Simulation of normal cardiovascular system and severe aortic stenosis using equivalent electronic model

Normal kardiyovasküler sistem ve ciddi aort darlığının bir elektronik devre eşdeğeri ile benzetimi

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ABSTRACT

Objective: In this study, we have designed an analog circuit model of the cardiovascular system that is able to simulate normal condition and cardiovascular diseases, such as mitral stenosis, aortic stenosis, and hypertension. Especially we focused on severe aortic stenosis, because it is one of the causes of sudden death in asymptomatic patients. In this study, we aim to investigate the simulation of the cardiovascular system using an electronic circuit model under normal and especially severe aortic valve stenosis conditions.
Methods: The Westkessel model including RLC pi-segments is chosen in order to simulate both systemic and pulmonary circulation. The left and right heart is represented by trapezoidal shape stiffnesses. Aortic capacitance and aortic valve characteristics are chosen nonlinear. Severe aortic stenosis is implemented by changing the value of the serial resistance to the aortic valve. MATLAB® software program is used for the model implementation.
Results: The results for normal conditions of the given electrical model are similar to the normal cardiovascular physiology. As a result of simulation, a remarkable increase of the left ventricle systolic blood pressure and aortic mean pressure gradient, and decrease of aortic systolic blood pressure are observed in severe aortic valve stenosis.
Conclusion: In conclusion, our model is effective and available for simulating normal cardiac conditions and cardiovascular diseases, especially severe aortic stenosis. *(Anadolu Kardiyol Derg 2010 December 1; 10(6): 471-8)*
Key words: Cardiovascular physiology, simulation, aortic valve stenosis, electronic circuit model

ÖZET

Amaç: Çalışmada normal durum ile beraber mitral darlık, aort darlığı, ve hipertansiyon gibi kardiyovasküler hastalıkları taklit edebilen elektronik bir devre modeli tasarlanmıştır. Çalışmada özellikle ciddi valvüler aort darlığı üzerinde durulmuştur, çünkü asemptomatik hastalarda ani ölümün sebeplerinden biri olmaktadır. Çalışmanın amacı, kardiyovasküler sistemin elektronik bir devre modelinden yararlanılarak normal ve özellikle ciddi valvüler aort darlığı durumlarının benzetimlerinin yapılmasıdır.
Yöntemler: Sistemik ve pulmoner dolaşımın benzetimi için RLC-pi segmentlerini içeren Westkessel modeli seçilmiştir. Sol ve sağ kalp yamuk biçimli stiffness modeli ile temsil edilmektedir. Aortik kapasitans ve aortik kapak karakteristikleri non-lineer seçilmiştir. Ciddi valvüler aort darlığı, aortik kapak direncinin değerinin değiştirilmesi ile gerçekleşmiştir.
Bulgular: Sunulan elektriksel modelden normal durumlar için elde edilen sonuçlar normal kardiyovasküler fizyoloji ile benzerlik göstermektedir. Ciddi valvüler aort darlığı durumunda, modelle de, sol ventrikül sistolik kan basıncında ve aortik ortalama basınç gradiyentinde artış ve aortik sistolik kan basıncında düşüş gözlemlenmiştir.
Sonuç: Sonuç olarak, önerilen model başta ciddi valvüler aort darlığı olmak üzere çeşitli kardiyovasküler hastalıkların ve normal kardiyak durumun benzetimini verimli bir biçimde yapabilecek düzeydedir. *(Anadolu Kardiyol Derg 2010 December 1; 10(6): 471-8)*
Anahtar kelimeler: Kardiyovasküler fizyoloji, benzetim, valvüler aort darlığı, elektronik devre modeli

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Introduction

In normal conditions, the aortic valve area is 3.0 to 4.0 cm^2. As aortic stenosis develops, minimal valve gradient is present until the orifice area becomes less than half of normal. The pressure gradient across a stenotic valve is directly related to the valve orifice area (1). A pressure gradient of 50 mmHg suggests a severe stenosis but valve area provides a more accurate assessment of severity. Less than 1.5 cm^2 is severe and below, 0.75 cm^2 is defined as critical. Severe aortic stenosis is also considered to be present if the valve area index is <0.6 cm^2/m^2 (2). The valve gradient is also directly related to the transvalvular flow (2).

Aortic valve stenosis can be caused by a congenital abnormality, rheumatic fever and senile degenerative stenosis. Many patients with aortic stenosis will not have any symptoms. When the aortic stenosis becomes severe, dyspnea, angina, near-syncope and sudden death may occur. Although the conventional treatment for severe aortic stenosis in most patients is open-heart surgery, in selected young adults and children, a stenotic aortic valve may be opened by aortic balloon valvotomy.

Simulation is available for investigating cardiovascular physiology. Several models for the cardiovascular system have been proposed for understanding cardiovascular physiology and physiopathology such as arrhythmia, myocardial ischemia, hypertension and valve diseases (3-8). Goldwyn et al. (9) used a third order Windkessel electrical model of the circulatory system. This vessel model consists of two capacitances, one inductance and one resistance. They calculated the model parameters by fitting the physiological pressure contours only for diastolic period that the source current (outflow of the left ventricle (LV)) is zero. Korürek (10) used the same model in his both electrical and hydromechanical models, and investigated the effects of the model parameter values on the model pressure contours, driving the model by a pulsatile flow source. Korürek (10) took the flow shape as a trapezoidal character. Rideout (11) used left and right ventricle (RV) capacitances as the sources of the model. The different characteristics of each stiffness (inverse of the capacitance) are tried, such as half-sine wave and trapezoidal.

In this study, we aim to investigate the simulation of the cardiovascular system using an electronic circuit model under normal and especially severe aortic valve stenosis conditions.

Methods

Models are useful tools for representing the systems. Usefulness comes from its easy handled properties. Sometimes, it is very difficult to analyze and search the dynamic and/or static behavior of the system. Instead, its model can be used for this purpose. Scientists try to build up the models in order to get more information about the system. It can easily be tested again and again for different conditions and for different parameter value sets. For instance, cardiovascular system is a complicated mechanism of the body in this sense. Sometimes scientists used its hydro-mechanical models (10), sometimes electrical (8-11). Goldwyn and Watt (9) built up the electrical model in order to diagnose the illnesses of the cardiovascular system. The model was the same for normal and illness conditions but not the values of the parameters (components) of the model. By looking at the parameter values, the illness classification (and the level of the illness) could be found out. Models can also be built up for teaching purposes; one can easily give information about the system by using its model. We also built up an electrical circuit diagram as a model of the cardiovascular system for training, research and system classification purposes.

Cardiovascular system simulation is done by using an electrical circuit model which is shown in Figure 1. In our model, LV and RV are represented by trapezoidal shaped stiffnesses and vessels are represented by modified Westkessel model including RLC pi-sections as used in Rideout's model (11). The flow-chart of the model is given in Figure 2. MATLAB® is used for the model implementation. Electrical units and their physiological equivalent values are given in Table 1. HRU stands for the hydraulic resistance unit in the model, HCU for hydraulic capacitance unit and HIU for hydraulic inductance unit. In the simulation of the model, the physiological limits are taken into account. In our model, similar with Rideout's component characteristics were used. The program language used in our model is MATLAB®, which is more sophisticated and has more mathematical and scientific tools compared to the program languages used by Rideout. That is why we simulated the severe aortic valve stenosis case (found the component values of this case) as well as the normal case of the cardiovascular system, and we could easily calculate the mean pressure area (and also the mean gradient).

After the construction of the model, the next important thing is the parameter estimation of the model. The parameters should be so evaluated or chosen that the state variables of the model should be equivalent to the corresponding state variables of the system. After this condition is met, model is said to represent or simulate the system. Korürek (10) showed that the most effective parameters in this simulation is the aortic capacitance of the system, then comes the peripheric resistance. Peripheric (systemic) resistance is easily found by the expression given below (Darsy's Law) (12);

$$R\_Systemic = \frac{P\_aortic\_mean}{F\_aortic\_mean}$$

The practical method in this simulation is that, changing the aortic capacitance value changes the amplitude of the aortic pressure without much affecting its mean value and changing the peripheral resistance value changes the mean value (offset) of the aortic pressure without much affecting its amplitude. Therefore, by changing the parameter values smartly, one can easily obtain the desired pressure contour related to these parameters. For instance, if the amplitude of the aortic pressure contour of the model is higher than the desired (normal or physiological) value, the value of the aortic capacitance (CAorta)

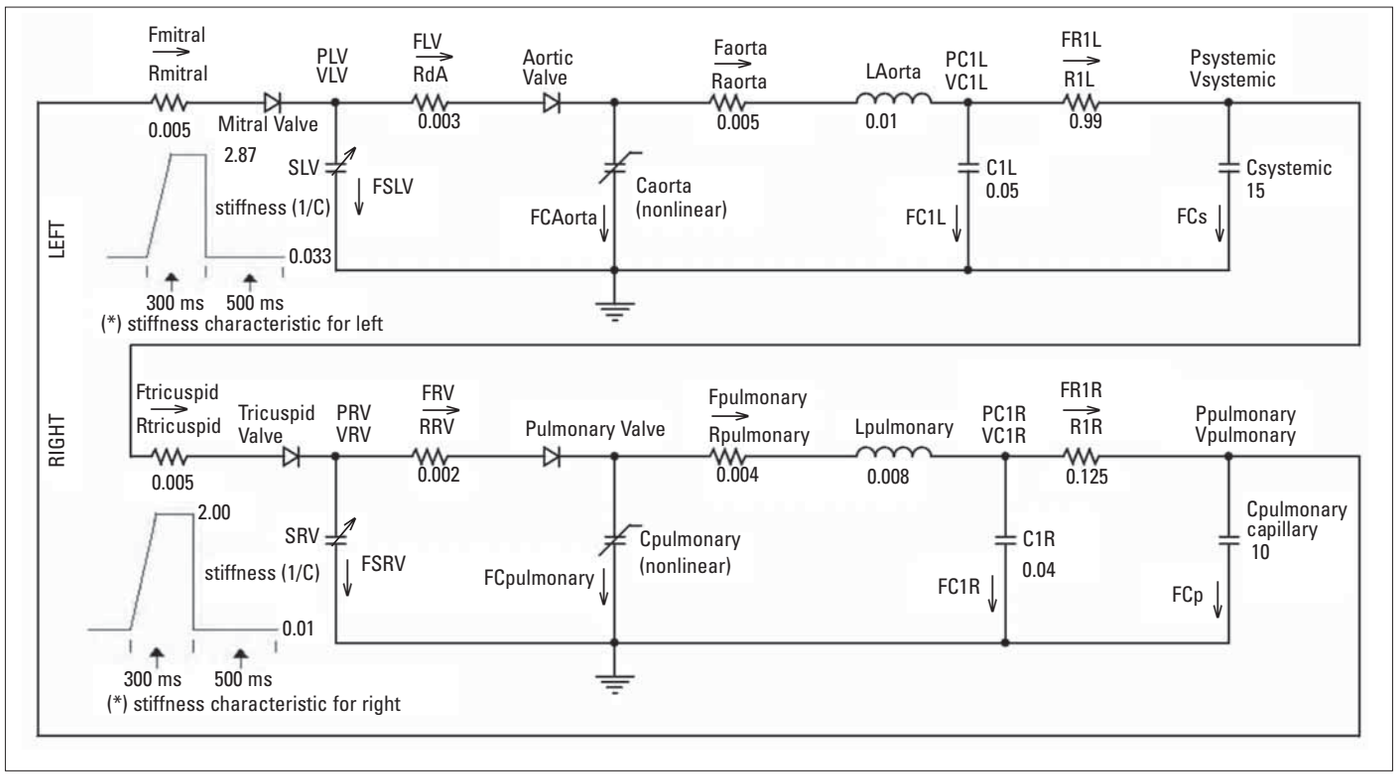

Figure 1. The electronic circuit model used for the simulation of the cardiovascular system

C - capacitance, Cp - pulmonary capillary capacitance, Cs - systemic capacitance, F - flow, L - inductance, LV - left ventricle, P - pressure, R - resistance, RV - right ventricle, S - stiffness, V - volume

should be increased, and if the mean aortic pressure is higher than the desired (physiologic) value, the systemic resistance (R1L) should be decreased. The same rule is valid for the pulmonary part of the model.

Goldwyn and Watt (9) found in their model that the aortic capacitance (first capacitance near to heart) value was almost half its normal value in the case of "aortic insufficiency". The inertance value of the model was almost twice the normal value in the same illness condition since the systemic resistance value was taken as 1 HRU for both conditions (cases) for normalization. Goldwyn and Watt (9) found out these parameter values by applying curve fitting techniques to the diastolic part of the pressure contours. They also obtained model parameter values for the "cardiomyopathy" case. They showed that the model parameter values could be used as indication of the illnesses. Goldwyn and Watt (9) modeled only systemic circulation of the cardiovascular system. Rideout (11) modified this model and handled the whole circulatory system. He mainly used nonlinear characteristics of the capacitances, applied nonlinear switching activities of the valves and used dynamic stiffness characteristics for the LV and RV parts of the cardiovascular system. Rideout (11) used a special modeling language. He did not deal with what the component values were in the case of different cardiovascular illnesses.

The main pressure and volume curves obtained from the model for normal condition are shown in Figure 3. The results for normal condition obtained from the model are similar to those

Table 1. The design of the circuit based on the principles of equivalent quantities

System	Units	Model	Units
Pressure	mmHg	Voltage	V
Flow	ml/s=cm^3/s	Current	A
Volume	ml=cm^3	Charge	C=A.s
Resistance	mmHg.s/ml=HRU	Resistance	Ohm
Compliance	ml/mmHg=HCU	Capacitance	F=A.s/V
Inertance	mmHg.s^2/ml/HIU	Inductance	H=V.s/A

HCU - Hydraulic capacitance unit, HIU - Hydraulic inductance unit, HRU - Hydraulic resistance unit

reported in the literature for the cardiovascular system (Table 2) (12). Normal condition is assumed as the healthy adult man whose body weight is 70 kg, body surface area is 1.8 m^2 and heart rate is 75 beats/min (heart period is Tp=0.8 sec).

Two synchronous pacemakers, two capacitances having similar time-varying stiffness characteristics, are connected in the circuit to drive each ventricle. The pacemakers have trapezoidal stiffness characteristic waves with adjustable frequency (given by* in Fig. 1). The pacemakers operate in 1.25 Hz frequency, 75 beat/minute, with durations of systole and diastole, 0.234 sec and 0.566 sec respectively.

The aortic capacitance characteristic is chosen as nonlinear whose volume- pressure function is given below;

$$VC = (VC\ max - VCo) \bullet (1 - exp\ (-a \bullet PC))$$

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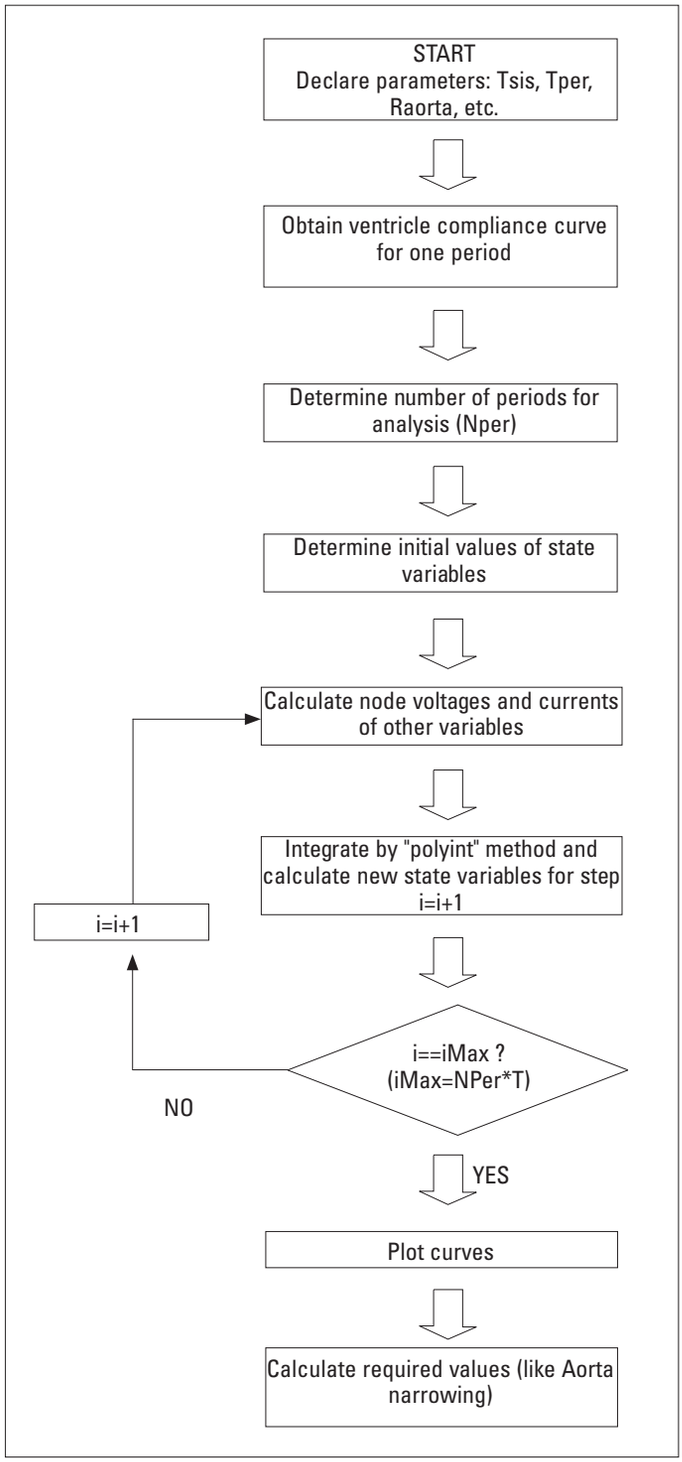

Figure 2. The flow-chart of the cardiovascular modeling program

Here, VC and PC are volume and pressure values of the capacitance, respectively; a=0.0068, VCmax=450 ml and VCo=10 ml. In working area of the capacitance, mean capacitance value can be calculated given below;

$$mean\ (CAor) = CAor = (VC2 - VC1) / (PC2 - PC1)$$

Here, PC2 and PC1 are the limit capacitance pressure values (LV peak pressure and LV end- diastolic pressure respectively) that aortic capacitance possessed when the model is working, VC2 and VC1 are the capacitance volume values corresponding to the PC2 and PC1. In normal condition, CAor is equal to 1.7HCU. The other parameter values of the model in normal condition are given in Figure 1 and in Table 2.

The aortic valve is simulated by a voltage-controlled switch with a piece-wise linear characteristic plus a serial resistance (RdA) having 0.003HRU. When the aortic valve is open, the switch is "on", simulating systolic phase, and then the ventricles are "off", simulating diastolic phase. The aortic valve is simulated by a diode with piece-wise linear voltage-current characteristic given in equation below;

$$ID = \begin{cases} 0 & Vd \le 0.2 \\ 1000 \bullet (Vd - 0.2) & other \end{cases}$$

(Id, diode current; Vd, diode voltage)

The cardiovascular model circuit is modified for the simulation of normal and severe aortic valve stenosis. To simulate severe aortic valve stenosis we increased the value of the serial resistance to the aortic valve to 0.2 HRU and 0.5 HRU. Severe aortic stenosis has been defined hemodynamically as a mean gradient >50 mmHg (2). LV, left atrium, ascending aorta and femoral artery pressure graphics obtained from the model in normal ("a") and in severe aortic stenosis ("b" for RdA=0. 2HRU and "c" for RdA=0. 5HRU) conditions are shown in Figure 4. LV volumes for the same conditions are shown in Figure 5. The pressure contours, including mean pressure area and mean gradient, obtained from the model in severe aortic stenosis conditions (for RdA =0.2 HRU and 0.5 HRU) are shown in Figure 6. The mean pressure area (MPA) and gradient pressure (GP) or mean gradient are calculated using the equations given below:

$$MPA\ (mmHg) = \frac{\int_{t1}^{t2} (PLV(t) - PAo(t))\,dt}{(t2 - t1)}$$

(t1 and t2 systole onset and offset times; PLV, LV systolic pressure; PAo, aortic pressure)

GP (mmHg)=LV peak systolic pressure-Aortic peak systolic pressure

To be used for comparison, the definitions of selected other cardiovascular parameters such as ejection fraction (EF), pulse pressure (PP) and mean arterial pressure (MAP) are given below.

$$EF\ (\%) = \frac{(LV\ diastolic\ volume - LV\ systolic\ volume)}{LV\ diastolic\ volume}$$

PP (mmHg)=Aortic systolic pressure-Aortic diastolic pressure
MAP (mmHg)=Aortic diastolic pressure +PP/3

Table 2. Simulation results and corresponding physiological measurements

Measurement	Physiological	Normal	Aortic stenosis RdA=0.2	Aortic stenosis RdA=0.5
LV, peak SP, mmHg	120	120	203	304
LV, end-DP, mmHg, supine	9	4	4	5
Aortic SP/DP, mmHg	120/80	120/80	117/80	100/72
Mean pressure area, mmHg		1.5	71.8	137.6
End-diastolic volume, LV, ml	120	120	130	151
End-systolic volume, LV, ml	40-50	40	53	84
Stroke volume, ml	80	100	95.5	84
Ejection fraction, %	67	67	59	44
Cardiac output, l/min, rest	4-7	5.9	5.7	5.0
RV, peak SP, mmHg	25	25	25	23
RV, end-DP, mmHg, supine	4	1	1	1
Pulmonary artery SP/DP, mmHg	25/10	25/10	25/10	23/10
Left atrium SP/DP, mmHg	8/4	8/4	8/4	8/5
Right atrium SP/DP, mmHg	3/1	3/1	3/1	3/1
Pulse pressure, mmHg	40	40	36	28
Pressure gradient, mmHg	0	0	86	204
Mean arterial pressure, mmHg	93	93	92	81

DP - distolic pressure, LV - left ventricle, RV - right ventricle, SP - Systolic pressure, In normal case: RdA = 0.003 HRU, R1L=0.99 HRU, Mean (CAorta) = CAorta = 1.7, LAorta = 0.01 HIU, C1L = 0.05 HCU - Heart rate = 75 bpm, EF = 83%

The pressure-volume loops belonging to left ventricular stiffness for normal and severe conditions are shown in Figure 7.

Maximum and minimum values of pressure and flow rate for normal cardiovascular system were obtained from (12). After setting up the model, model parameters were adjusted in order to simulate the cardiovascular system for normal condition. In this step, model parameters were adjusted due to the pre-information listed below:

a) Systemic resistance (load, peripheral resistance) is dependent to the rate of average aortic pressure to average aortic flow-rate-change. Thereby, when knowing average aortic pressure, one can change the value of this resistance for obtaining desired average aortic flow rate change (vice versa).
b) Aortic capacitance stands for aortic elasticity. Changing this capacitance has no effect on average aortic pressure but difference between maximum and minimum aortic pressures. Thus, after obtaining average aortic pressure, minimum and maximum values were adjusted by changing this capacitance.
c) If one knows the effects of capacitors and resistors to the model's results, values of other capacitor and resistors can be changed meaningfully. The important thing is peripheral resistance accounts for the most of the resistance in the loop while effects of other serial resistance (valve resistance, aortic resistance, etc) to the average aortic pressure change can be ignored. Also, other parallel capacitances (C2L; distal aortic capacitance, CSystemic; systemic capacitance, etc) has little effect when compared to aortic capacitance.

The next step after simulation of normal condition is simulating of aortic valve stenosis. This was achieved by changing R_{dA} (aortic valve resistance). Here, we consider the validity of the aortic stenosis model by looking at the EF value. Decrease in EF can be a symptom of aortic stenosis.

Results

Results for the cardiovascular system under normal conditions and severe aortic valve stenosis are presented in Table 2. A remarkable increase of the left ventricle systolic blood pressure and aortic mean pressure gradient and decrease of aortic systolic blood pressure is observed in severe aortic valve stenosis.

In Table 2, as the first column belongs to the physiological (normal) values of the pressures and volumes of the healthy cardiovascular system (12), the second column belongs to the corresponding values of the electrical equivalent model introduced in this study. Almost every values are the same. Aortic stenosis case of the model is accomplished by increasing the value of the serial RdA. Since the normal value of RdA is 0.003 HRU, two aortic stenosis conditions are obtained by changing the value of RdA as 0.2 HRU and 0.5 HRU. Increasing the RdA

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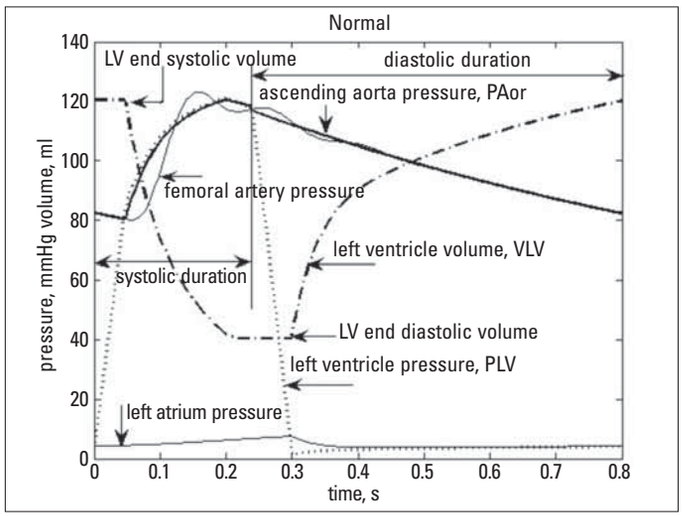

Figure 3. The main pressure and volume contours obtained from the model for normal conditions

LV - left ventricle

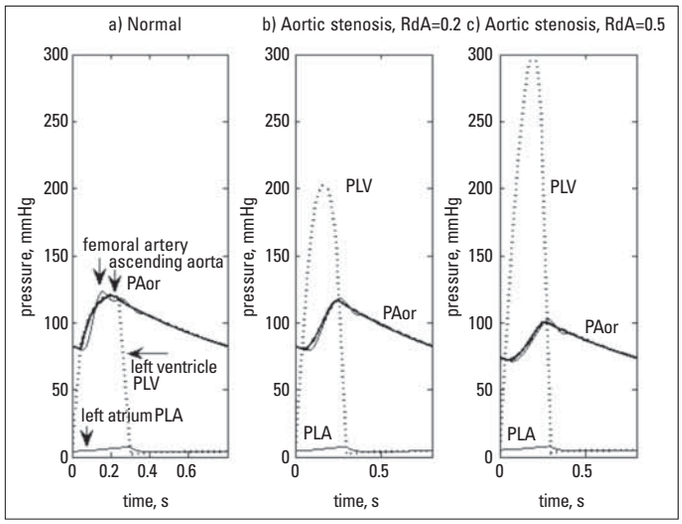

Figure 4. Left ventricle, left atrium, ascending aorta and femoral artery pressures in normal ("a") and in severe aortic stenosis ("b" for RdA=0.2 HRU and "c" for RdA=0.5 HRU) conditions

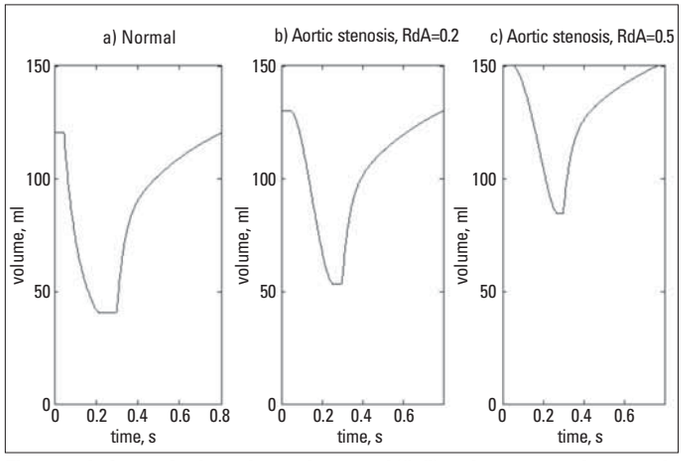

Figure 5. Left ventricular volumes in normal ("a") and severe aortic stenosis ("b" for RdA=0.2 HRU and "c" for RdA=0.5 HRU)

causes the increase of the LV peak systolic pressure (from 120 mmHg to 203 mmHg and 304 mmHg), increase of the mean pressure area (73 mmHg and 139 mmHg) (Fig. 4), increase of the pressure gradient (86 mmHg and 204 mmHg) (Fig. 4.), decrease of the stroke volume (from 100 ml to 95.5 ml and 84 ml) and decrease of the pulse pressure (from 40 mmHg to 36 mmHg and 28 mmHg) (Table 2).

In normal conditions, simulated EF is 0.67 which is the same with physiological data. For aortic stenosis, R_{dA} was set 0.2 HRU and 0.5HRU and obtained EFs are 0.59 and 0.44, respectively. These values are valid in aortic stenosis conditions. Other results are shown in Table 2 and Figures 4-7.

Discussion

The equivalent electronic cardiovascular circuit model introduced in this work is very useful for studying the whole cardiovascular system and its abnormalities. Different heart and vascular abnormalities can be studied by changing the model parameters. By combining the classification processing which uses the model parameters, the model can be used for diagnostic purposes. Suitable modifications can be done on this model and the number of parameters can easily be increased.

An analog circuit for simulating normal condition and severe aortic valve stenosis has been designed. Especially we focused on severe aortic stenosis, because it may cause a sudden death in asymptomatic patient (13, 14).

The measurements we obtain for severe aortic stenosis is close to what is reported in the literature: increase of the LV systolic pressure and aortic mean pressure gradient, decrease of the aortic systolic pressure (13, 14). Severe aortic stenosis results in 1) reduced ventricular stroke volume due to increased after load, which decreases ejection velocity, 2) increased end-systolic volume and 3) a compensatory increase in end diastolic volume and pressure. The changes in ventricular pressures and volumes are best depicted using pressure-volume loops given in Fig. 7. As the severity of the stenosis worsens, the pressure-volume loop gets bigger and slides to the right side of the graphic.

The stenotic aortic valve creates a resistance to flow and causes a drop in systolic pressure from the LV to the aorta. In response, the LV wall is thickened. The thick ventricle wall causes a decrease in diastolic ventricular compliance and therefore end-diastolic pressure must increase in order to perpetuate the same end-diastolic volume (13, 14). Despite the wall thickens, end-diastolic volume is largely unchanged. In the normal heart, during systole, the contracting fibers develop force that is used to increase intraventricular pressure to overcome aortic pressure and to eject stroke volume. This force (Fo), usually called wall stress, is difficult to measure but can be calculated if intraventricular pressure (P), radius (r) and wall thickness (h) are known by using Laplace's law:

$$Fo = \frac{P.r}{2h}$$

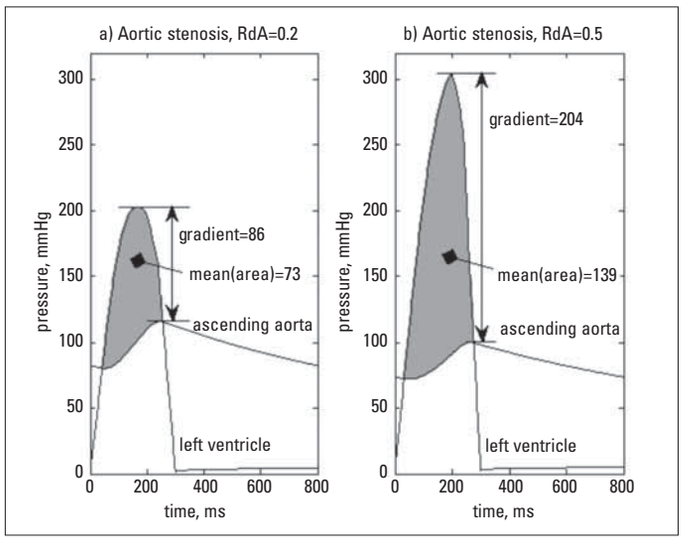

Figure 6. Mean pressure areas and gradient pressures severe aortic stenosis ("a" for RdA=0.2 HRU and "b" for RdA=0.5 HRU)

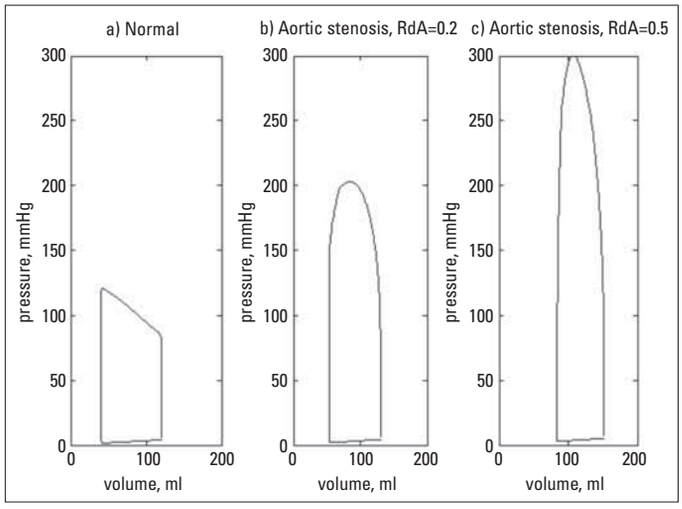

Figure 7. Left ventricular pressure- volume loops in normal ("a") and severe aortic stenosis ("b" for RdA=0.2 HRU and "c" for RdA=0.5 HRU)

Laplace's law shows that wall stress increases if intraventricular pressure (P) and/or radius (r) increase, but it falls if the wall (h) of the ventricle thickens (13-15).

Due to the stenotic valve and the limitations on maximum LV pressure (260 to 300 mmHg), it takes longer time to eject the blood and systole occupies a greater amount of time in total cardiac cycle. In severe aortic stenosis, it is difficult to increase cardiac output. Increased cardiac output needs the valve gradient to rise about the square of the output. As compensatory hypertrophy reaches its limits, ventricle muscle degeneration occurs, cardiac contractility decreases and the LV dilate to perpetuate chamber pressure by the Frank-Starling mechanism (12). As a result, low ejection fraction and cardiac output cause LV failure. Ischemia and angina are common in aortic stenosis, even in the absence of coronary artery disease (15, 16). In severe aortic stenosis, myocardial oxygen demand is high, but oxygen delivery is impaired by the effects of low aortic pressure, the high LV end-diastolic pressure and the thick myocardial wall. Episodic ischemia may cause ventricular arrhythmias, syncope or even sudden death (15, 16).

Study limitations

The main limitations of our study are: i) No clinical case was used in the study. Therefore, we studied with the data obtained from the literature. As a result, there was no a chance to make a statistical study; ii) Only the EF value was studied as evidence of severe aortic valve stenosis. With new clinical cases collected from real patients, we will be able to analyze validity and reliability of the model with new clinical cases.

Conclusion

In this study, we assert the validity of the model by relying on the data of normal (physiologic) and aortic stenosis from the literature. For further proofs for the models validity, studies using statistical research in patients with aortic stenosis need to be addressed. Our model is effective and available for simulating normal cardiac condition and cardiovascular diseases, especially severe aortic stenosis.

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