, 23]. 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.

Past mitral valve models

Various models of mitral valve with a wide range of complexity had been in the field for past years. They had been utilized for different purposes from the researchers to the medical practitioners mainly for deeper understanding on the mitral valve itself and also as aid for better decision on the patients' treatments [24-26].

Different modeling approaches had also been taken by researchers such as finite elements method (FEM), fluid-structure interaction and physical modeling by software. Windkessel [27] and Burkhoff [28] are some of the established models that had been intrroduced.

Minimal Cardiovascular System model started with minimal hemodynamic model with interaction between ventricles [29]. The model captured the behaviour of left and right ventricles, but the discussion was focusing more on left ventricle. On the early stage of minimal hemodynamic model, the simulation was focusing on left and right ventricles with rough estimations on the overall cardiovascular system. The model continued to be developed in series until it captured the overall model of cardiovascular system which is very useful in the case of this study.

Paeme et. al [30] utilized the CVS model with modifications to analyze mitral insufficiency. The model used in the study was first developed by Smith et al. [29, 31] which was verified with published experimental results. With additional elements of mitral valve aperture area, the model was able to simulate the deficiency of the mitral valve. Their model however is extendable with some modification to mitral valve prolapse characteristic to be simulated in the model.

Additionally, Paeme et al [32, 33] had also studied the structural behaviour of mitral valve leaflet with extension to CVS model. The model was extended from their earlier CVS model. Although the above-mentioned CVS model had been developed with the elements of structural behaviour of the mitral valve leaflet, the correlation of mitral valve leaflet condition and the severity of mitral regurgitation was never been taken into consideration. The structural mitral valve leaflet behaviour was based on rotational spring concept which only reflects the stiffness of the mitral valve, not the Young's modulus.

Hemalatha et. al. [34] simulated the velocity across heart valve by electrical analogy approach with lump parameters. However, the study was generalized to all heart valves. The results were on velocity profiles across heart valves for normal and abnormal heart valves.

Various models had been developed over the past years with improvements. However, there are still no model that relates directly the mitral valve leaflet degenerative behaviour and mitral regurgitation volume. Therefore, the relationship between mitral regurgitation severity and mitral valve leaflet degenerative behaviour was the highlight of this research to enhance existing models so that the understanding on mitral regurgitation and mitral valve prolapse behaviours would be more comprehensive. Table 1 summarized the past mitral valve models discussed in this section.

Table 1. Summary of past mitral valve models

AUTHORS	Model & Focus Area
Smith [29]	Minimal haemodynamic closed loop model with ventricles interaction.
Paeme [30]	Cardiovascular System Model with mitral insufficiency **applicable only for functional regurgitation*
Moorehead [33]	Simplified model of mitral valve dynamics – prediction of mitral valve stiffness based on angle of leaflet
Hemalatha [34]	Simulation of velocity across cardiac valve by electrical analogy of human circulation system

2. METHODOLOGY

Blood flow governing equations

The base model for this study is the minimal hemodynamic model which had been verified by several researchers [31]. It is a six chambers model of the human circulation system with focus on the heart. The following were considered as chambers in the model:

a) Pulmonary vein
b) Left ventricle
c) Aorta
d) Vena cava
e) Right ventricle
f) Pulmonary artery

Figure 1 shows the analogy of the cardiovascular system as an electrical circuit system. All chambers are characterized by the pressure, *P*, volume, *V*, and elastance, *E*, of the chambers. While valves are characterized by diode, resistors and inductors as indicated in the diagram. Diode in electrical circuit only allow one-directional flow of current which in the case of cardiovascular system, current is represented by flow rate, *Q*. The cardiovascular system modeled the systemic and pulmonary circulation system with resistors analogy which provides resistance, *R*, to the flow. Ventricular interaction modeled the interaction between ventricular walls within the heart to simulate pressure and volume interaction between left ventricle and right ventricle in a cardiac cycle. Left atrium and right atrium inside this model are treated as transit point for blood to flow to left ventricle and right ventricle thus no volume are simulated for both of the atriums. The pressure of left atrium will be the same as pulmonary vein and for right atrium, the pressure shall be the same as vena cava.

Blood flow in the human circulation system was assumed to be a flow through a tube which was governed by Navier-Stokes equation as in Eq. (1).

$$\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}=\frac{1}{\rho}\frac{\partial P}{\partial z}+\nu\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right\} \tag{1}$$

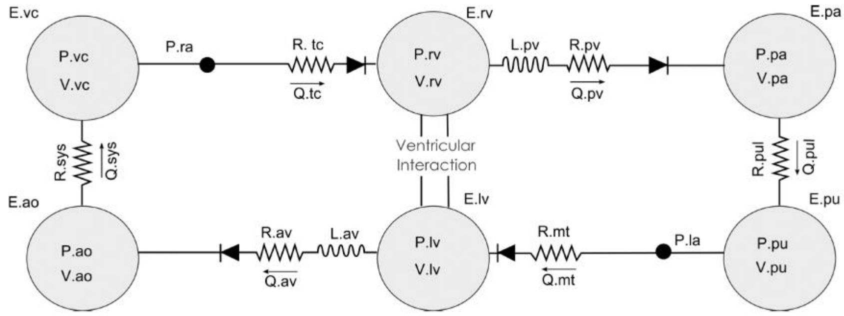

Figure 1. Cardiovascular system (CVS) model as an analogy of electrical circuit [30].

Cardiovascular system modelling equations

Each cardiac chamber is characterized by the time varying elastance which relates the pressure and volume in the chamber [29, 31, 35, 36]. First, the pressure-volume relationships during end systole and end diastole are defined by Eq. (2) and (3).

$$P_{es}=E_{es}\left(V_{es}-V_d\right) \tag{2}$$

$$P_{ed}=P_o\left(\exp\left(\lambda(V-V_o\right)-1\right) \tag{3}$$

Elastance of each cardiac chamber at any time is determined by the control of driver function e(t). Driver function values ranges from 0 to 1. At e(t) = 1, the chamber is at end systole phase, while e(t) = 0 indicate that the chamber is at end diastole phase.

There are several profiles of driver function with ranges of complexity by previous researchers [29, 37-40]. Driver function as defined in Eq. (4) was utilized in the study. This driver function had been used previously in several cardiovascular system models [30, 41]. Driver function governs the elastance of the left ventricle which represent the muscle contraction and relaxation.

$$e(t)=\sum_{i}^{N}A_i\exp(-B_i((t \bmod period)-C_i)^2) \tag{4}$$

Then, pressure-volume relationship in the cardiac chamber at any time, t, is defined by Eq. (5).

$$P(V,t)=e(t)P_{es}+(1-e(t))P_{ed} \tag{5}$$

Flow rate defined in Eq. (6) represent flow rate across a point in the cardiovascular system where in the case of this research would be the mitral valve.

The flow rate is dependent on the pressure differential between the two chambers that is connected by the point and resistance on the point to blood flow.

$$Q = \frac{P_{in} - P_{out}}{R} \tag{6}$$

The volume change rate of a cardiac chamber is governed by Eq. (7). The difference between incoming flow rate an outgoing flow rate determine the volume change rate of any cardiac chamber in the CVS Model. Incoming and outgoing flow rates can be calculated by Eq. (6).

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{7}$$

When the inertial added into the system in term of inertance as defined by Eq. (8), first order differential equation is formed that reflect the rate of change for flow rate at any time across a point in the cardiovascular system as defined by Eq. (9). Resistance in Eq. (6) and Eq. (9) is assumed constant which does not vary with flow rate based on the assumption that the flow is a fully developed flow.

$$L = \frac{\rho l}{\pi r_o^{\,2}} \tag{8}$$

$$\frac{dQ}{dt} = \frac{P_{in} - P_{out} - QR}{L} \tag{9}$$

The complete system of ordinary differential equations representing the CVS Model as in Figure 1 are defined by Equation (10)-(17) [30]:

$$\frac{dV_{pu}}{dt} = Q_{pul} - Q_{mt} \tag{10}$$

$$\frac{dQ_{mt}}{dt} = \frac{P_{pu} - P_{lv} - Q_{mt}R_{mt}}{L_{mt}} \tag{11}$$

$$\frac{dV_{lv}}{dt} = Q_{mt} - Q_{av} \tag{12}$$

$$\frac{dQ_{av}}{dt} = \frac{P_{lv} - P_{ao} - Q_{av}R_{av}}{L_{av}} \tag{13}$$

$$\frac{dV_{ao}}{dt} = Q_{av} - Q_{sys} \tag{14}$$

$$\frac{dV_{vc}}{dt} = Q_{sys} - Q_{tc} \tag{15}$$

$$\frac{dQ_{tc}}{dt} = \frac{P_{vc} - P_{rv} - Q_{tc}R_{tc}}{L_{tc}} \tag{16}$$

$$\frac{dV_{rv}}{dt} = Q_{tc} - Q_{pv} \tag{17}$$

The basic of CVS Model of Eq. (10)-(17) is the volume change rate of Eq. (7) and the rate of change for flow rate of Eq. (9). The first order ordinary differential equation (ODE) set consists of ten unknowns representing volumes for all six chambers and flow rates for all four valves in the cardiovascular system. In order to obtain required parameters of volume for left ventricle and flow rate for mitral valve, the ODE set must be solved as a closed loop CVS Model.

The CVS Model ODE set model in detail the six chambers and four valves in the cardiovascular system including systemic and pulmonary circulations throughout the entire body. Each of Eq. (10), Eq. (12), Eq. (14), Eq. (15), and Eq. (17) relates the change in volume of a cardiac chamber with the inlet and outlet flow rate through valves at each chamber. Eq.(11), Eq. (13), and Eq. (16), each of them relates the change of flow rate at respective valve to the pressure inside two nearby chambers, flow rate across valves, resistance across valve and inertance of the valve.

Solution for unknowns in the CVS Model was obtained by a computer program code written in MATLAB environment. The program was written to provide solution of instantaneous flow rate across cardiac valves, instantaneous volume and pressure in any cardiac chamber. Extraction of information for mitral valve and left ventricle was programmed to be automatic so that the information can be directly utilized without the need to quit the computer program.

Mitral regurgitation volume

Mitral regurgitation can be visualized as flow of liquid through an orifice plate. Therefore, the mitral regurgitation volume can be calculated based on the following Gorlin hydraulic orifice equation [42-45]:

$$V_{reg,mt} = A_{reg,mt} \times C_{d,mt} \times \sqrt{\Delta P_{mean}} \times t_{reg} \tag{18}$$

Mean pressure gradient, in Eq. (18) is the mean pressure different between left ventricle and left atrium. Left atrium pressure on average is assumed to be the same as pulmonary artery pressure in the CVS Model. The area of regurgitation is the mitral regurgitation orifice area which was modelled as percentage over the maximum effective opening area of mitral valve.

The importance of mitral regurgitation volume in the study was to determine the severity of mitral regurgitation. Therefore, to have a better illustration in the severity of mitral regurgitation, the mitral regurgitation volume was also expressed in term of percentage over the left ventricle stroke volume. The percentage illustrates the amount of blood flowing back to the left atrium instead of being ejected of the heart from the left ventricle.

Mitral leaflet mechanics

The opening and closing of mitral valve can be related to the differential of pressure between the left ventricle and left atrium. Mitral valve will close when the pressure in the left atrium is lower than the pressure in the left ventricle and will open on the opposite condition of pressure differential.

A simple deflection method was utilized to determine the Young's modulus value of the mitral valve leaflet during the regurgitation. The deflection of mitral valve leaflet was determined based on the regurgitation orifice area which reflected the approximate length of the mitral valve leaflet deflected into the left atrium. Eq. (19) estimates the deflection of mitral valve leaflet.

$$\delta_{reg,mt} = \frac{A_{reg,mt}}{l_{contact,mt}} \tag{19}$$

The Young's modulus for mitral valve leaflet during the regurgitation was then calculated based on Eq. (20) with modification to stress to be taken as pressure gradient between left atrium and left ventricle [46] with the analogy of deflection of a flexible beam. Left atrium pressure in this study was considered as the same as pulmonary vein pressure due to no valve was separating between the left atrium and pulmonary vein, $\Delta P = P_{lv} - P_{la} = P_{lv} - P_{pu}$.

$$E_{mt} = \frac{(\Delta P) l_{mt}}{\delta_{reg,mt}} \tag{20}$$

Borneo International Journal eISSN 2636-9826; Vol. 2 (2); 2019; 1-15
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l_{mt} in Eq. (24) is referring to the radial length of the mitral valve leaflet. The length represents the longest length of mitral valve leaflet from the heart wall.

4. RESULTS AND DISCUSSIONS

Left ventricle pressure-volume relationship

The PV diagram generated by the CVS Model in this research was validated with previously published PV diagram by other researchers as shown in Fig. 2 [29, 30]. The trend of PV diagram generated by the simulation in this research matched the trend of both PV diagrams published by Smith and Paeme. Pressure and volume values were slightly in offsets from Paeme. But there was difference in the stroke volume between PV diagrams generated in this research with Smith's PV diagram. This is due to the difference in values for input parameters used between Smith and this research. The input data used in this research however, close to Paeme input data which justify the relation between PV diagram generated in this research and Paeme's PV diagram. Pressure values did not differ much between all the three PV diagrams.

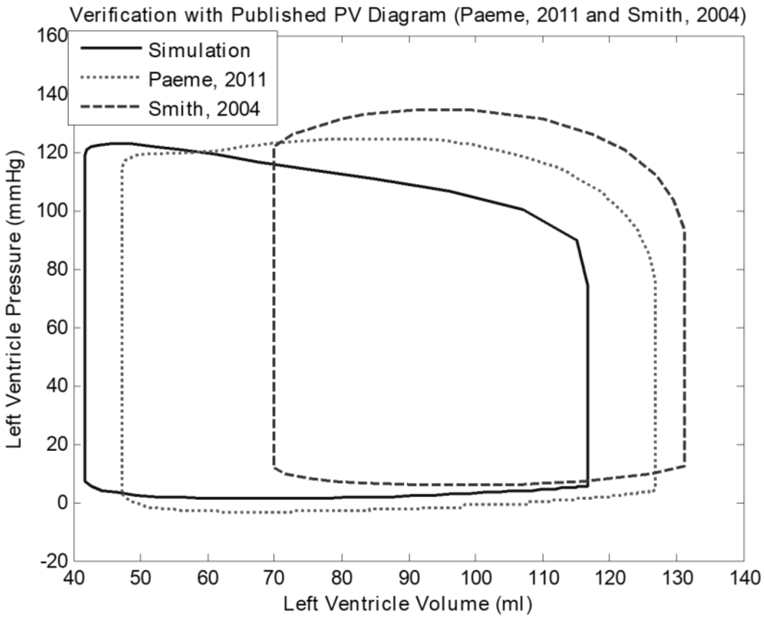

Fig. 2. Verification of PV Diagram

Mitral regurgitation

Regurgitation across mitral valve occurs during systolic phase when the blood partially returns to the left atrium. In this research, the severity of mitral regurgitation is determined by the negative flow rate that occurs when mitral regurgitation orifice area was introduced in the simulation. Mitral regurgitation orifice area was specified in percentage of effective normal mitral valve opening orifice area. This will make the program universal to various subjects as human bodies are different from one person to another. Hence, medical practitioners can utilize the model directly by obtaining the input parameters of mitral regurgitation orifice area from echocardiogram images in percentage of effective mitral valve opening area.

Mitral regurgitation orifice area introduced in the simulation was 0% to 55% of effective mitral valve opening for healthy mitral valve. 0% of mitral regurgitation orifice area represents healthy mitral valve leaflet. Calculation of mitral regurgitation flow rate was made by modification of resistance value of the mitral valve based on Eq. (21). The radius in Eq. (21) is the radius of full opening of the healthy mitral valve. With the introduction of mitral regurgitation orifice area, the value of resistance varies according to the regurgitation orifice area being introduced to the simulation. The orifice area of regurgitation was reflected in the opening radius of the mitral valve.

$$R = \frac{8\eta l}{\pi r_o^4} \tag{21}$$

The mitral regurgitation area was introduced up to only 55% of the mitral valve opening based on the initial trial where at 55%, the mitral regurgitation flow rate was almost the same as the transmitral flow rate during filling phase. This indicates that almost all of the blood flowing from the left atrium into the left ventricle during filling phase is flowing back into the left atrium from the left ventricle during ejection phase. Hence the assessment for the case of mitral regurgitation area beyond 55% was not an issue as it is considered as critical stage and the patient should undergo a replacement or repair. Additionally, that case might contributes to the fatal outcome of the patient.

The results presented are for mitral regurgitation orifice area of 5%, 10%, 20%, 30%, 40%, 50% and 55% shown in Fig. 3. Starting with 5% mitral regurgitation orifice, the simulated results does not show significant regurgitation flow rate into the left atrium during the mitral valve closure. When the mitral regurgitation orifice area was increase to 10%, the regurgitation flow rate was still low as compared to transmitral flow rate during left ventricle filling stage. The peak regurgitation flow rate at this point was recorded at less than 20 ml/s which was approximately 5% of the peak transmitral flow rate during filling phase.

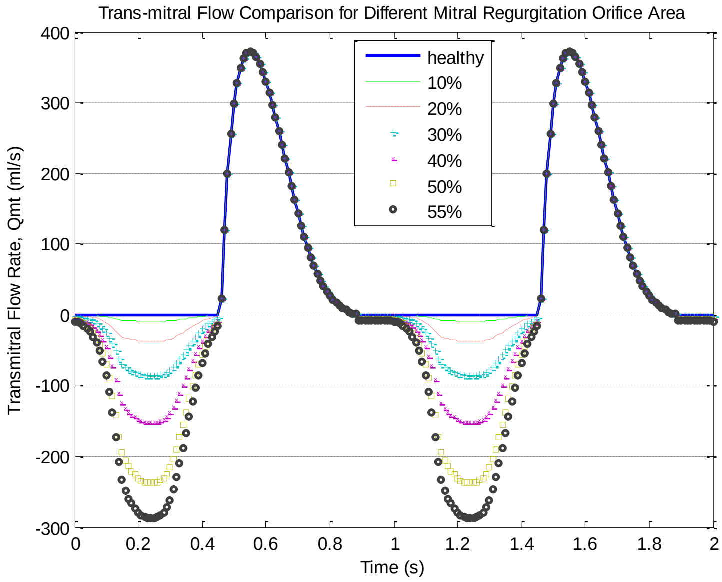

Fig. 3. Mitral regurgitation flow for mitral regurgitation areas of 10%, 20%, 30%, 40%, 50% and 55% of maximum mitral opening area.

Next, the mitral regurgitation orifice area increased to 20%. Mitral regurgitation had developed flow rate peaked at about 40 ml/s which was about 13% of the transmitral flow rate during filling phase. The result also shows that regurgitation happened for 0.43 seconds in a single cardiac cycle. The mitral regurgitation orifice area was further increased to 30%. Even though the increment of mitral regurgitation orifice area was about 10% from the previous result (20% regurgitation orifice area), which was the same increment of area from 10% to 20% of regurgitation orifice area, the mitral regurgitation developed almost twice of the peak regurgitation flow rate. The significant regurgitation time was still at about 0.43 seconds in a single cardiac cycle of 1 second. The peak regurgitation flow rate for 30% regurgitation orifice area was recorded at about 80 ml/s.

The assessment was continued with another increment of 10% to the mitral regurgitation orifice area which was 40% mitral regurgitation area over the effective mitral valve opening orifice. The result indicates that regurgitation flow rate developed further by 60 ml/s hence resulting in a peak of 140 ml/s in a single cardiac cycle. It was approximately 40% of the peak transmitral flow rate during filling phase. The increase in regurgitation flow rate was 50% more on top of the previous increment even though the regurgitation orifice area was introduced at the same increment as in the previous situation. This could be caused by non-linear decreased in the mitral valve resistance as the regurgitation orifice area was not linearly related to the mitral valve resistance.

Borneo International Journal eISSN 2636-9826; Vol. 2 (2); 2019; 1-15
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The mitral regurgitation orifice areas were further increased to 50% and 55% of the mitral valve opening orifice area. Regurgitation flow rate developed approximately with the peaks of 230 ml/s and 290 ml/s respectively for 50% and 55% regurgitation areas. The mitral regurgitation flow rates were about 61% and 78% of the peak transmitral flow rate during filling phase in a cardiac cycle. Additionally, the time of regurgitation happened was also significantly increased from previously 0.43 seconds to 0.5 seconds of a total 1 second cardiac cycle. If the data is transferred to echocardiogram images, the results would be classified as severe mitral regurgitation.

Fig. 4 shows the correlation between mitral regurgitation flow rate and mitral regurgitation orifice area. The mitral regurgitation flow rate shows negative correlation with mitral regurgitation orifice area if the graph is interpreted directly. But as mentioned earlier, in this chapter, negative transmitral flow rate represents mitral regurgitation flow rate. Therefore, the mitral regurgitation flow rate is showing positive correlation with mitral regurgitation orifice area. Mitral regurgitation flow rate increased with mitral regurgitation orifice area with an increasing rate.

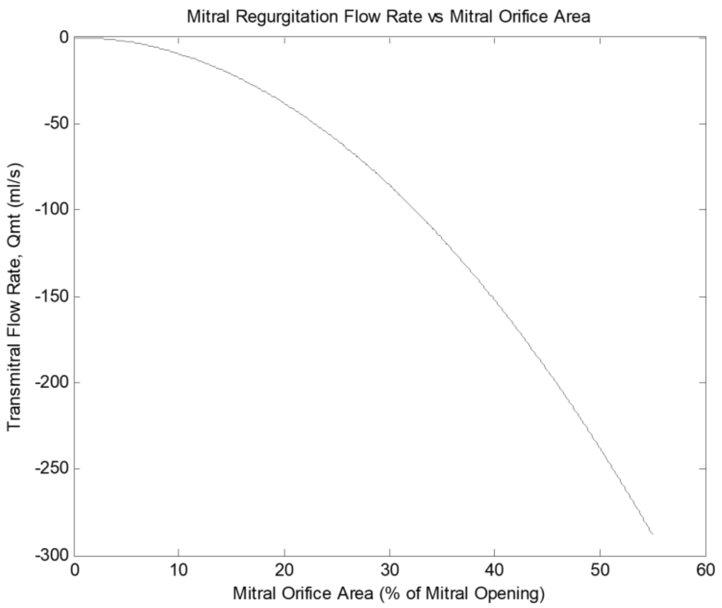

Fig. 4. Mitral regurgitation flow rate vs mitral regurgitation orifice area.

Mitral regurgitation volume

Mitral regurgitation volume is another important parameter to be assessed when determining the severity of mitral regurgitation apart from the mitral regurgitation flow rate. Determination of mitral regurgitation volume for this research was by integration of mitral regurgitation flow rate with time for any steady periodic state cardiac cycle. Although two methods were available to calculate the mitral regurgitation volume, integration method was chosen over Gorlin's hydraulic orifice equation as integration would give more accurate results with fewer assumptions to be made as compared to Gorlin's hydraulic orifice equation. Gorlin's hydraulic orifice equation only utilize single pressure difference to calculate the mitral regurgitation volume while integration method considers all changes in the pressure difference throughout the cardiac cycle for the calculation of mitral regurgitation volume. Hence, integration method is more accurate as more data from the cardiac cycle was utilized for the calculation.

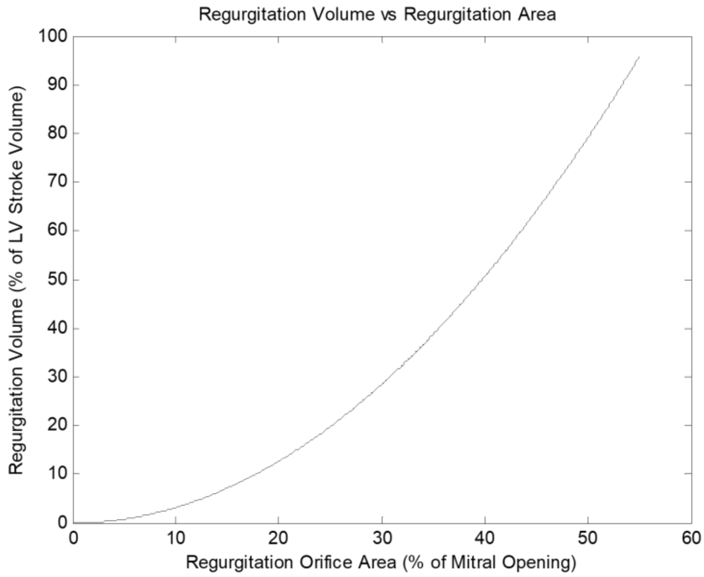

Fig. 5. Mitral regurgitation volumes (in percentage of LV stroke volume) with respect to mitral regurgitation area

Mitral regurgitation volume in this research was as percentage over the left ventricle stroke volume. The significance of expressing mitral regurgitation volume in term of percentage over left ventricle stroke volume was to assess the severity of mitral regurgitation based on the amount of blood which was supposed to be ejected out of the heart from left ventricle but flowing back into the left atrium.

Mitral regurgitation volume is presented in Fig. 5. The representation of mitral regurgitation volume by percentage over left ventricle stroke volume provides clearer indication on the amount of blood supposed to leave the heart but being delivered back to the left atrium unintentionally. The positive correlation between mitral regurgitation volume and mitral orifice area shows that mitral regurgitation volume increased with the increase of mitral regurgitation orifice area with increasing rate. At the critical point of mitral orifice area was 55% of the effective mitral valve opening area, mitral regurgitation volume had reached more than 90% of left ventricle stroke volume. This indicates that only less than 10% of blood was delivered out of the heart. The left ventricle at this point can be considered as failed to function accordingly.

Mitral Valve Leaflet Young's Modulus and Mitral Regurgitation Volume Correlation

The parameter mitral regurgitation severity on standalone basis did not provide significant additional information to the medical practitioners as it already is. While mitral valve leaflet elastic behaviour is not measurable with current equipment available in the medical field. Therefore, the correlation between the two parameters was established in this study to allow medical practitioners to utilize this model with available data by measurable by their current available equipment.

Correlation between mitral valve leaflet Young's modulus and mitral regurgitation volume is shown in Fig. 6. Determination of the correlation between mitral valve leaflet Young's modulus and mitral regurgitation volume will provide clearer representation on the condition of the mitral valve leaflet in term of mitral valve strength in relation to the mitral regurgitation severity.

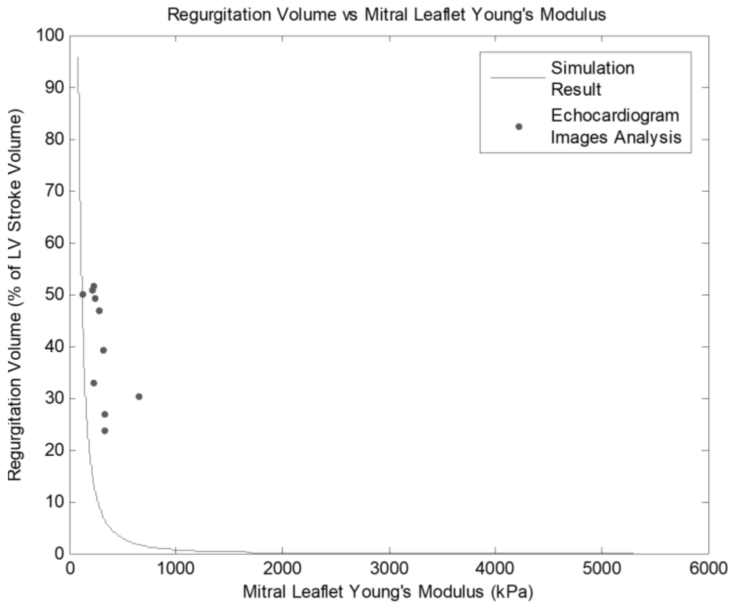

Fig. 6. Correlation between mitral valve leaflet Young's modulus and mitral regurgitation volume

Comparison between the result obtain via echocardiogram images analysis [49] and simulation result shows that the plots for the result from echocardiogram images analysis scatter close to the plotted simulation result. Difference was on average less than 10 kPa of mitral valve leaflet Young's modulus for the same mitral regurgitation volume between the results. Trend was not able to be developed for the result obtained by echocardiogram images analysis due to insufficient number of subjects involved in this research. However, initial result from the echocardiogram images analysis shows similar pattern with the increment of mitral regurgitation volume with the decrease of mitral valve leaflet Young's modulus.

At the initial stage of mitral regurgitation, mitral regurgitation volume increment was not significant with the reduction of mitral valve leaflet Young's modulus. This means that the mitral valve leaflet structure is able to hold certain amount of load with reducing strength until certain limit which at this limit mitral valve is considered no longer functioning well. The limit was observed at approximately 1000 kPa where below this Young's modulus value, the mitral regurgitation volume starts to show significant increment.

When the mitral valve leaflet Young's modulus reduced to 500 kPa, mitral regurgitation volume increased from less than 1% to approximately 5% of the left ventricle stroke volume. Further drop in mitral valve leaflet Young's modulus to 100 kPa shows sudden increased in mitral regurgitation volume from 5% to about 96% of the left ventricle stroke volume. The region where mitral valve leaflet Young's modulus is below 500 kPa is a critical region where large increment of mitral regurgitation volume happened with only slight decreased of mitral valve leaflet Young's modulus value.

Therefore, it is important to observe the region where mitral valve leaflet Young's modulus changes at a small value but with big effect on the mitral valve regurgitation volume. This indicates that once the mitral valve leaflet Young's modulus reached its lower limit for that particular mitral valve, the failure can occur out of a sudden and can possibly cause sudden death if it is unmonitored.

Degeneration of mitral valve

Degeneration of mitral valve represents the condition of mitral valve leaflet. In this research, degeneration value will increase if the Young's modulus value decreases or in other words, the condition of mitral valve leaflet is worsening with the increase of mitral valve leaflet degeneration value.

The critical point in the result shown in Fig. 7 is when mitral valve leaflet degenerate by 90% and beyond. This is because, beyond 90% of degeneration, mitral regurgitation showed rapid increased in volume with respect to slight increase in degeneration value. Furthermore, when mitral valve leaflet degenerate at about 97%, more than 95% of left ventricle volume had been flowing back unintentionally to the left atrium leaving only about 5% to be ejected out of the heart. The correlation also suggests that even though mitral regurgitation volume is low, mitral valve leaflet might be degenerating and might cause sudden increase in mitral regurgitation volume when the leaflet degenerates over 90%. At this point, the medical practitioners shall take fast action to avoid fatality of the patients.

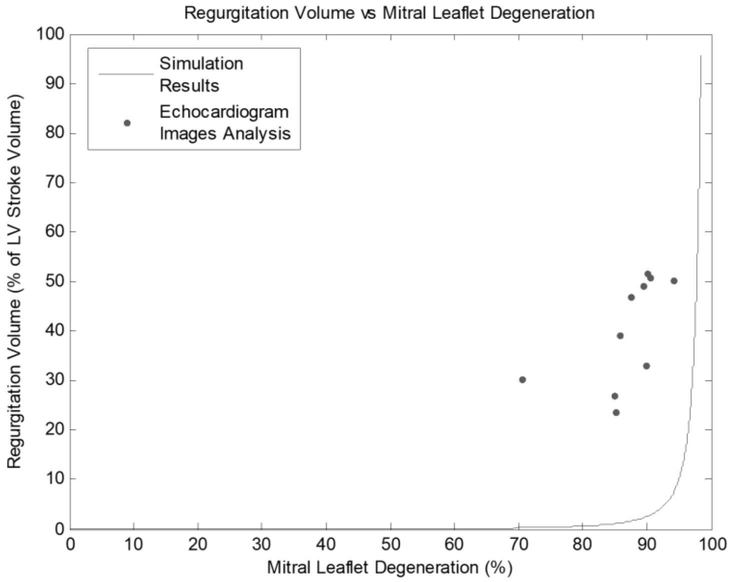

Fig. 7. Mitral regurgitation volume against mitral valve leaflet degeneration

5. CONCLUSIONS

The results discussed in this study were generated by enhanced CVS Model which is a part of the progress for the development of a better tool for medical practitioners for the assessment of their patients. The CVS Model was enhanced with the following additional elements for determination mitral valve leaflet condition and mitral regurgitation severity:

a) Mitral regurgitation flow rate determination by mitral regurgitation orifice area input into the CVS Model.
b) Mitral regurgitation volume calculation utilizing mitral regurgitation flow rate data generated by CVS Model.
c) Calculation of mitral valve leaflet Young's modulus and degeneration from mitral regurgitation orifice area.
d) Establishment of correlation between mitral regurgitation severity and mitral valve leaflet condition.

Mitral valve leaflet condition had been modeled in this research by estimation of mitral valve elastic behaviour. Correlation between mitral regurgitation volume and mitral valve leaflet elastic behaviour provide useful information on the condition of mitral valve leaflet which was previously was only being determined by mitral regurgitation jet and left ventricle function assessments. The model confirmed the diagnosis of mitral valve prolapse does not necessarily accompany by mitral regurgitation [5]. The critical point to be observed for mitral regurgitation severity is at 90% mitral valve leaflet degeneration where at this point mitral regurgitation volume was about 4% of the left ventricle stroke volume.

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