Real Heart Valve Model for Different Severity Level of Mitral Regurgitation

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Abstract - *The purpose of Electrical based Cardiovascular System Modeling is to study pressure signals at the vascular level. This work proposes a model to study abnormal heart valve conditions, which are diagnosed using blood flow velocity profiles, leading us to a dynamic model using the 3 phases of a real valve operation; quick opening, slow closing, and quick closing. The model is used for mitral valve regurgitation conditions and tested three severity conditions. For testing purposes the model was implemented in VHDL-AMS for the electrical analog circuit of the valves, for mitral valve regurgitation, giving the corresponding pressure signals. Our dynamic blood flow model was implemented in VENSIM, which allows for generation of blood flow velocity profiles and volumes; thus allowing medical personnel to simulate several conditions in regurgitation and observe the ultrasound derived blood flow velocity profile for severity level of regurgitation.*

Keywords: *Cardiovascular system, Mitral valve, Regurgitation, Model, Cardiac cycle*

1 Introduction

Cardiovascular system analysis started with the modeling of arterial flow using Windkessel model. This was subsequently expanded to cover the modeling of other organs such as the heart, heart valves, and veins [1]. Cardiovascular system models using electrical systems have two limitations: using diodes to represent heart valves, and not including a representation for chambers. Using VHDL-AMS heart valves can be replaced using model of real heart valve operation [2] and observe blood flow and blood pressure. For the case of abnormal valve with regurgitation the electrical model does not provide a way to observe chamber volume and velocity profile that are used to diagnose regurgitation. This led us to develop a dynamic model for the cardiovascular system that does allow for chamber volume and velocity profile observation. The velocity profile is commonly used for the calculation of the severity of this kind of diseases from an echocardiogram [3], and by observing the E and A waves; it is possible to observe abnormal performance of the valves.

Models offer parameters in order to experiment physiological dynamics with different purposes, i.e. improving the diagnosis by simulating some abnormal states for the modeled region of the human body, in this case the heart. The heart is composed by 4 chambers and 4 valves, the valves control de blood flow through the heart when it pumps [3].

The design of a functional valve model helps to improve the understanding of its dynamics given that valves dysfunctions are important heart abnormalities [4]; such as, the ischemic mitral insufficiency, mitral regurgitation, that can be defined as the backflow of blood into the left atria, when the ventricle contracts. This abnormality was represented by the abnormal closing of the mitral valve [5].

Use of the hydraulic-electric analogy to model the cardiovascular system dynamics is a common one [6] [2] [7] [8] [9], in these models, the representation of the heart valve is a diode with a resistance, this analogy describes the ideal flow through the valve, but it is no possible to simulate the backflow for a dysfunction as the regurgitation. In order to show the valves' function there are studies focused in modeling the valves and heart dynamics, Moorheada et al. [10], use a non-linear rotational spring model for the dynamics of the mitral valve, that incorporates into a cardiovascular model, can be used to investigate the hemodynamic repercussions of several pathological conditions; Paeme et al. [11], present a cardiovascular model that includes the mitral valve dynamics, this model was designed with the purpose of studying the Ischemic mitral insufficiency, but it has a large number of parameters, the author mentions the need for new minimal and more physiologically relevant mitral valve models, our study works toward a simpler model.

This work proposes a valve model that uses cardiac cycle phases and the flow control in order to model a closer representation of their operation based on its shape and values of the blood flow through the valve in order to study some dysfunctions such as mitral regurgitation and how these affect the cardiovascular dynamics.

2 Valve's Model

The valve's model used in this paper, see Fig. 1, is based in the 7 phases of cardiac cycle for timing control, depending on the heart rate Fig. 2. From [12] three distinct phases of aortic valve operation were observed: a rapid valve opening, a slow systolic closure, and a rapid valve closing operations. Our model has three stages for representing the valves' operation as well, these are: quick opening, slow closing and quick closing for each valve.

The opening and closing stages are synchronized with the heart rate and the flow shape of the valve aperture is given by,

$$f_{MV}(t) = \frac{f_M}{1+\rho_{MV}^{-(t_S * f_M)}} \qquad (1)$$

Where, $f_{MV}(t)$ is the blood flow function through the valve, f_M is the transmitral flow, ρ_{MV} gives slope of the opening function, t_s is the stage time of the valve, this parameter is given by the cardiac cycle phases. The slow closing stage is the period of time that the valve reaches the fully open state and starts to closing. Using this valve's model allows to represent mitral regurgitation by changing some of its parameters.

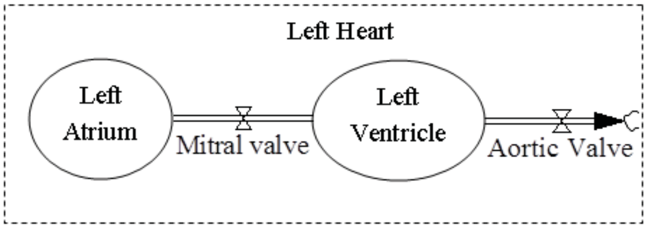

Fig. 1 Schematic representation of valves and left chambers.

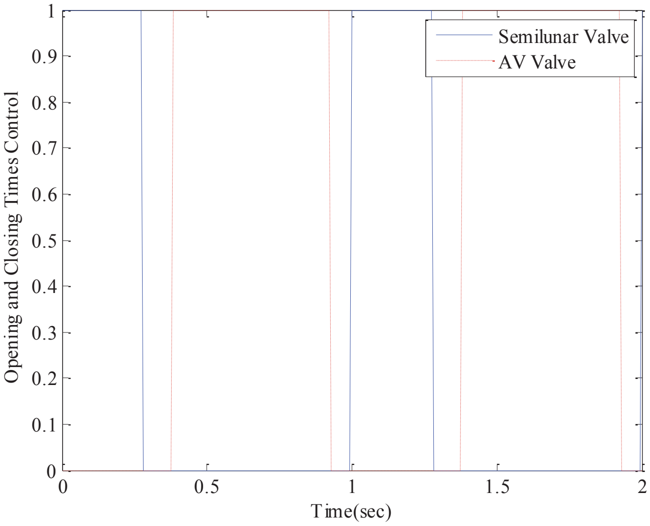

Fig. 2 Semilunar an atrioventricular valves timing.

2.1 Valve's Replacement

From the cardiovascular system study and literature review is clear that real valve operation to allow blood flow is a more complex procedure than a simple change of status between open and closed as described by the idealized diode model [1]. This model represents the operation of the valve by using three stages, based on real opening and closing characteristics [13].

The ideal diode in [6] was replaced with the proposed model and the performance of the cardiovascular model was tested, the original model is in Fig. 3 .

Fig. 4 shows the replacement of diodes by modules with proposed design. With the purpose to demonstrate the functionality of this model, the cardiovascular model from [2] was used and the ideal valve model of valves was replaced with the proposed design, as illustrated in Fig. 4.

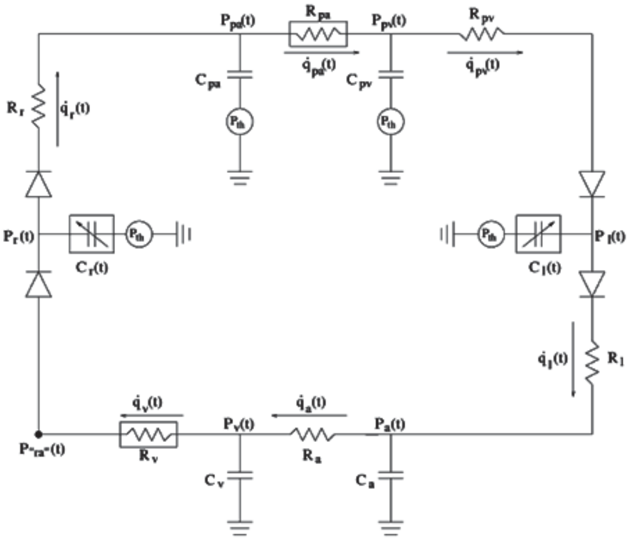

Fig. 3 Electrical circuit analog of the human cardiovascular system. Figure extracted from [2].

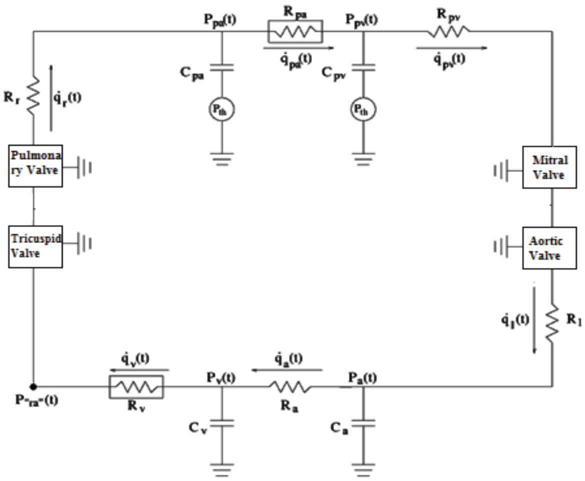

Fig. 4 Electrical circuit analog of the human cardiovascular system with valve replacement. Figure adapted from [2].

2.2 Valve's Modules in VHDL-AMS

With the purpose to test our model in an electrical model of the cardiovascular system, and due to its nature, it became necessary to choose a platform to implement it and replace the diodes of the common cardiovascular system model of an electrical. VHDL-AMS was a convenient choice, because of the facility to develop parameterized modules, as well as flexibility in modifying the design and the components connection, that comes with the VHDL environment.

Two modules were developed: one for each type of valve (AV valve and Semilunar Valve) and each one was parameterized depending on the heart valve replaced. The modules are designed as electrical components with the functions previously presented that model real heart valve operation, and are controlled by the timing given by the cardiac cycle phases; this model definition is in Listing 1. The design has one module per component: a capacitor, a resistor, an inductor, a diode. The connection of the electrical model is in Listing 2, including the designed model for the valves. The aortic pressure waveforms are shown in Fig. 5.

```
-- Atrio-ventricular valve.
ENTITY AV_valve IS
GENERIC (   Fa : REAL     :=0.65;
--Valve Parameters
            HB : REAL     :=150.0;
            Base : REAL     := 3.0;
            period: real := 1.0;
      -- Cardiac Cycle phases
      A: real:=0.14;
      C: real:=0.12;
      D: real:=0.16;
      E: real:=0.1;
      F: real:=0.15;
      G: real:=0.26);
    PORT(TERMINAL p,m: ELECTRICAL;SIGNAL
input1,input2: in bit); --Interface ports.
END AV_valve;

-- Semilunar valve.
ENTITY Sem_valve IS
GENERIC (    Fa : REAL     := 1.5; --Valve
parameters
             HB : REAL     := 150.0;
             Va: REAL  := 1.96;
             Base : REAL     := 3.0;
             period: real := 1.0; -- HR control
      -- Cardiac cycle phases
      A: real:=0.14;
      C: real:=0.12;
      D: real:=0.16;
      E: real:=0.1;
      F: real:=0.15;
      G: real:=0.26);
    PORT(TERMINAL p,m: ELECTRICAL;SIGNAL
input1,input2: in bit); --Interface ports.
END Sem-valve;
```

Listing 1. VHDL-AMS Valves Module definition

Once the replacement was done, we noticed that was not possible to illustrate the regurgitation with the signals obtained from the electric analog model, so a cardiovascular model based on blood flow and volume dynamics was designed due to the main purpose of this work is to study the mitral regurgitation effects and these are not notorious in this kind of models.

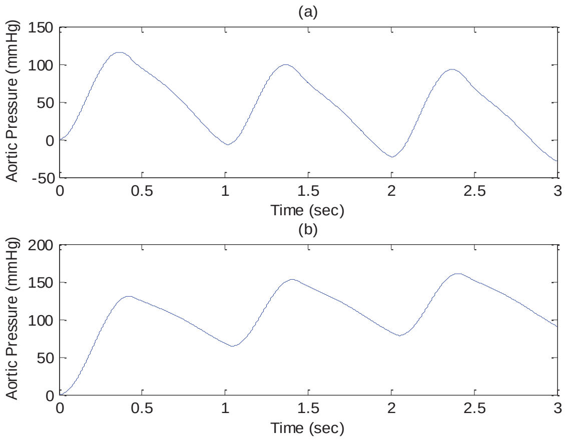

Fig. 5 Aortic Pressure waveform from [2], (b) Aortic Pressure waveform with our valve model.

2.3 Cardiovascular blood flow dynamics model in Vensim

The heart is formed by four chambers, two atria and two ventricles. The atria receive blood from lungs and body and pass it into the ventricles. During each cardiac cycle, the atria contract first, ejecting blood into their respective ventricles, then the ventricles contract, ejecting blood into the pulmonary and systemic circuits [3].

It is important to mention that the two ventricles contract at the same time and eject equal volumes of blood to the lungs and body.

Our proposed model subdivides the human cardiovascular system into six blocks or compartments, four of these compartments are the heart chambers representation; the remaining two are for pulmonary's and body's vascular systems, see Fig. 6. All compartments are inter-connected and hold to the volume conservation law.

Each cardiac chamber is described by volume and blood flow dynamics and cardiac cycle phases. Four chambers (right atria, left atria, right ventricle and left ventricle) are modeled as container compartments. Each one has an initial volume value, which is given by the user, depending on the heart's size. Their dynamics are regulated by the opening, slow closing, and quick closing times for valves, in turn controlled by the cardiac cycle phases.

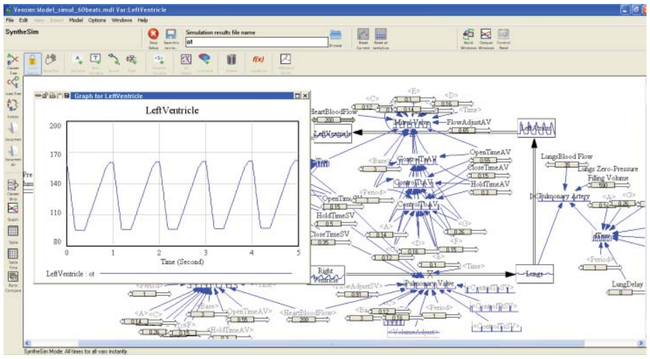

Fig. 6 Proposed cardiovascular model in Vensim [14].

Each chamber has two valves controlling input and output blood flow; these valves allow the diastole (filling) and systole (draining) for each chamber, these actions (diastole and systole) represent the complete cardiac cycle and are used to estimate the stroke volume; that is, the volume of blood pumped from one ventricle of the heart for each beat. Its value is obtained by subtracting end-systolic volume (ESV) from end-diastolic volume (EDV) for a given ventricle [3].

$$SV = EDV - ESV \tag{2}$$

The cardiac output (CO) as the volume of blood being pumped by the heart in one minute, either the left or right ventricle, is given by the following formula

$$CO = SV * HR \tag{3}$$

Where HR is the heart rate and SV is the stroke volume. These values are used for the volume analysis, and are used to verify that the model is working properly.

As previously mentioned before the volume in each chamber is controlled by their input and output valves. The chamber volume is the accumulation of the difference of blood flow through the valves.

3 Mitral Regurgitation Modeling

The mitral regurgitation is modeled by introducing to the normal valve's model different parameters and timing control (reversed opening and closing times, in order to hold the valve partially open (during closing stage), when the mitral valve has to be fully closed, we introduce a backflow into the atria that represents the regurgitation flow.

From (1), the f_M parameter, can be changed by a regurgitant blood flow as is shown in Fig. 7.

```
LIBRARY DISCIPLINES;
USE DISCIPLINES.ELECTROMAGNETIC_SYSTEM.ALL;

ENTITY cardioVas4  IS
END;

ARCHITECTURE behav OF cardioVas4  IS
    TERMINAL  n1,n2,n3,n4,n5,n6,n7,n8,n9,n10,n11,n12:
ELECTRICAL;
  SIGNAL S1,S2,S3,S4: BIT;
BEGIN
    -- Circuit conections
rpu:ENTITY resistor(behav) GENERIC MAP (0.006) PORT
MAP (n1, n2);
rp:ENTITY resistor(behav) GENERIC MAP (0.07)PORT MAP
(n2, n3);
rm:ENTITY  resistor(behav)  GENERIC  MAP  (0.006)PORT
MAP (n3, n4);
rv:ENTITY resistor(behav) GENERIC MAP (0.04)PORT MAP
(n7, n8);
rs:ENTITY resistor(behav) GENERIC MAP (1.0)PORT MAP
(n8, n9);
ra:ENTITY  resistor(behav)  GENERIC  MAP  (0.006)PORT
MAP (n9, n10);
   -- Capacitors
cpu: ENTITY c (behav) GENERIC MAP (9.0)PORT MAP (n2,
electrical_ground);
cpa: ENTITY c (behav) GENERIC MAP (7.7)PORT MAP (n3,
electrical_ground);
cv:  ENTITY  c  (behav)  GENERIC  MAP  (100.0)PORT  MAP
(n8, electrical_ground);
cs: ENTITY c (behav) GENERIC MAP (2.0)PORT MAP (n9,
electrical_ground);
      -- Valves replacement
rx:  ENTITY resistor (behav) GENERIC MAP (1.0) PORT
MAP (n4, n5);
ry:  ENTITY resistor (behav) GENERIC MAP (1.0) PORT
MAP (n6, n7);
rz:  ENTITY resistor (behav) GENERIC MAP (1.0) PORT
MAP (n10, n11);
rw:  ENTITY resistor (behav) GENERIC MAP (1.0) PORT
MAP (n12, n1);
rxx:ENTITY resistor (behav) GENERIC MAP (1.0) PORT
MAP (n11, n12);
ryy:ENTITY resistor (behav) GENERIC MAP (1.0) PORT
MAP (n5, n6);
 --Valves
ao:     ENTITY    sem_valve    (behav)     PORT    MAP
(n11,electrical_ground,S1,S2);
mit:       ENTITY    Av_valve    (behav)    PORT    MAP
(n12,electrical_ground,S3,S4);
pul:    ENTITY    sem_valve    (behav)    PORT    MAP
(n5,electrical_ground,S1,S2);
tric:      ENTITY    Av_valve    (behav)    PORT    MAP
(n6,electrical_ground,S3,S4);

FF:   ENTITY FlipFlop_s_ao   (behav) PORT MAP (S1);
FF1:   ENTITY FlipFlop_b_ao   (behav) PORT MAP (S2);
FF2:   ENTITY FlipFlop_su   (behav) PORT MAP (S3);
FF3:   ENTITY FlipFlop_b   (behav) PORT MAP (S4);

END behav;
```

Listing 2. Cardiovascular system for Fig. 2.

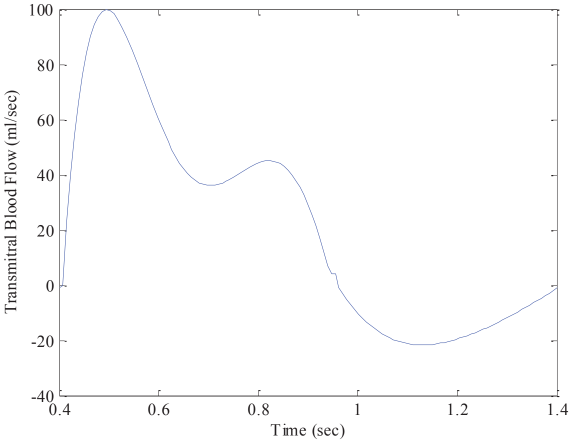

Fig. 7 Transmitral blood flow with regurgitation

The velocity profile was calculated by using the aperture area, and the regurgitant blood flow; these parameters are customizable in order to modify the severity of the regurgitation, the relation used for the velocity is given,

$$\frac{dv}{dt} = \frac{f_{MV}(t)}{A} \tag{4}$$

Where, v is the velocity, $f_{MV}(t)$ is the blood flow through the valve, and A is the aperture area of the valve.
To compute the regurgitant volume, we use the Proximal Isovelocity Surface Area or PISA method where the regurgitant volume is given by,

$$Rvol = EROA \times MR\_VTI \tag{5}$$

Where *Rvol* is the regurgitant volume, *EROA* is the Effective Regurgitant Orifice Area and *MR_VT*I is the Velocity Time Integral of the regurgitation. Model's parameters are given in Table 1.

Table 1: Model Parameters

General Parameters		
Parameter	**Normal sample value**	**Test range**
Heart rate (HR) (bpm)	60	60–180
$V_{RV}(t_0)$ (ml)	160	100-160
$V_{LV}(t_0)$ (ml)	165	100-165
$V_{RA}(t_0)$ (ml)	34	14-56
$V_{LA}(t_0)$ (ml)	35	15-58
Valve Parameters		
f_M (ml/sec)	100	50-100
ρ_{MV}	3	0-5
MR TVI (m)	0	10-500
EROA (m)	0	0-2

4 Simulations and Results

Simulations were made for different severity levels of the regurgitation, mild, moderate and severe regurgitation [15]. The parameter modified for the simulations is the EROA.

The TVI was measured using the velocity profile obtained for each simulation, by calculating the integral of the regurgitant velocity. These values were used to calculate the regurgitant volume using (5). The results are given in Table 2.

Table 2: Simulation parameters and results

Severity	**EROA (cm2)**	**TVI (cm)**	**Rvol (ml/beat)**
Mild	0.05	188	9.4
	0.1	141	14.1
	0.15	147	22.1
	0.18	166	29.9
Moderate	0.2	165	33
	0.25	170	42.5
	0.3	168	50.4
	0.35	166	58.1
Severe	0.5	125	62.5
	0.8	88	70.4
	1	79	79
	1.2	72	86.4

Fig. 8, shows the velocity profile for a mild, moderate and severe regurgitations, these graphs were used to calculate the TVI from the baseline to the velocity peak wave.

From the results it is observable that the velocity decreases when the EROA increases, this is due to the relation that exists between the area and transmitral blood flow. Validation of the Rvol corresponds with the standard values for the severity classification of mitral regurgitation given in, 2014 AHA/ACC Guideline for the Management of Patients With Valvular Heart Disease [16].

5 Conclusions

Our model was implemented in VHDL-AMS, to check its functionality with an electrical model of the cardiovascular system. These models do not represent chambers. This type of model does not provide blood flow velocity profile; thus, we provide aortic pressure to observe the real valve operation.

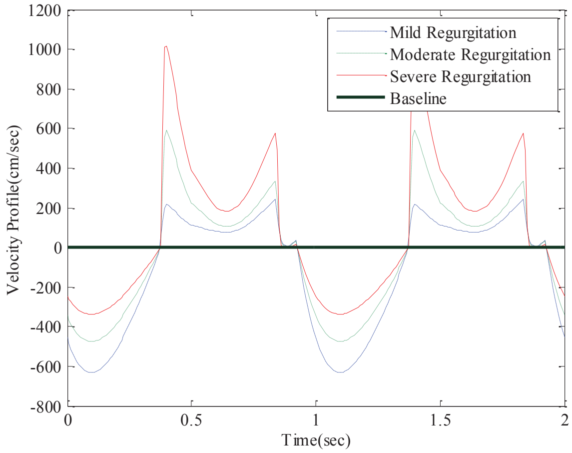

Fig. 8 Velocity profile with mitral regurgitation levels.

To provide blood flow, and volume information that will enable visualization of velocity profiles, the valve model was implemented, simulated and presented results that are consistent with medical diagnosis techniques of some abnormal conditions in valves. For this we used Vensim from Ventana Systems, Inc.

This valve model can represent a variety of abnormal valve's operations by using parameters. Models based on electrical analogs use diodes as valves, and then valves' dynamics does not closely represented and do not offer abnormal functioning. Valves were designed in its three real stages; opening, slow closing and quick closing, and each one have a parameterized function for their operation. The valves' parameters control shape and time; this enables representation for mitral regurgitation. This disease is represented by the changes in the velocity profile calculated by the model. It is possible to represent the different levels of severity for the regurgitation by changing some of the available parameters of the model.

6 References

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