MODELING AND IDENTIFICATION OF CULPRIT CORONARY ARTERIES

by
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MODELING AND IDENTIFICATION OF CULPRIT CORONARY ARTERIES

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ABSTRACT

MODELING AND IDENTIFICATION OF CULPRIT CORONARY ARTERIES

Cardiovascular diseases are the leading causes of death in the world. Acute coronary syndromes are the categories of the cardiovascular disease group. In recent years, researches using non-invasive methods have been performed to prevent the increase in the mortality rate with early diagnosis. Cardiovascular system modeling with Lumped parameters comes first among these methods. In the lumped parameter model, coronary vessels are designed as an electrical circuit. In this study, patient-specific values were used and the patient-specific coronary artery tree model was developed using an electrical circuit model. The stenosis effect observed in acute coronary syndromes was applied on Lumped parameters and the change in blood pressure and blood flow was observed with graphics. The stenosis percentages were determined as 30, 60 and 90 and they were applied on only one point of the patient-specific coronary tree. When the graphics were examined, the change caused by the stenosis effect arteries could be observed more clearer on the right coronary compared to the left coronary arteries. In addition, it was aimed the identification of culprit coronary arteries according to the changes in the graphs.

ÖZET

SUÇLU KORONER ARTERLERİN MODELLENMESİ VE TANIMLANMASI

Dünyada ölüm nedenlerinin başında kardiyovasküler hastalıklar gelmektedir. Akut koroner sendromlar kardiyovasküler hastalıklar grubunun başında gelir. Son zamanlarda erken teşhis ile ölüm oranındaki artışın önüne geçilmesi için invazif olmayan yöntemler kullanılan araştırmalar yapılmaktadır. Bu yöntemlerin başında Lumped parametrelerle kardiyovasküler sistem modellenmesi gelmektedir. Lumped parametre modeli koroner damarların elektriksel devre olarak tasarlanmasını kapsar. Bu çalışmada hastaya özel değerler kullanılmıştır ve koroner arter ağaç modeli elektriksel devre modeli kullanılarak geliştirilmiştir. Akut koroner sendromlarda gözlenen tıkanıklık etkisi Lumped parametrelere uygulandığında kan basıncındaki ve kan akışındaki değişim grafiklerle gözlemlenmiştir. Tıkanıklık yüzdeleri 30, 60 ve 90 olmak üzere belirlenmiştir ve hastaya özel koroner arter modelinin yalnızca tek bir noktasına uygulanmıştır. Grafikler incelendiğinde, tıkanıklığın yarattığı değişim sağ koroner damalarlarda sol koroner damarlara göre daha net gözlemlenebilmiştir. Ayrıca grafiklerdeki değişime bakılarak suçlu koroner arterlerinin belirlenmesi hedeflenmiştir.

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LIST OF SYMBOLS/ABBREVIATIONS

ACS	Acute coronary syndrome
AV	Atrioventricular
BP	Blood pressure
CVD	Cardiovascular disease
CVS	Cardiovascular system
CT	Computed tomography
DBP	Diastolic blood pressure
LAD	Left anterior descending artery
LCX	Left circumflex artery
PDA	Posterior descending artery
PLA	Posterior lateral artery
LMCA	Left main coronary artery
NSTEMI	Non- ST elevation myocardial infarction
RCA	Right coronary artery
SA	Sinoatrial
SBP	Systolic blood pressure
STEMI	ST elevation myocardial infarction
UA	Unstable angina
WHO	World Health Organization

A_0	Normal cross-sectional area
A_s	Stenotic cross-sectional area
C	Capacitor
C_c	Vessel compliance
C_e	Capacitor as an electrical circuit component
C_s	Capacitance of blood vessel with stenosis
D	Blood vessel diameter
E	Blood vessel elasticity module
F	Blood flow
h	Blood vessel thickness

I	Current
l	Blood vessel length
L	Inductor
L_c	Blood inertia
L_e	Inductor as an electrical circuit component
L_s	Inductance of blood vessel with stenosis
Q	Blood flow rate
P	Blood pressure
R	Resistor
R_c	Blood vessel resistance
R_e	Resistor as an electrical circuit component
R_s	Resistance of blood vessel with stenosis
v	Voltage
α	Cross-sectional area reduction
μ	Blood viscocity
ρ	Blood density
π	Pi number

mmHg	Millimeters of mercury

1. INTRODUCTION

1.1. AIM OF THE STUDY

The aim of this study is to identify the culprit coronary arteries by electrical modeling of the coronary artery system using Lumped parameters technique.

For that purpose, the high performance simulation software, known as LTspice, was used for easing modeling of the coronary arteries as an electrical circuit. According to the percentage of the vascular occlusion, this electrical circuit was designed using the Lumped parameters method. The stenosis percentages were used as 0, 30, 60, and 90. After the data is obtained by using LTspice XVII, MATLAB was used to analyze the effect of the stenosis on the aortic pressure by plotting the graphs. According to the stenosis area and the stenosis percentages, the changes in the blood flow and the blood pressure were assessed with the help of traces in the aortic pressure graphs. In addition, it was aimed the identification of culprit coronary arteries according to the changes in the graphs.

1.2. CARDIOVASCULAR SYSTEM

Cardiovascular system (CVS) is a transporter system that contains important components such as the blood, the blood vessels and the heart and it is important for all cells of the whole body. CVS is also known as circulatory system. Besides to carrying nutrients and oxygen to tissues, CVS provides homeostasis by exchanging the necessary gas and fluid in the tissue. It is necessary to pay attention to the health of this vital system. To diagnose cardiovascular problems is important as quickly as possible using a non-invasive technique. The cardiovascular health is related to the blood pressure, and its condition is diagnosed by how the blood pressure changes over time [1].

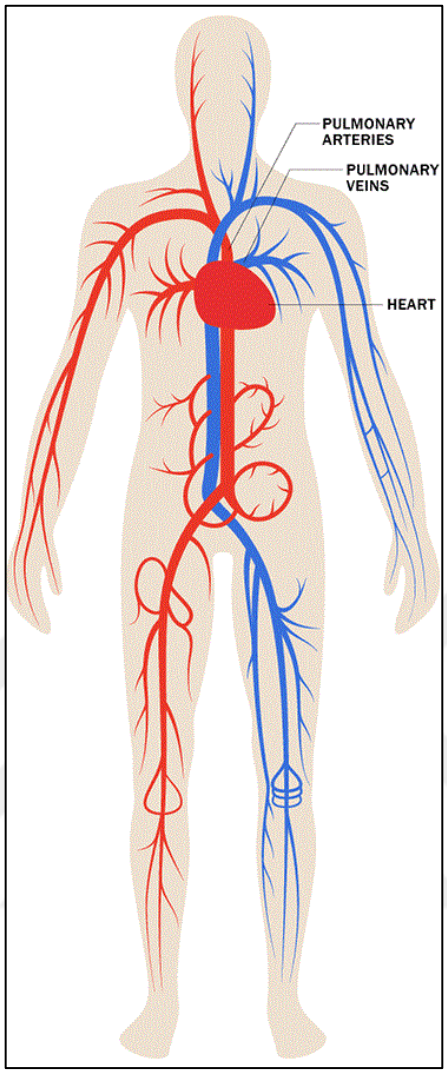

Figure 1.1. The cardiovascular system [2]

According to World Health Organization (WHO) statistics, the main cause of death globally is the cardiovascular disease (CVD). Approximate 17.9 million people, which have CVD, lose their life each year [3]. Having healthy and balanced nutrition, and avoiding tobacco alcohol use and stress are important to protect heart health. Besides, people with a family history of heart disease are recommended to see a cardiologist from the age of 30. If there is no family member with heart disease, the people should have regular check-ups from the age of 40. During these controls, several tests, such as electrocardiography, echocardiography, effort test, and blood tests, are performed at regular intervals. Diabetes and high blood pressure patients, overweight people should have these controls done more meticulously [4].

1.3. HEART

The heart is a muscular organ that collects oxygen-poor (deoxygenated) blood from the tissues and pumps oxygen-rich (oxygenated) blood to tissues for cellular respiration using blood vessels of the circulatory system. Besides pumping blood, the heart regulates body temperature, remove residual products as a result of metabolism activities, maintain acid-base balance, and transport hormones and enzymes to the necessary parts of the body. The heart lies in the chest cavity, which is known as the mediastinum, just posterior to the breastbone, between the lungs, and rests on the superior to the diaphragm (Figure 1.2) [5,6].

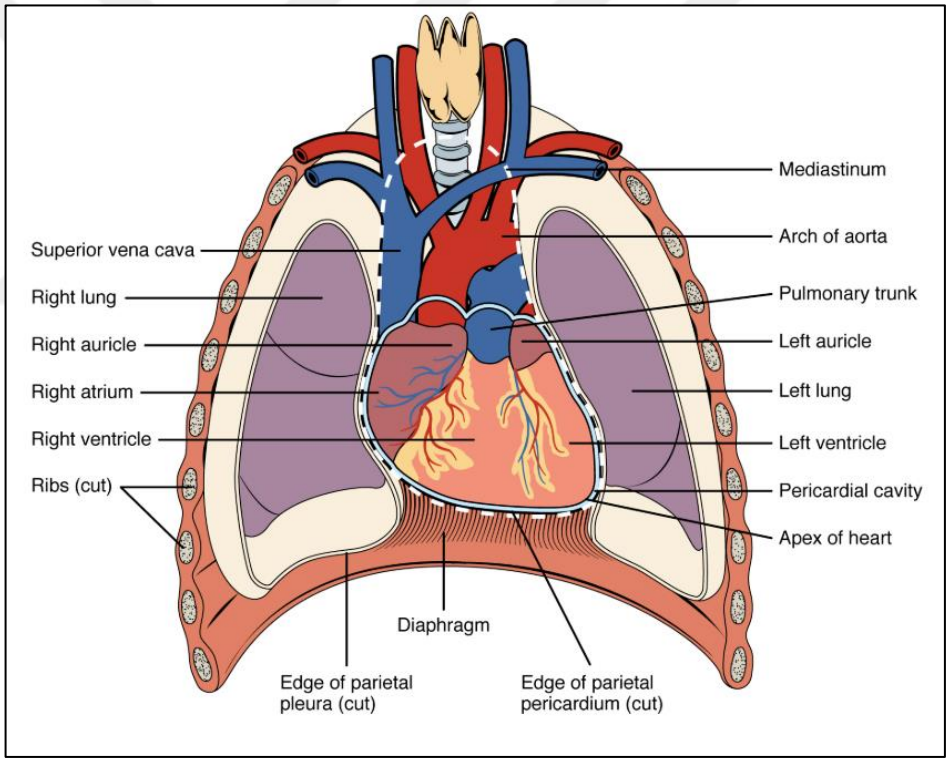

Figure 1.2. The heart position in the chest cavity [5]

The size of the heart is approximately equal to the person's fist (Figure 1.3). Besides, the weight of the heart varies between genders. For example, most women have lighter heart weights on average than men. Moreover, the size and weight of the heart can vary depending on the amount of exercise. The well-trained athlete can have larger hearts than normal and their hearts can have more effectively blood-pumping at low heart-rate [4,5].

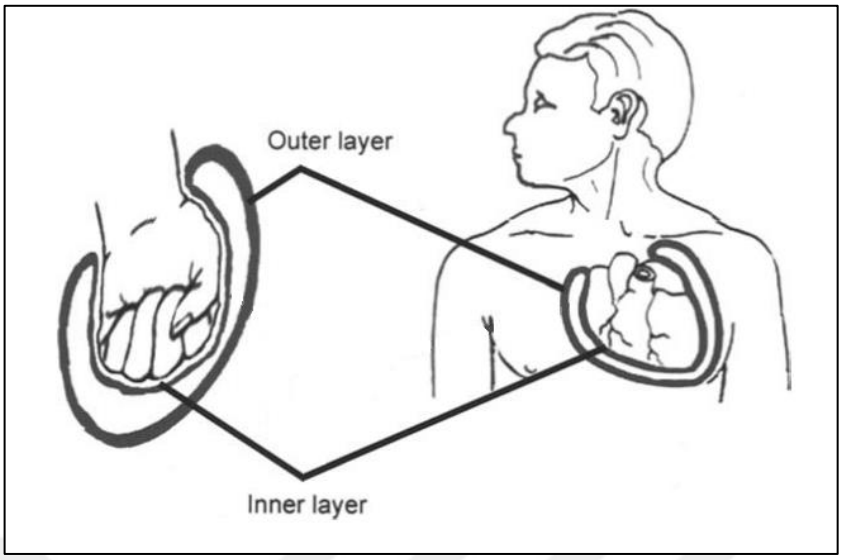

Figure 1.3. The size of the heart [6]

The heart has covered a membrane known as the pericardium (Figure 1.4). The pericardium, which is a double-walled fibrous sac, covers the roots of the great arteries, the superior vena cava pulmonary veins, and the heart [7]. The functions of the pericardium are separating the heart from the lungs and the other structures in the mediastinum and fixing it to the mediastinum. It is also effective in the volume-pressure equilibrium of cardiac chambers while the heartbeats and acts as a mechanical barrier against infection. When the blood volume increases, the pericardium prevents the heart from over-expanding [8]. The pericardium consists of two layers derived from mesothelium: the serous layer and the fibrous layer [9]. Besides, the serous pericardium is divided into two layers: the parietal pericardium and the visceral pericardium. The layer which protects the heart from external organs is the fibrous pericardium and it is adjacent to the diaphragm at the bottom. It covers all the vessels related to the heart, except the vena cava inferior. The parietal pericardium layer of the serous pericardium is also fibrous and thin layer. It is fused inextricably with the fibrous pericardium. The visceral pericardium is a part of the epicardium that is the layer of the heart wall. The pericardial cavity is a space between the parietal pericardium and the visceral pericardium layers. That cavity contains sterile and slippery substance that is called pericardial fluid. The heart sits in the pericardial cavity and the pericardial fluid helps the heart to work by reducing friction with the tissues around it [4, 7, 8]. Besides, there are two pericardial sinuses through the pericardial space. A sinus is a passageway or channel. The

transverse pericardial sinus is located above the left atrium of the heart, anterior to the superior vena cava, and posterior to the pulmonary trunk and ascending aorta. The oblique pericardial sinus is located posterior to the heart and is limited by the inferior vena cava and pulmonary veins [8].

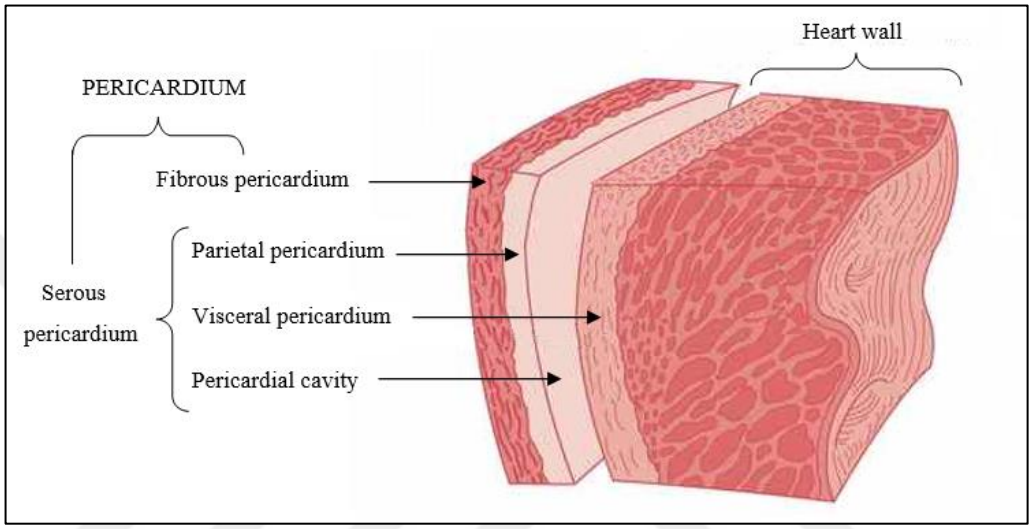

Figure 1.4. The heart membrane layers known as the pericardium

1.3.1. Heart Wall Layers

The heart wall consists of three layers named as the epicardium, the myocardium and the endocardium from superficial to deep (Figure 1.5). The first layer is the epicardium. The epicardium, which is the elastic connective tissue, is the thinner layer of the heart wall [10]. It contains coronary blood vessels. The epicardium layer is also known as the visceral pericardium. The second layer is myocardium. The myocardium is the thickest and middle layer of the heart wall. It is responsible for pumping blood and contains the cardiac muscle tissue, or cardiomyocytes. The cardiomyocytes contract as other muscle cells but they have different shapes. When they compared to muscle cells such as skeletal muscle cells, cardiac muscle cells are shorter and number of their nuclei is lower. It contains one or two large nuclei centrally located. The thickness of the myocardium varies in different parts of the heart. The ventricles have a very thick myocardium layer because of pumping blood to the

lungs or all over the body. The right-side walls of the heart have less myocardium layer than the left side because the left side has to pump blood through the whole body while the right side only has to pump to the lungs [5]. Third layer is endocardium. The endocardium is thin, smooth and squamous endothelium layer that lines the cavities and valves of the heart. Its role is to block blood from sticking to the inside of the heart and to prevent forming potentially deadly blood clots [11].

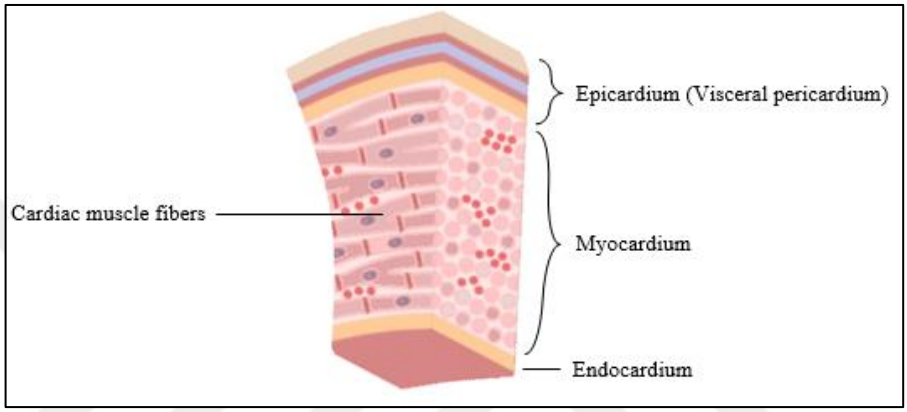

Figure 1.5. Heart wall layers

1.3.2. Heart Chambers

The heart consists of four chambers which are two upper chambers (atrium) and two lower chambers (ventricles). The right and left parts of the heart are completely separated from each other via the septum. The interatrial septum is located between the right atrium and the left atrium. The interventricular septum is located between the right ventricle and the left ventricle. If they are compared with each other, the interventricular septum is thicker than the interatrial septum because ventricles have more pressure than atria while they contract [5]. The septum prevents mixing oxygenated blood with deoxygenated blood. The right heart which is made up of right atrium and right ventricle contains deoxygenated blood. There is a collapsible valve named as tricuspid valve between the right atrium and the right ventricle. The left heart which is made up of the left atrium and left ventricle contains oxygenated blood. There is a valve named as mitral valve between the left atrium and the left ventricle. The oxygenated blood and deoxygenated blood go out from the ventricles by passing through

the semilunar valves. One of the semilunar valves is the pulmonary valve which is located between the right ventricle and the pulmonary artery. The pulmonary valve allows the pumping blood from the heart to the lungs. The other semilunar valve is the aortic valve which is located between the left ventricle and the aorta. The aortic valve allows the blood to be pumped from the heart to the whole body. These valves in the heart prevent backward leakage of the blood and keep blood moving in the right direction [11-13].

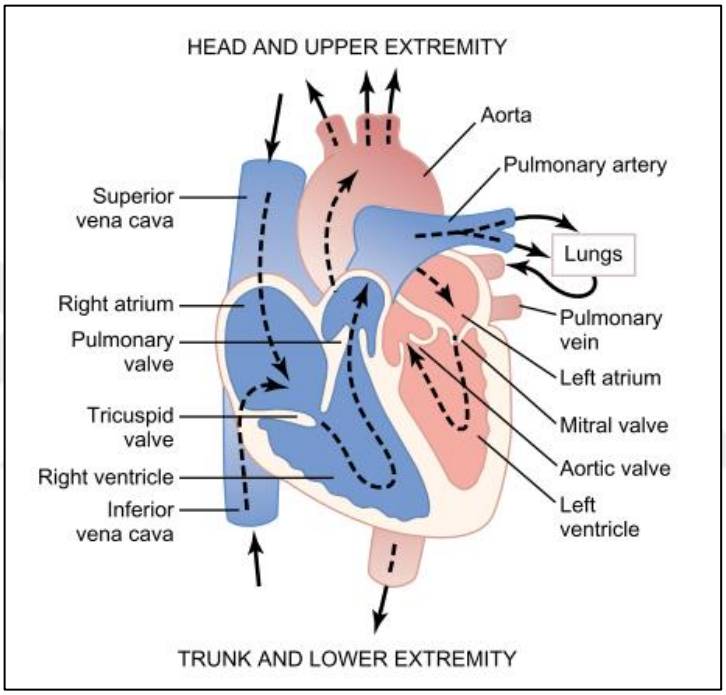

Figure 1.6. The heart chambers and the heart valves (blue: deoxygenated blood, red: oxygenated blood) [14]

1.3.3. Electrical Conduction of the Heart

The conducting system of the heart is made up of specialized cardiac muscle fibers that send an impulse to the heart to contract. It is responsible for the initiation and conduction of cardiac impulses. In the conducting system of the heart, there are five components. These components are sinoatrial (SA) node, atrioventricular (AV) node, atrioventricular bundle (bundle of His), right and left branches of bundle of His and Purkinje fibers (Figure 1.7).

The normal cardiac impulse starts at the SA node. The SA node has specialized myocardial fibers situated in the wall of the right atrium and it works as an internal dynamic pacemaker. SA node spontaneously generates an electrical impulse in a very organized to contract the atrial myocardium. This cardiac impulse is at about 60-100 times per minute. Then the impulse slows and travels to the AV node between the atria and ventricles. The AV node can be thought of as an electrical bridge and it allows electrical signals to travel from the atria to the ventricles. Before the electrical conduction reaches the ventricles, it is held in the atrioventricular node for a short time. Thus, the atria and ventricles are prevented from contracting at the same time. That delay is to ensure that the atria have ejected all the blood into the ventricles before the ventricles contract. The AV node receives signals from the SA node and passes them onto the bundle of His. The cardiac impulse accelerates again in there. The bundle of His is then divided into right and left bundle branches that conduct impulses toward the apex of the heart. The signals are then passing onto Purkinje fibers, turning upward and spreading throughout the ventricular myocardium [15].

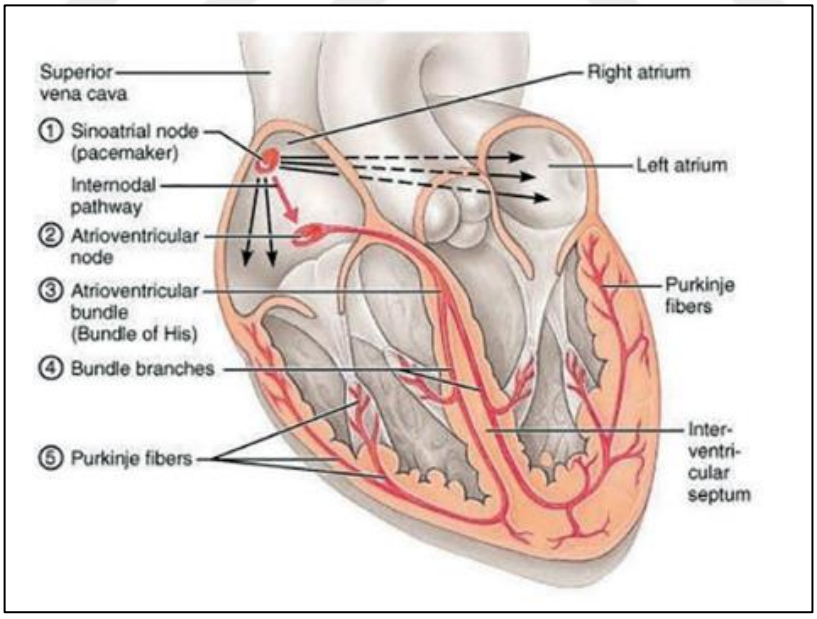

Figure 1.7. Electrical conduction system fibers in the heart [16]

1.3.4. Blood Circulation

There are three types of blood circulation in the body: pulmonary circulation, systemic circulation and coronary circulation. In pulmonary circulation, deoxygenated blood which contains carbon dioxide and metabolic wastes is pumped through the tricuspid valve from the right atrium into the right ventricle, then pumped from the right ventricle to the lungs via pulmonary artery. After carbon dioxide and oxygen exchange in the lungs, the oxygenated blood is returned to the left atrium via pulmonary vein. Then, the blood passes through the mitral valve to the left ventricle. In systemic circulation, the oxygenated blood is pumped from the left ventricle to the body through the aorta. After the blood deoxygenation in the capillaries in the body, the blood returns to the right atrium via vena cava. Thus, the blood continues its circulation in the body through the pulmonary circulation and the systemic circulation (Figure 1.8) [17,18].

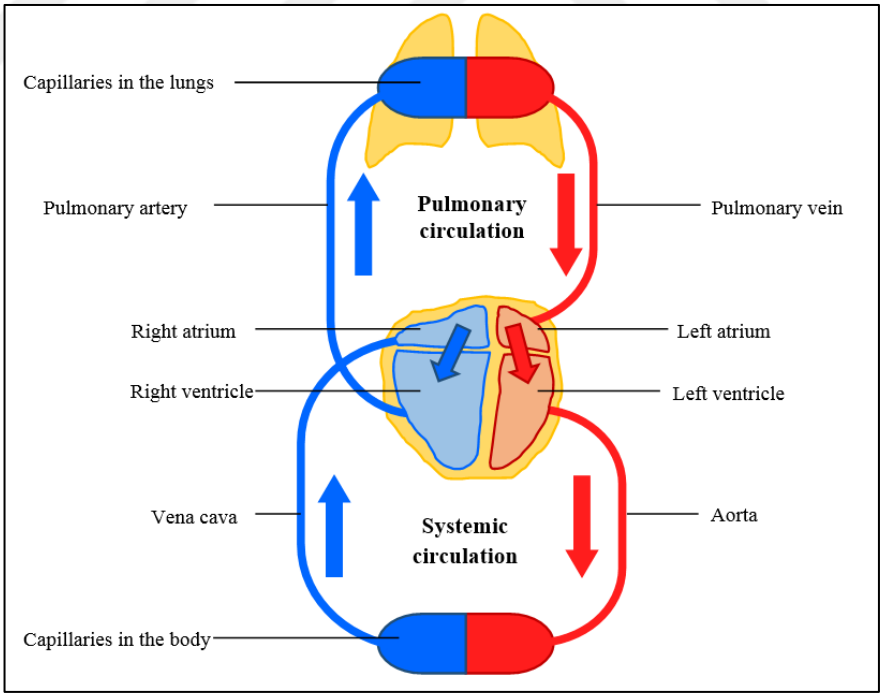

Figure 1.8. The pulmonary circulation and the systemic circulation in the human body (blue: deoxygenated blood, red: oxygenated blood)

Coronary circulation is the small loop of the systemic circulation and it is the movement of blood throughout the vessels that supply the myocardium. Cardiomyocytes require a steady supply of oxygen, nutrients and a way to eliminate wastes. Although the heart is continually pumping blood throughout its chambers, the myocardium is too thick for the diffusion of blood to happen effectively. So instead, the coronary circulation provides an efficient way for the exchange of substances to occur. It is mainly made up of arteries and veins. In coronary circulation, the heart takes blood directly from the main artery which is aorta coming from the heart. The aorta can be divided into three sections: the ascending aorta, the aortic arch, and the descending aorta. From proximal to distal, three major branches of aortic arch are the left subclavian artery arteries, the left common carotid artery, and the brachiocephalic trunk which splits into the right common carotid artery and right subclavian. The ascending aorta branches into two main coronary blood vessels: the right coronary artery (RCA) and the left main coronary artery (LMCA) [15,16,19]. LMCA heads along the left coronary sulcus. The coronary sulcus is a groove on the outer surface of the heart that marks the point of division between the ventricles and the atria. LMCA divides into two major branches. The first is the left anterior descending artery (LAD). It travels down the anterior interventricular sulcus and it have diagonal branches. LAD supplies the anterior two-thirds of the interventricular septum, the anterior lateral papillary muscle and the anterior surface of the left ventricle via diagonal branches. The second branch is the left circumflex artery (LCX). It goes along the coronary sulcus around the left side of the heart and supplies the left atrium and the posterior walls of the left ventricle. Alternatively, RCA heads in the opposite direction following the coronary sulcus and the along the way it supplies the SA node. It later divides into branches. The first is the right marginal artery which stretches along the margins of the bottom right side of the heart supplying the right ventricle. The second branch is posterior lateral artery (PLA). The other branch is the posterior descending artery (PDA). It goes down the posterior interventricular sulcus towards the hearts apex while supplying the posterior one-third of the interventricular septum, the posterior two-thirds of the ventricular walls and the posterior medial papillary muscle. At the apex the posterior descending artery merges with its anterior counterpart through interconnected arterial branches called anastomoses. They supply the atrium and nearly all of the ventricle together. The coronary arteries and their main branches lie in the epicardium or the outer layer of the heart wall and they send branches inward to supply the myocardium [5].

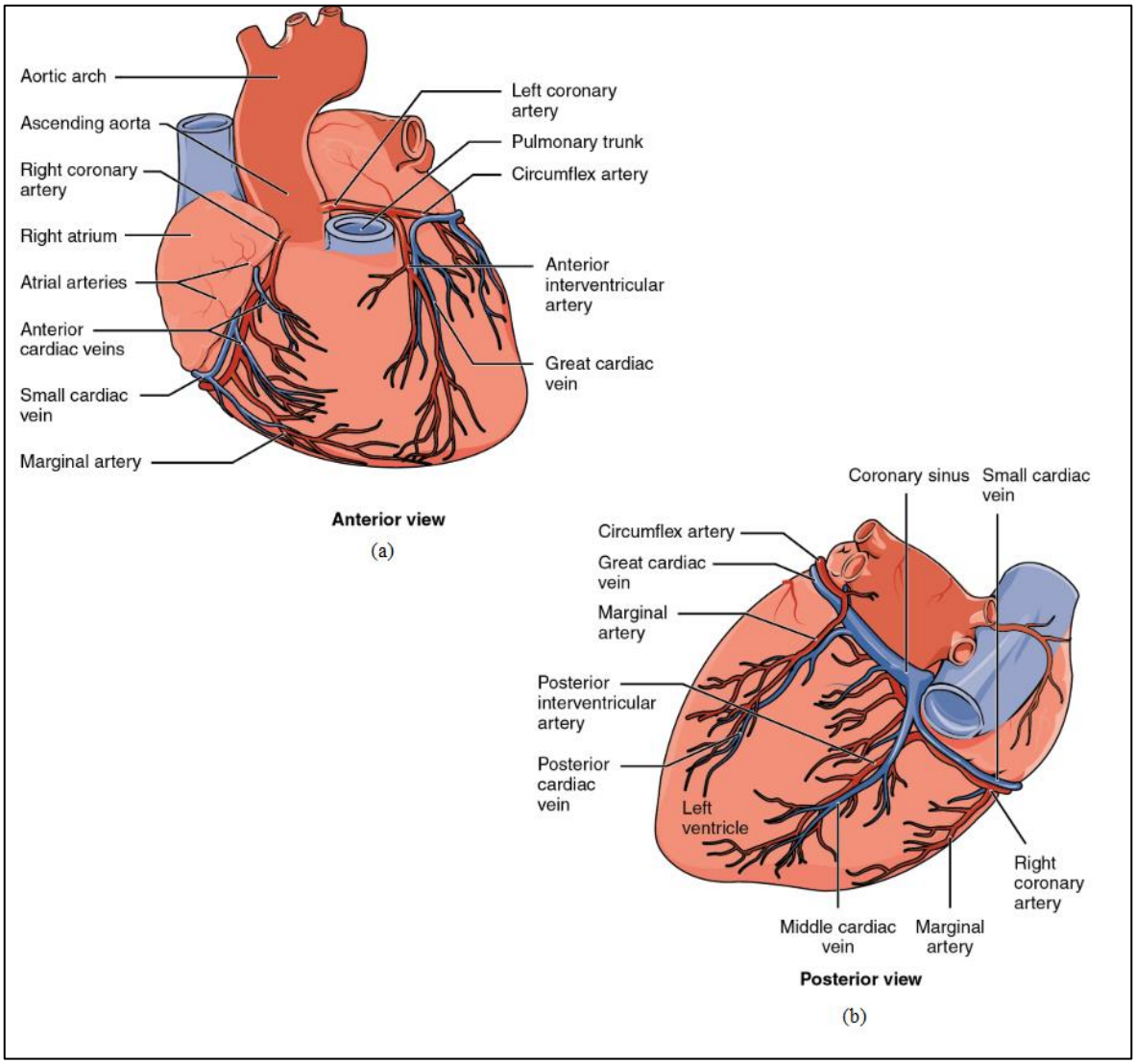

Figure 1.9. The coronary surface vessels of the heart: (a) the anterior view of the heart (b) the posterior view of the heart [5]

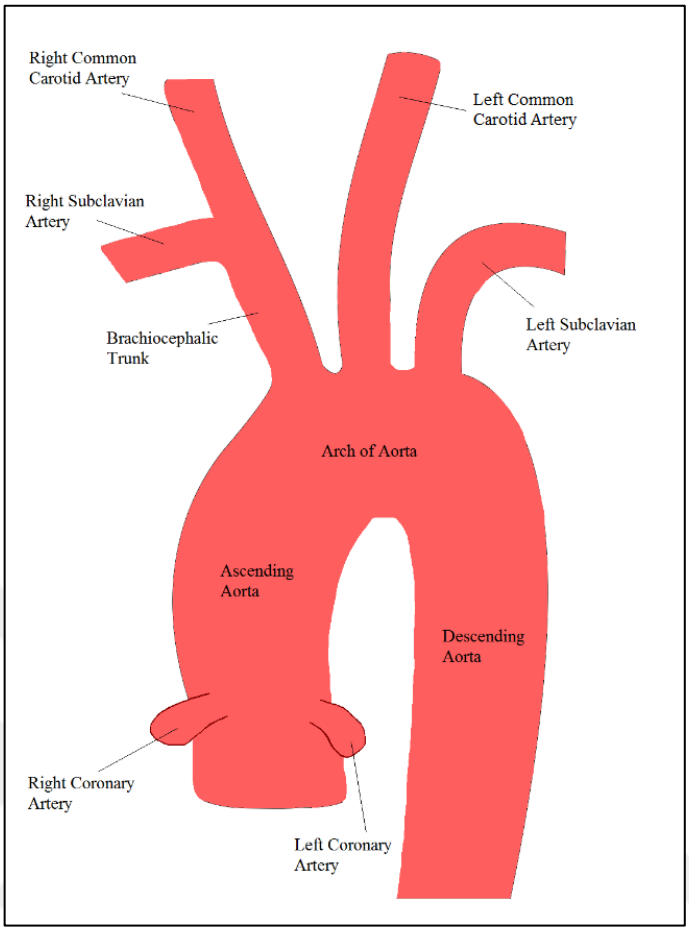

Figure 1.10. The branches of the aorta

1.3.5. Cardiac Cycle

When the heart muscle contracts and relaxes, the four valves in the heart open and close to allow blood flow through the heart and they make two different heart sounds known as the heartbeat. The contraction and the relaxation period occur over and over again with each heartbeat and this cycle is known as the cardiac cycle. The contraction period occurs with that the heart pumps blood to the circulation and it is called systole. The relaxation period occurs with that the chambers refill with blood and it is called diastole. In this way, the blood alternately fills the chambers of the heart and goes out from the heart to the coronary circulation. At the beginning of the heart cycle, all chambers relax. When the right and left ventricle relax, the tricuspid and mitral valve open and semilunar valves close. Meanwhile, the atrium contracts and the blood passes through from the atrium to the ventricles. As blood-

filled ventricles contract, they force the semilunar valves to open and the tricuspid and mitral valve close. Blood is pumped from ventricles into the aorta and the pulmonary artery. When the ventricles begin to relax, the semilunar valves close thereby finishing the one heart cycle [14].

When the heart contracts and relaxes, it causes that the circulating blood forces the walls of the blood vessels. This force is measured as blood pressure (BP). BP depends on the pumping of blood from the heart, the resistance of the intermediate vasculature and the elasticity of the arterial walls. BP represents the pressure in the arteries of the systemic circulation and it is measured in millimeters of mercury (mmHg). It has two levels, systolic blood pressure (SBP) and diastolic blood pressure (DBP). SBP is the highest level of the blood pressure reaches. It measures the force of blood pushed around the body when the blood is squeezed out of the heart in a bolus fashion with the contraction of the heart. DBP is the lowest level of the blood pressure reaches. It measures when the heart relaxes between heartbeats. Resting blood pressure is measured approximately 120/80 mmHg in a healthy adult. It means that the SBP is 120 mmHg and the DBP is 80mmHg [20]. Moreover, a cardiac cycle take time 0.8 seconds and it is shown in Figure 1.11.

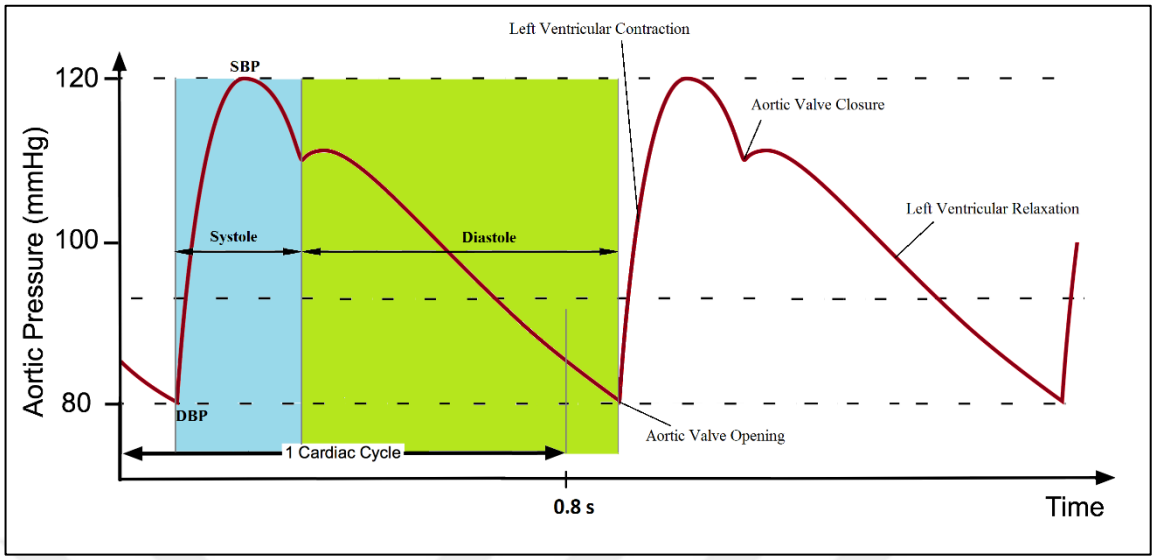

Figure 1.11. The aortic pressure graph. The highest level in the graph shows SBP and the lowest level in the graph shows DBP. The systole situation occurs in the blue zone and the diastole situation occurs in the green zone.

1.4. ACUTE CORONARY SYNDROME

Acute coronary syndrome (ACS) is a kind of CVD. It is a condition characterized by symptoms and clinical manifestations associated with acute myocardial ischemia. Several coronary risk factors for ACS are hypercholesterolemia, hypertension, diabetes, physical inactivity, and smoking. The common symptom of ACS is the pain that creates a feeling of pressure, tightness, or burning in the chest that spreads to the neck, jaw, or left arm. The other symptoms are irregular heartbeats, sweating, nausea, shortness of breath, dizziness and fainting. ACS can be diagnosed by the findings on physical examination, 12-lead ECG, and cardiac biomarker assays. ACS occurs as a result of plaque buildup on coronary vessel walls (atherosclerosis) [21]. Plaques susceptible to complications can be injured due to the thinness of the fibrous cover, excess lipid content, and increased inflammation efficiency. Injured plaque loses its endothelial cover. When the endothelial layer is removed, thrombocytes in the blood adhere to there with glycoprotein receptors to prevent extravascular bleeding. The activated platelets undergo formal change and become stickier. Thus, platelets cling to each other and begin to cluster (aggregation) [22]. The clot formed on the plaque disrupts the

blood flow in the coronary artery. Although there is no cell death in ACS, the decreased blood flow causes malfunctioning in the heart and it is a sign of a high risk of heart attack [23].

Table 1.1. Properties of the acute coronary syndromes

<table>
<tr><td></td><td>Unstable Angina</td><td>NSTEMI</td><td>STEMI</td></tr>
<tr><td rowspan="2">Pathophysiology</td><td>Ischemia without necrosis</td><td colspan="2">Ischemia with necrosis</td></tr>
<tr><td colspan="2">Transient thrombotic blockage</td><td>Complete occlusion</td></tr>
<tr><td>12-lead ECG</td><td colspan="2">No abnormalities, T-wave inversion, transient ST-elevation or ST-depression</td><td>Permanent ST-elevation</td></tr>
</table>

ACSs are categorized into ST elevation myocardial infarction (STEMI), non-ST elevation myocardial infarction (NSTEMI) and unstable angina (UA) as seen in Figure 1.12 and Table 1.1. UA and NSTEMI have similar characteristic in terms of pathophysiological and clinical examination [24,25]. While complete occlusion of the culprit artery and extra fibrin are observed in STEMI, transient thrombotic blockage of the culprit artery occurs in NSTEMI and UA [20, 22].

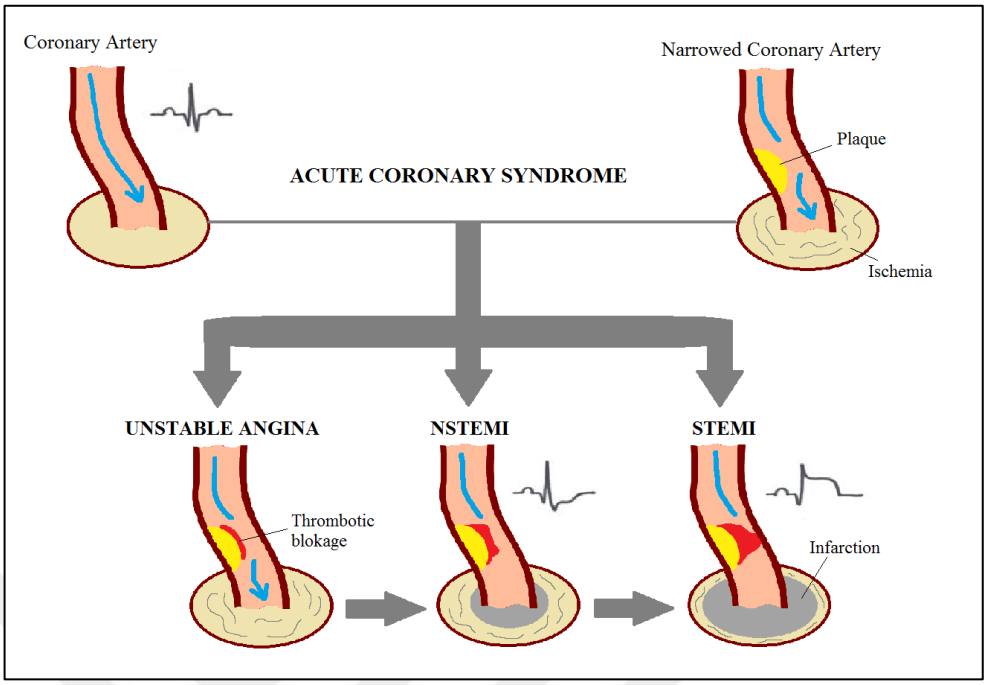

Figure 1.12. Types of the acute coronary syndromes

1.5. MODELING OF THE CARDIOVASCULAR SYSTEM

The CVS is a closed circulation system that transports oxygen, carbon dioxide, nutrients and vital substances to the tissues of the human body with blood. It interacts with other systems such as nervous and respiratory system and it also structurally connect with each other. The computer-based engineering modeling has become more popular, helpful and useful tool both to understand the interactions and functions of the CVS and to diagnose CVD [26]. Moreover, the modeling of the CVS may provide more effective and less expensive medical treatment than usual. Also, the students in medicine can use the cardiovascular simulation application to learn the blood flow dynamics and to test the dynamic process [27].

The CVS modeling is divided into two group mathematically. The first group is the lumped parameter model. The lumped parameter model is named as 0D models. The 0D model describes the distribution of the blood pressure, the blood flow, and the blood volume in every organ and every blood vessel in every moment of time for specific physiological conditions of whole CVS [28]. The second group is distributed parameter model. The distributed parameter model contains 1D models, 2D models and 3D models. The 1D models

are used to simulate the change in blood flow velocity along the length of the blood vessel by representing the pulsed wave reflection effect in the systemic circulation. The 2D models can be select an effective way to examine the radial changes of blood flow velocity in the vessels with an axial symmetry. Lastly, the blood flow in the branches of the blood vessels, and heart chambers and also through heart valves can be simulated in details using the 3D models [27].

1.5.1. Lumped Parameter Modeling

In the last few decades, the lumped parameter model has been commonly used modeling technique to analyze the blood flow dynamics of the CVS, known as hemodynamics. The blood pressure is a significant indicator to identify the medical conditions such as the detection of the irregular heartbeat, the estimating hypovolemia, and monitoring respiratory variatinos [1]. The 0D models are used to simulate the blood flow and pressure in the circulatory system in an attempt to explain the pressure-flow relationship by many researchers [29]. Momentously, lumped parameter models that are one of the 0D modeling techniques explain the physics of the CVS and the existing problem in the system. Thus the behavior of the CVS can be observed when the parameters in the model are changed [30].

In the lumped parameter model, every compartment of CVS can be described with the electronic circuit elements such as the resistor (R), the inductor (L) and the capacitor (C) . The equivalents of CVS compartments as the electrical circuit elements are illustrated in Table 1.2. The dynamics in the CVS and the electrical circuit elements of the CVS system compartments [28] and they are also as in the following [31]:

- The blood pressure (P) is respectively equivalent to the voltage (v).
- The blood flow (F) is respectively equivalent to the current (I).
- The blood vessel resistance (R_c) is respectively equivalent to the resistor (R_e).
- The vessel compliance (C_c) is respectively equivalent to the capacitor (C_e).
- The blood inertia (L_c) is respectively equivalent to the inductor (L_e).

Table 1.2. The dynamics in the CVS and the electrical circuit elements of the CVS system compartments [28]

Cardiovascular System	Electronic Circuit Elements	Equation for Electrical Circuit	Equation for Cardiovascular System
Vessel Resistance	Electrical Resistance (R_e) 	$v = I\,R_e$	$P = F\,R_c$
Vessel Capacitance	Capacitance (C_e) 	$C_e \frac{dv}{dt} = I$	$C_c \frac{dv}{dt} = F$
Blood Inertia	Inductance (L_e) 	$L_e \frac{dI}{dt} = v$	$L_c \frac{dF}{dt} = P$

The hemodynamic elements of the CVS are shown in Table 1.2. Their expressions as a series of equivalent elements in an electric circuit are illustrated in Figure 1.13 by using the Lumped parameters model.

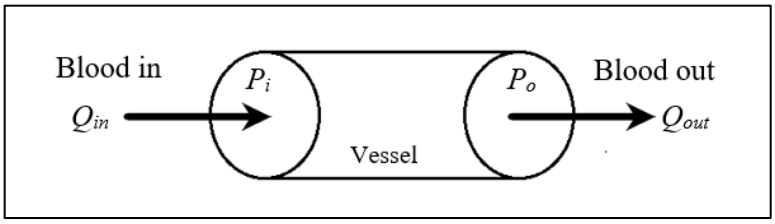

Figure 1.13. Hemodynamic elements of a blood vessel. (Q: blood flow rate, P: blood pressure)

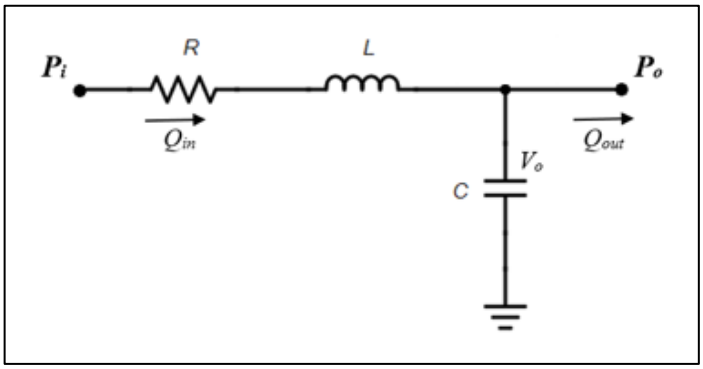

Figure 1.14. The equivalent analogous circuit of the vascular hemodynamic elements

The voltage and current laws can be used to calculate the node voltages in the Lumped parameters model. This means that the blood pressure and the blood flow rate can be calculated in the selected branches of the vessels in the CVS. Besides, the vesssel resistance, the vessel capacitance and the blood inertia also change, if there is a change in the structure of the blood vessel. This change affects the electrical circuit elements in the Lumped parameters model. In this way, it is easier to detect when there is any problem in the blood vessels.

1.5.2. Calculations in the Lumped Parameters Model

The hydraulic resistance is represented as R and it is calculated by

$$R = \frac{128\,\mu\,l}{\pi\,D^4} \tag{1.1}$$

where μ denoted the blood viscosity, l is the segment length and D is the diameter of the blood vessel compartment. The inertia of the blood flow is represented as L and it is calculated by

$$L = \frac{4\,\rho\,l}{\pi\,D^2} \tag{1.2}$$

where ρ denoted the blood density. The elastic capacitance of each blood vessel is represented as C and it is calculated by

$$C = \frac{\pi D^3 l}{4 E h} \tag{1.3}$$

where E is the elasticity module and h is the thickness of the arteries [31,32].

2. MATERIALS AND METHODS

2.1. PATIENT-SPECIFIC CORONARY TREE MODELING

The structure of the whole coronary tree and their segments with names were determined according to the computed tomography (CT) terminology. The coronary arterial tree was divided into several segments. The coronary tree model was reprensented using the reconstruction of the model based on CT scans in the study of Zheng *et al.* [33]. The LMCA and the RCA and their branches were illusturated as a tree in Figure 2.1 and 2.2. The root impedances were added to whole ends of the branches.

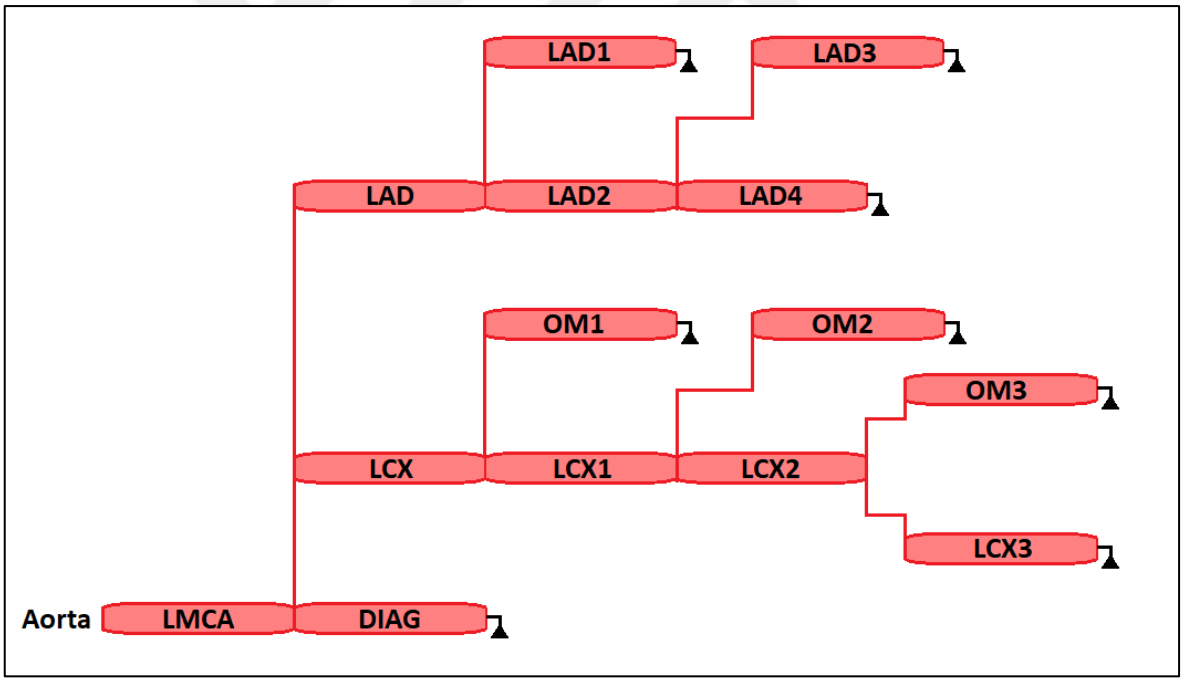

Figure 2.1. The structure of the LMCA and its branches. LMCA branches out as the diagonal (DIAG), the left circumflex (LCX, LCX1, LCX2, LCX3), and the left anterior descending (LAD, LAD1, LAD2, LAD3, LAD4). The left circumflex have obtuse marginal branches (OM1, OM2, OM3).

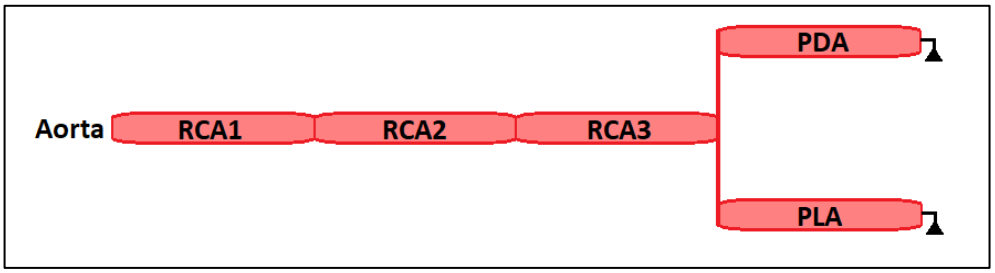

Figure 2.2. The structure of the RCA and its branches. The RCA is divided into 3 parts as RCA1, RCA2 and RCA3. PDA and PLA are the branches at the end.

2.2. LUMPED PARAMETER MODELING OF THE PATIENT-SPECIFIC CORONARY TREE

Modeling of LMCA, RCA, and their branches as an analogous circuit using lumped parameters is shown in Figure 2.3 and 2.4. The electrical circuit of the lumped parameters model was designed according to the strcuture of the coronary arteries in Figure 2.1 and 2.2. It was simulated using LTspice XVII that is an analog electronic circuit simulator software. In the model, the coronary tree has the root impedances at the end of the coronary branches. According to the names of the coronary artery branches, the names of the circuit components were specified. The values of the electrical components, which are the resistances, the inductors and the capacitances, were obtained from the study of Zheng *et al*. as shown in Table A.1. Lumped parameters of the patient-specific coronary tree model without stenosis [33].

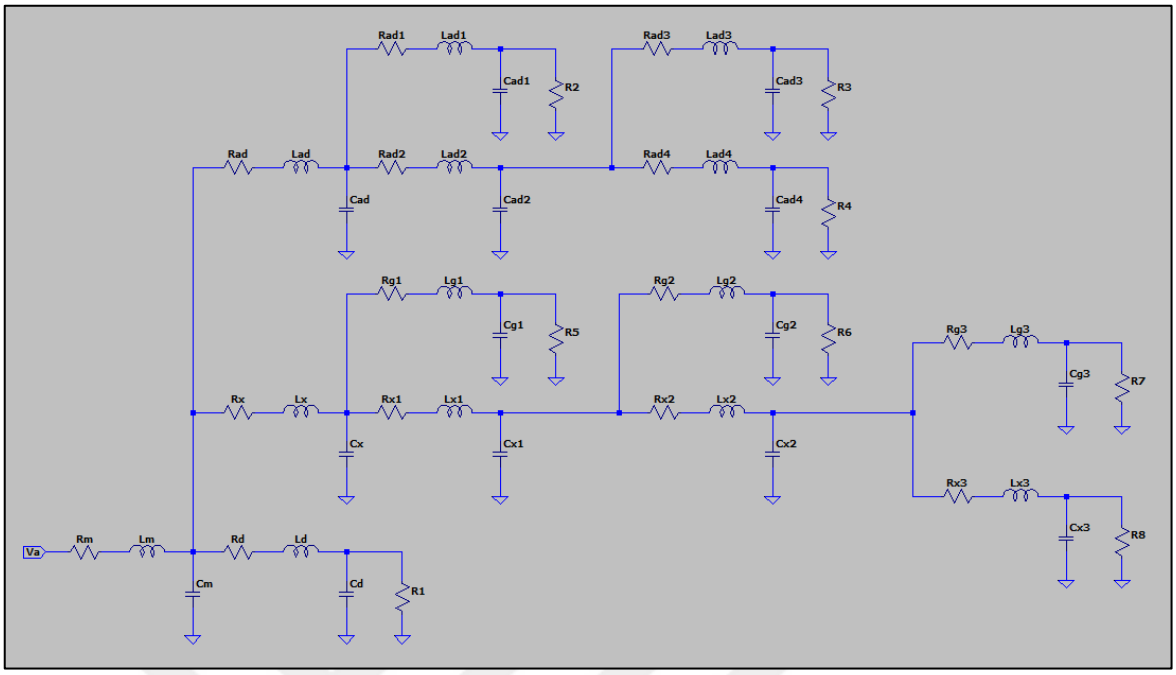

Figure 2.3. Lumped parameters modeling of the LMCA and its brances. The root impedances are shown as $R1$ to $R8$.

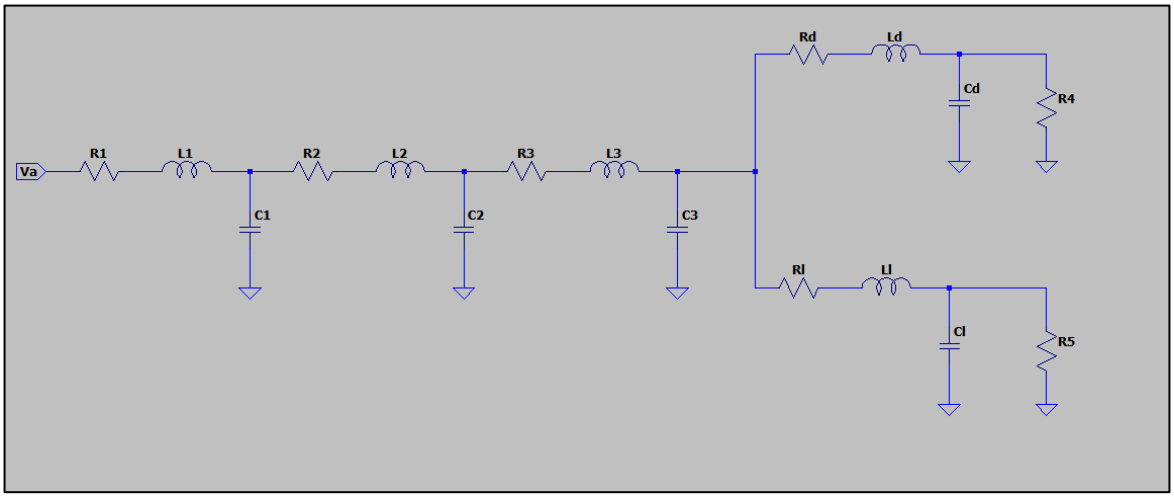

Figure 2.4. Lumped parameters modeling of the RCA and its branches. The root impedances are shown as $R4$ and $R5$.

After the patient specific coronary tree model was designed, an input voltage was applied. This input voltage was obtained from aortic pressure versus time graph. To obtain the voltage

values, the aortic pressure graph was manually digitized with a ruler on a graph paper. After the input voltage was applied for 5 cardiac cycle as seen in Algorithm B.1 andAlgorithm B.2, the node voltages and the current values were obtained as a table for whole branches of the patient-specific coronary artery tree model. Algorithm B.1 and B.2 were designed in LTSpice XVII by using node voltage analysis method. All data were used to plot the voltage versus time graphs and the current versus time graphs by using MATLAB (Algorithm C.1 and C.2).

2.3. STENOSIS EFFECT IN THE PATIENT-SPECIFIC CORONARY TREE MODELING

In the study of Zheng *et al.*, the stenosis degree is defined as α using a cross-sectional area reduction

$$\alpha = A_s/A_0 \tag{2.1}$$

where A_0 defines the normal cross-sectional area of the artery segment and A_s defines the stenotic one. Thereby, the resistance, the capacitance, and the inductance of the blood vessel with stenosis are calculated

$$R_s = R_c\ \alpha^{-2} \tag{2.2}$$

$$C_s = C_c\ \alpha^{3/2} \tag{2.3}$$

$$L_s = L_c\ \alpha^{-1} \tag{2.4}$$

where R_c represents the resistance of the blood vessel without stenosis, C_c represents the capacitance of the blood vessel without stenosis, and L_c represents the inductance of the blood vessel without stenosis, respectively. R_s, C_s, and L_s are stenotic ones. If p is the percentage of the area reduction,

$$\alpha = 100 - p \tag{2.5}$$

can be assumed [33].

The Lumped parameters of the electrical circuit were calculated using (2.1), (2.2), (2.3), (2.4), and (2.5) according to the stenosis degree. The stenosis effect was applied on the Lumped parameters and these parameters values were calculated by using Microsoft Office Excel. By using the new Lumped parameter values in Algorithm B.1, and B.2, the data was obtained with stenosis effect. The data files were used to determine stenosis effect on the graphs by Algorithm C.3.

3. RESULTS

3.1. THE LUMPED PARAMETERS WITHOUT STENOSIS EFFECT

By using Lumped parameters without stenosis, the graphs of LMCA and RCA were obtained. These graphs were plotted in MATLAB as seen in Figure 3.1, 3.2, 3.3 and 3.4.

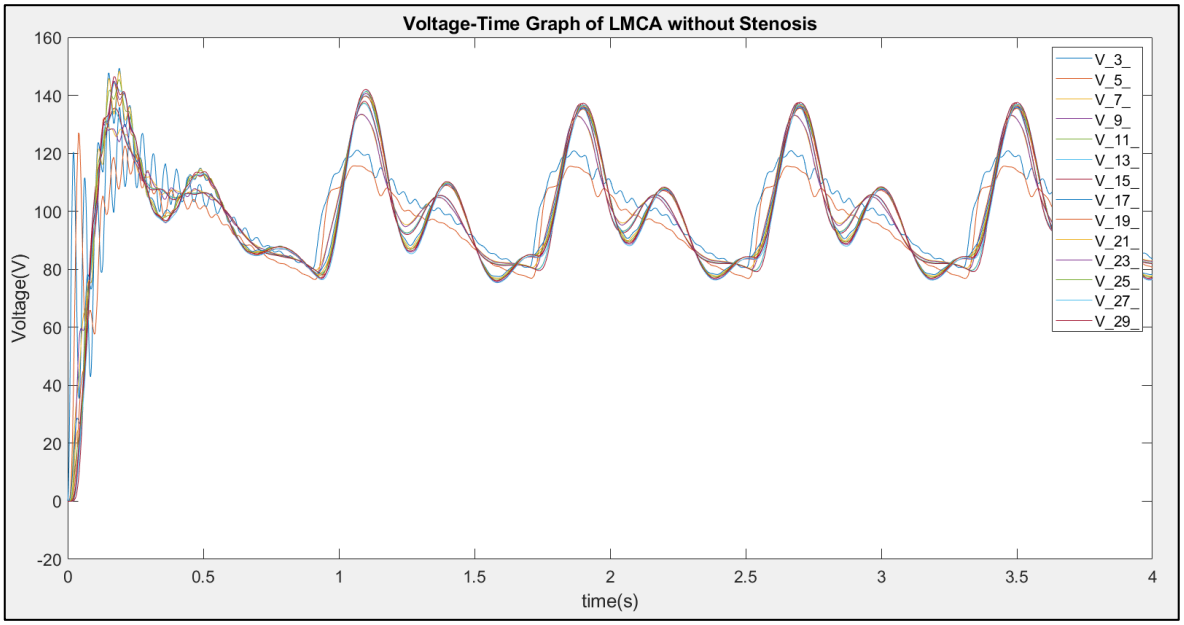

Figure 3.1. Voltage versus time graph of LMCA without stenosis

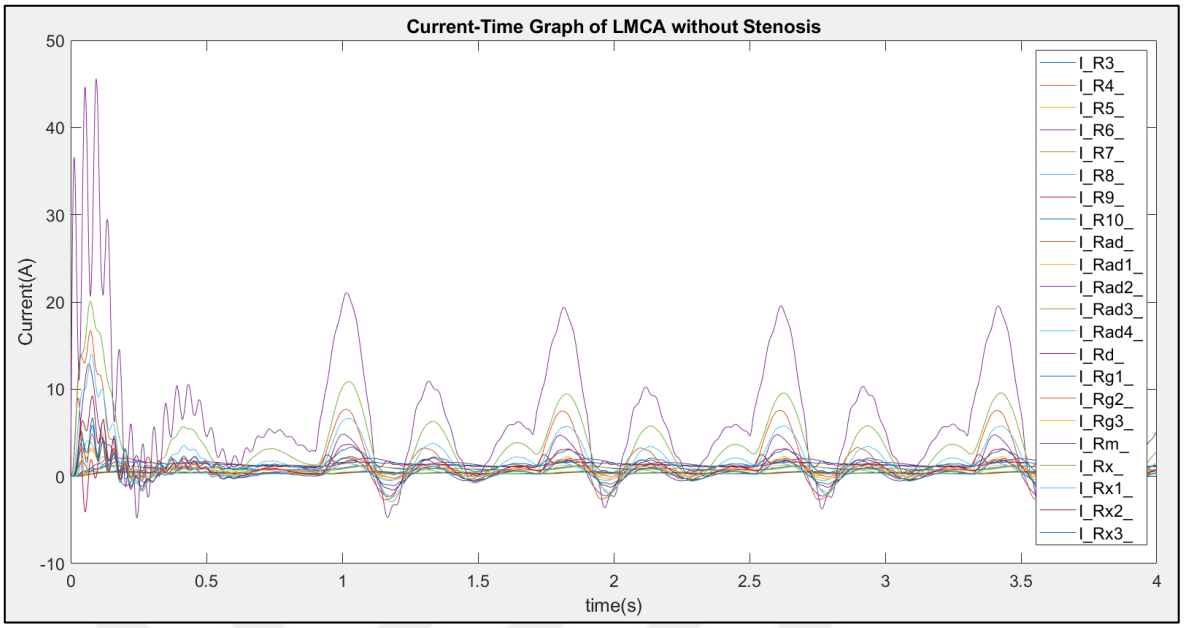

Figure 3.2. Current versus time graph of LMCA without stenosis

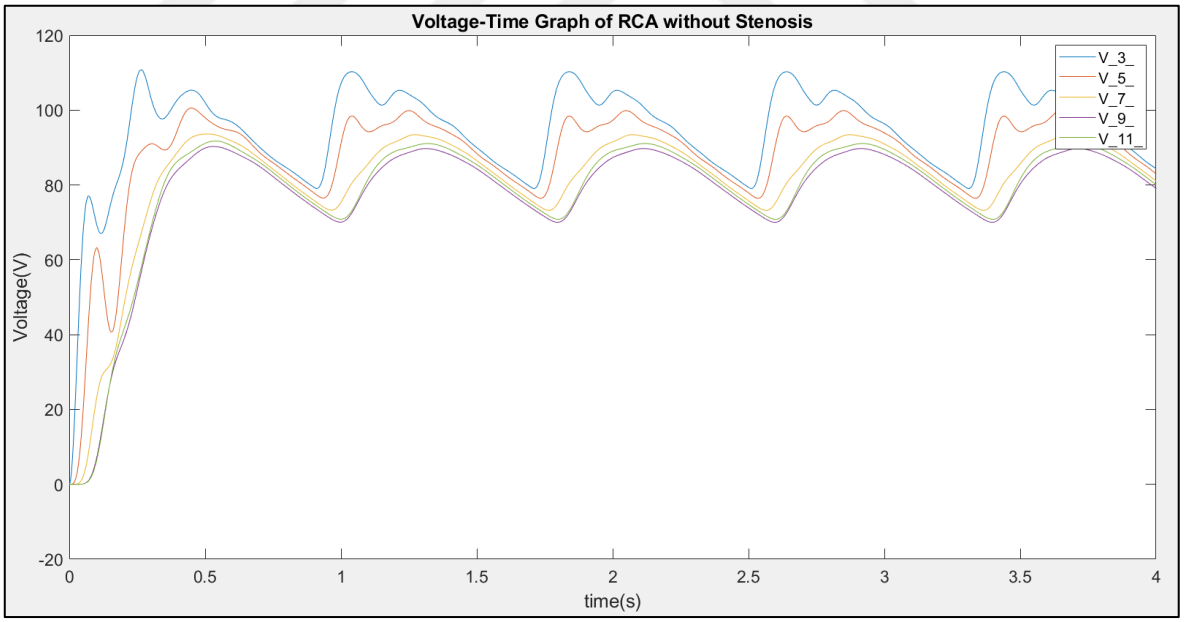

Figure 3.3. Voltage versus time graph of RCA without stenosis

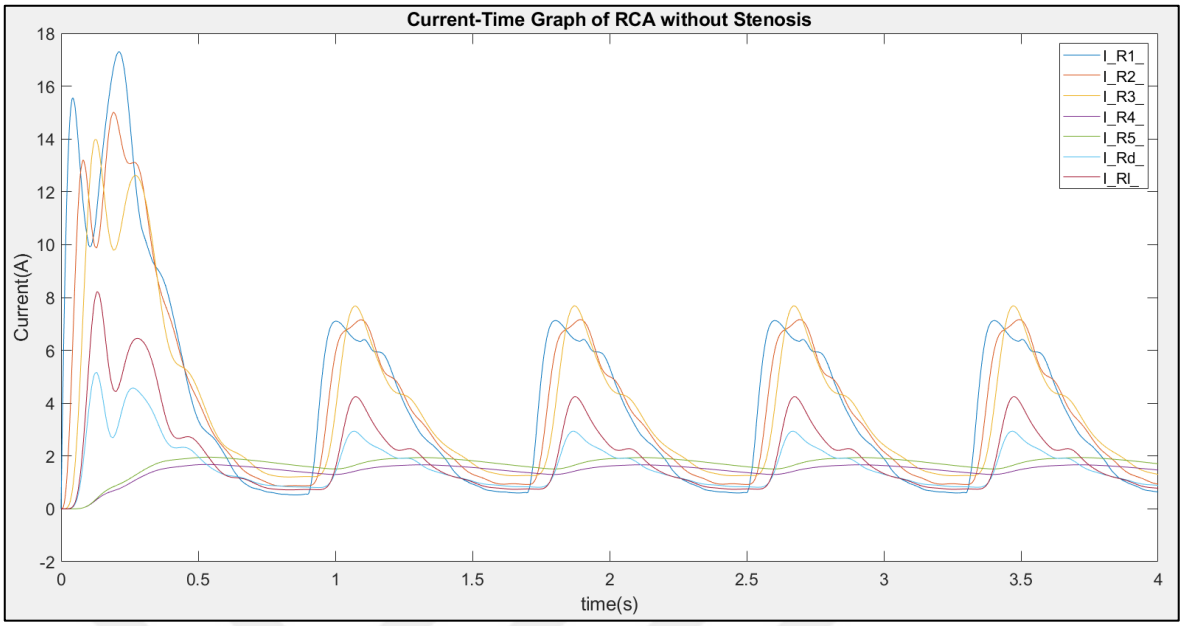

Figure 3.4. Current versus time graph of RCA without stenosis

3.2. THE LUMPED PARAMETERS WITH STENOSIS EFFECT

In this study, the stenosis percentages were used as 30, 60, and 90. According to these percentage of the area reduction, the Lumped parameters were calculated. These values were shown in Table 3.1, 3.2 and 3.3.

According to the values with stenosis effect in Table 3.1, 3.2 and 3.3, the graphs were plotted. These graphs were shown in Figure D.1 to D.8 as the example results.

Table 3.1. Lumped parameters of the patient-specific coronary tree model with 30 percent stenosis effect

BRANCH NAME	R ($mmHg.s.ml^{-1}$)	L ($mmHg.ml^{-1}$)	C ($ml.mmHg^{-1}.10^{-3}$)
LMCA	0.285714	0.025714	2.049817
LAD	1.020408	0.205714	0.685225
LAD1	0.489796	0.032857	1.347023
LAD1(R)	221.8367		
LAD2	1.77551	0.095714	2.635479
LAD3	0.877551	0.044286	0.105419
LAD3(R)	591.4286		
LAD4	1.285714	0.058571	1.112758
LAD4(R)	514.0816		
DIAG	6.510204	0.171429	0.761361
DIAG(R)	144.0816		
LCX	0.346939	0.228571	0.995625
LCX1	0.285714	0.018571	0.761361
LCX2	0.387755	0.024286	0.087849
LCX3	0.77551	0.047143	1.581287
LCX3(R)	513.6735		
MARG1	1.44898	0.07	1.581287
MARG1(R)	137.551		
MARG2	2.387755	0.091429	1.22989
MARG2(R)	238.1633		
MARG3	3.959184	0.115714	0.937059
MARG3(R)	461.8367		
RCA1	3.346939	0.171429	3.748237
RCA2			
RCA3			
PDA	4.714286	0.112857	6.442282
PDA(R)	109.7959		
PLA	2.673469	0.091429	9.956254
PLA(R)	95.71429		

Table 3.2. Lumped parameters of the patient-specific coronary tree model with 60 percent stenosis effect

BRANCH NAME	R ($mmHg.s.ml^{-1}$)	L ($mmHg.ml^{-1}$)	C ($ml.mmHg^{-1}.10^{-3}$)
LMCA	0.875	0.045	0.885438
LAD	3.125	0.36	0.295989
LAD1	1.5	0.0575	0.581859
LAD1(R)	679.375		
LAD2	5.4375	0.1675	1.13842
LAD3	2.6875	0.0775	0.045537
LAD3(R)	1811.25		
LAD4	3.9375	0.1025	0.480666
LAD4(R)	1574.375		
DIAG	19.9375	0.3	0.328877
DIAG(R)	441.25		
LCX	1.0625	0.4	0.43007
LCX1	0.875	0.0325	0.328877
LCX2	1.1875	0.0425	0.037947
LCX3	2.375	0.0825	0.683052
LCX3(R)	1573.125		
MARG1	4.4375	0.1225	0.683052
MARG1(R)	421.25		
MARG2	7.3125	0.16	0.531263
MARG2(R)	729.375		
MARG3	12.125	0.2025	0.404772
MARG3(R)	1414.375		
RCA1	14.4375	0.1975	2.782804
RCA2			
RCA3			
PDA	14.4375	0.1975	2.782804
PDA(R)	336.25		
PLA	8.1875	0.16	4.300698
PLA(R)	293.125		

Table 3.3. Lumped parameters of the patient-specific coronary tree model with 90 percent stenosis effect

BRANCH NAME	R ($mmHg.s.ml^{-1}$)	L ($mmHg.ml^{-1}$)	C ($ml.mmHg^{-1}.10^{-3}$)
LMCA	14	0.18	0.11068
LAD	50	1.44	0.036999
LAD1	24	0.23	0.072732
LAD1(R)	10870		
LAD2	87	0.67	0.142302
LAD3	43	0.31	0.005692
LAD3(R)	28980		
LAD4	63	0.41	0.060083
LAD4(R)	25190		
DIAG	319	1.2	0.04111
DIAG(R)	7060		
LCX	17	1.6	0.053759
LCX1	14	0.13	0.04111
LCX2	19	0.17	0.004743
LCX3	38	0.33	0.085381
LCX3(R)	25170		
MARG1	71	0.49	0.085381
MARG1(R)	6740		
MARG2	117	0.64	0.066408
MARG2(R)	11670		
MARG3	194	0.81	0.050596
MARG3(R)	22630		
RCA1	164	1.2	0.347851
RCA2			
RCA3			
PDA	231	0.79	0.347851
PDA(R)	5380		
PLA	131	0.64	0.537587
PLA(R)	4690		

4. DISCUSSION

Cardiovascular diseases are the leading causes of death in the world. According to WHO statistics, the main cause of death globally is CVD [3]. Acute coronary syndromes are the categories of the cardiovascular disease group. Because of that the modeling is a non-invasive technique to to prevent the increase in the mortality rate with early diagnosis, the modeling of coronary arteries is widely used in recent researches [1,26,33]. In this study, a coronary tree model was developed for ACS which is the leading heart disease. In developed model, the stenosis effect were applied on the coronary artery branch for identification of the culprit coronary artery.

According to the stenosis percentage, appearent changes were observed in the blood flow and the blood pressure. As the percentage of the stenosis effect had been increased, the current decreased although the voltage increased. This situation means that when the occlusion area increase in the coronary artery branch, the blood flow rate decrease and the blood pressure increases in the stenotic vessel.

When the voltage versus time and the current versus time graphs of the coronary artery model are examined, it can be evaluated how far the branches with stenosis effect are from the main arteries. Therefore, the distance of the culprit coronary artery branch from the aorta can be identified. In addition, as the distance of the coronary artery branch with stenosis from the aorta increses, to evaluate the obtained graphs of this branch becomes difficult. When the stenosis effect was applied on the coronary branch farther from the aorta, there is not much difference in the blood pressure and the blood flow for different stenosis percentages.

When the results of each side of the coronary artery model are examined separately, the change in blood pressure and blood flow caused by the stenosis effect arteries could be observed more clearer on RCA compared to LMCA. Because of that there is more branch on tha left side of coronary artery tree than the right side, identification of the culprit artery branch is more complex in LMCA.

In this study, the coronary artery tree model was developed as a patient-specific model. Because of that the specific parameter values obtained from CT of the patient was used, this model cannot be used for another patient. This model can only be used for another patient

with necessary corrections. According to this study, a new model should be developed for each patient.

In this study, the stenosis effect was applied on just one branch of the coronary artery tree. When it was applied on more than one vessel, excessive data were obtained and the data comparison could not be performed. Because of that reason, this application was not needed.

Limitation of this model in the actual pumping heart there is very strong mechanical action (movement) of the organ. This will cause changes in the predicted pressure variations and it can be expected that differential equations describing such a movement be nonlinear in nature. Such pressure and flow waveforms have phase differences. Note, however that such models main still have discrepancies in simulative actual waveforms and can only be specific to a patient and cannot be generalized.

5. CONCLUSION

In this study, firstly, the coronary artery were divided into two parts as RCA and LMCA and they were illustrated. Following that, the electrical circuit of the coronary artery tree was designed by using Lumped parameters method, and then, the electrical circuit model of the coronary artery was developed. The study of Zheng *et al.* [33] was searched for the Lumped parameter values. Because of that these parameters had been obtained from CT scans of a patient, they were patient-specific values. Thereby, the patient-specific coronary artery model was designed as an electrical circuit. This electrical circuit was set up by node voltage method. Each node indicated a diffent branch of the coronary arteries.

The stenosis effect was applied on all Lumped parameter for modeling of culprit arteries. The stenosis percentages were selected as 30, 60 and 90. It was assumed that there was an occlusion in only one branch of the coronary arteries and therefore, the stenosis effect was used in one compartment of the coronary tree model at each time.

While the electrical circuit was simulated, an input voltage was applied on the patient-specific model. The aortic pressure wave was used as an input voltage. The aortic pressure versus time graph was manually digitized by using a graph paper to obtain the input voltage values. The simulation time was selected as 5 cardiac cycle to get the regular traces. 5 cardiac cycle is equal to 4 seconds. After all these process steps, the obtained graphs and data were analyzed and compared in terms of voltage and current values.

As a consequence, the change of blood flow and blood pressure in the branches of the coronary arteries were observed using the Lumped parameter modeling, which is a non-invasive diagnostic technique, according to the location and the percentage of the blockage in the vessel.

6. FUTURE STUDY

Instead of the aortic pressure value used in this study, the input voltage can be measured separately from individuals for each patient. In this way, more accurate results can be obtained when the stenosis effect is applied on the coronary artery branches.

To compare the data of healthy patients and patients with ACS, CT scans of more than one patient may be included. Therefore, general information can be obtained rather than patient-specific.

In future studies, coronary artery modeling can be improved by considering the structure of the vessel. Besides, the mechanics of blood pumping from the heart should be also evaluated in these studies.

Finally, analysis and simulation of multiple lesions can be performed in a future study. In many cases, there exists more than one lesion area (blockage) of coronary arteries. Therefore, it is needed to have a simulation study showing the waveforms (pressure and flow) caused by such occlusions of related arteries.

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APPENDIX A: LUMPED PARAMETERS WITHOUT STENOSIS

Table A.1. Lumped parameters of the patient-specific coronary tree model without stenosis

BRANCH NAME	R ($mmHg.s.ml^{-1}$)	L ($mmHg.ml^{-1}$)	C ($ml.mmHg^{-1}.10^{-3}$)
LMCA	0.14	0.018	3.5
LAD	0.5	0.144	1.17
LAD1	0.24	0.023	2.3
LAD1(R)	108.7		
LAD2	0.87	0.067	4.5
LAD3	0.43	0.031	0.18
LAD3(R)	289.8		
LAD4	0.63	0.041	1.9
LAD4(R)	251.9		
DIAG	3.19	0.12	1.3
DIAG(R)	70.6		
LCX	0.17	0.16	1.7
LCX1	0.14	0.013	1.3
LCX2	0.19	0.017	0.15
LCX3	0.38	0.033	2.7
LCX3(R)	251.7		
MARG1	0.71	0.049	2.7
MARG1(R)	67.4		
MARG2	1.17	0.064	2.1
MARG2(R)	116.7		
MARG3	1.94	0.081	1.6
MARG3(R)	226.3		
RCA1	1.64	0.12	6.4
RCA2			
RCA3			
PDA	2.31	0.079	11
PDA(R)	53.8		
PLA	1.31	0.064	17
PLA(R)	46.9		

APPENDIX B: ALGORITHMS OF THE CORONARY TREE MODEL

Algorithm B.1. The algorithm of the coronary artery tree model for RCA

```
*fractional flow reserve computation TR analysis for right branch of the coronary artery tree
vi 1 0 pwl(0.0 85.3 0.01 85.0 0.02 84.5 0.03 83.7 0.04 83.5 0.05 82.8 0.06 82.4 0.07 81.8 0.08 81.5 0.09
81.0 0.10 80.0 0.11 87.5 0.12 91.0 0.13 100.0 0.14 104.0 0.15 108.5 0.16 111.4
+ 0.17 114.5 0.18 116.4 0.19 118.0 0.20 119.0 0.21 119.8 0.22 119.9 0.23 120.0 0.24 119.7 0.25 119.5 0.26
119.0 0.27 118.6 0.28 117.8 0.29 116.8 0.30 117.3 0.31 113.5 0.32 111.5
+ 0.33 110.0 0.34 110.9 0.35 111.0 0.36 111.2 0.37 111.3 0.38 111.0 0.39 110.6 0.40 110.4 0.41 110.0 0.42
109.8 0.43 109.4 0.44 108.8 0.45 107.9 0.46 107.5 0.47 107.0 0.48 106.0
+ 0.49 105.5 0.50 104.6 0.51 104.0 0.52 103.6 0.53 102.7 0.54 102.0 0.55 101.5 0.56 100.5 0.57 99.8 0.58
99.3 0.59 98.5 0.60 98.0 0.61 97.0 0.62 96.0 0.63 95.5 0.64 95.0
+ 0.65 94.0 0.66 93.5 0.67 93.0 0.68 92.2 0.69 91.5 0.70 91.1 0.71 90.4 0.72 89.7 0.73 89.0 0.74 88.2 0.75
87.8 0.76 87.4 0.77 86.8 0.78 86.2 0.79 85.8 0.80 85.3
+ 0.81 85.0 0.82 84.5 0.83 83.7 0.84 83.5 0.85 82.8 0.86 82.4 0.87 81.8 0.88 81.5 0.89 81.0 0.90 80.0 0.91
87.5 0.92 91.0 0.93 100.0 0.94 104.0 0.95 108.5 0.96 111.4
+ 0.97 114.5 0.98 116.4 0.99 118.0 1.00 119.0 1.01 119.8 1.02 119.9 1.03 120.0 1.04 119.7 1.05 119.5 1.06
119.0 1.07 118.6 1.08 117.8 1.09 116.8 1.10 117.3 1.11 113.5 1.12 111.5
+ 1.13 110.0 1.14 110.9 1.15 111.0 1.16 111.2 1.17 111.3 1.18 111.0 1.19 110.6 1.20 110.4 1.21 110.0 1.22
109.8 1.23 109.4 1.24 108.8 1.25 107.9 1.26 107.5 1.27 107.0 1.28 106.0
+ 1.29 105.5 1.30 104.6 1.31 104.0 1.32 103.6 1.33 102.7 1.34 102.0 1.35 101.5 1.36 100.5 1.37 99.8 1.38
99.3 1.39 98.5 1.40 98.0 1.41 97.0 1.42 96.0 1.43 95.5 1.44 95.0
+ 1.45 94.0 1.46 93.5 1.47 93.0 1.48 92.2 1.49 91.5 1.50 91.1 1.51 90.4 1.52 89.7 1.53 89.0 1.54 88.2 1.55
87.8 1.56 87.4 1.57 86.8 1.58 86.2 1.59 85.8 1.60 85.3
+ 1.61 85.0 1.62 84.5 1.63 83.7 1.64 83.5 1.65 82.8 1.66 82.4 1.67 81.8 1.68 81.5 1.69 81.0 1.70 80.0 1.71
87.5 1.72 91.0 1.73 100.0 1.74 104.0 1.75 108.5 1.76 111.4
+ 1.77 114.5 1.78 116.4 1.79 118.0 1.80 119.0 1.81 119.8 1.82 119.9 1.83 120.0 1.84 119.7 1.85 119.5 1.86
119.0 1.87 118.6 1.88 117.8 1.89 116.8 1.90 117.3 1.91 113.5 1.92 111.5
+ 1.93 110.0 1.94 110.9 1.95 111.0 1.96 111.2 1.97 111.3 1.98 111.0 1.99 110.6 2.00 110.4 2.01 110.0 2.02
109.8 2.03 109.4 2.04 108.8 2.05 107.9 2.06 107.5 2.07 107.0 2.08 106.0
+ 2.09 105.5 2.10 104.6 2.11 104.0 2.12 103.6 2.13 102.7 2.14 102.0 2.15 101.5 2.16 100.5 2.17 99.8 2.18
99.3 2.19 98.5 2.20 98.0 2.21 97.0 2.22 96.0 2.23 95.5 2.24 95.0
+ 2.25 94.0 2.26 93.5 2.27 93.0 2.28 92.2 2.29 91.5 2.30 91.1 2.31 90.4 2.32 89.7 2.33 89.0 2.34 88.2 2.35
87.8 2.36 87.4 2.37 86.8 2.38 86.2 2.39 85.8 2.40 85.3
+ 2.41 85.0 2.42 84.5 2.43 83.7 2.44 83.5 2.45 82.8 2.46 82.4 2.47 81.8 2.48 81.5 2.49 81.0 2.50 80.0 2.51
87.5 2.52 91.0 2.53 100.0 2.54 104.0 2.55 108.5 2.56 111.4
+ 2.57 114.5 2.58 116.4 2.59 118.0 2.60 119.0 2.61 119.8 2.62 119.9 2.63 120.0 2.64 119.7 2.65 119.5 2.66
119.0 2.67 118.6 2.68 117.8 2.69 116.8 2.70 117.3 2.71 113.5 2.72 111.5
+ 2.73 110.0 2.74 110.9 2.75 111.0 2.76 111.2 2.77 111.3 2.78 111.0 2.79 110.6 2.80 110.4 2.81 110.0 2.82
109.8 2.83 109.4 2.84 108.8 2.85 107.9 2.86 107.5 2.87 107.0 2.88 106.0
+ 2.89 105.5 2.90 104.6 2.91 104.0 2.92 103.6 2.93 102.7 2.94 102.0 2.95 101.5 2.96 100.5 2.97 99.8 2.98
99.3 2.99 98.5 3.00 98.0 3.01 97.0 3.02 96.0 3.03 95.5 3.04 95.0
+ 3.05 94.0 3.06 93.5 3.07 93.0 3.08 92.2 3.09 91.5 3.10 91.1 3.11 90.4 3.12 89.7 3.13 89.0 3.14 88.2 3.15
87.8 3.16 87.4 3.17 86.8 3.18 86.2 3.19 85.8 3.20 85.3
+ 3.21 85.0 3.22 84.5 3.23 83.7 3.24 83.5 3.25 82.8 3.26 82.4 3.27 81.8 3.28 81.5 3.29 81.0 3.30 80.0 3.31
87.5 3.32 91.0 3.33 100.0 3.34 104.0 3.35 108.5 3.36 111.4
+ 3.37 114.5 3.38 116.4 3.39 118.0 3.40 119.0 3.41 119.8 3.42 119.9 3.43 120.0 3.44 119.7 3.45 119.5 3.46
119.0 3.47 118.6 3.48 117.8 3.49 116.8 3.50 117.3 3.51 113.5 3.52 111.5
+ 3.53 110.0 3.54 110.9 3.55 111.0 3.56 111.2 3.57 111.3 3.58 111.0 3.59 110.6 3.60 110.4 3.61 110.0 3.62
109.8 3.63 109.4 3.64 108.8 3.65 107.9 3.66 107.5 3.67 107.0 3.68 106.0
+ 3.69 105.5 3.70 104.6 3.71 104.0 3.72 103.6 3.73 102.7 3.74 102.0 3.75 101.5 3.76 100.5 3.77 99.8 3.78
99.3 3.79 98.5 3.80 98.0 3.81 97.0 3.82 96.0 3.83 95.5 3.84 95.0
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+ 3.85 94.0 3.86 93.5 3.87 93.0 3.88 92.2 3.89 91.5 3.90 91.1 3.91 90.4 3.92 89.7 3.93 89.0 3.94 88.2 3.95 87.8 3.96 87.4 3.97 86.8 3.98 86.2 3.99 85.8 4.00 85.3
+ 4.01 85.0 4.02 84.5 4.03 83.7 4.04 83.5 4.05 82.8 4.06 82.4 4.07 81.8 4.08 81.5 4.09 81.0 4.10 80.0 4.11 87.5 4.12 91.0 4.13 100.0 4.14 104.0 4.15 108.5 4.16 111.4
+ 4.17 114.5 4.18 116.4 4.19 118.0 4.20 119.0 4.21 119.8 4.22 119.9 4.23 120.0 4.24 119.7 4.25 119.5 4.26 119.0 4.27 118.6 4.28 117.8 4.29 116.8 4.30 117.3 4.31 113.5 4.32 111.5
+ 4.33 110.0 4.34 110.9 4.35 111.0 4.36 111.2 4.37 111.3 4.38 111.0 4.39 110.6 4.40 110.4 4.41 110.0 4.42 109.8 4.43 109.4 4.44 108.8 4.45 107.9 4.46 107.5 4.47 107.0 4.48 106.0
+ 4.49 105.5 4.50 104.6 4.51 104.0 4.52 103.6 4.53 102.7 4.54 102.0 4.55 101.5 4.56 100.5 4.57 99.8 4.58 99.3 4.59 98.5 4.60 98.0 4.61 97.0 4.62 96.0 4.63 95.5 4.64 95.0
+ 4.65 94.0 4.66 93.5 4.67 93.0 4.68 92.2 4.69 91.5 4.70 91.1 4.71 90.4 4.72 89.7 4.73 89.0 4.74 88.2 4.75 87.8 4.76 87.4 4.77 86.8 4.78 86.2 4.79 85.8 4.80 85.3
+ 4.81 85.0 4.82 84.5 4.83 83.7 4.84 83.5 4.85 82.8 4.86 82.4 4.87 81.8 4.88 81.5 4.89 81.0 4.90 80.0 4.91 87.5 4.92 91.0 4.93 100.0 4.94 104.0 4.95 108.5 4.96 111.4
+ 4.97 114.5 4.98 116.4 4.99 118.0 5.00 119.0 5.01 119.8 5.02 119.9 5.03 120.0 5.04 119.7 5.05 119.5 5.06 119.0 5.07 118.6 5.08 117.8 5.09 116.8 5.10 117.3 5.11 113.5 5.12 111.5
+ 5.13 110.0 5.14 110.9 5.15 111.0 5.16 111.2 5.17 111.3 5.18 111.0 5.19 110.6 5.20 110.4 5.21 110.0 5.22 109.8 5.23 109.4 5.24 108.8 5.25 107.9 5.26 107.5 5.27 107.0 5.28 106.0
+ 5.29 105.5 5.30 104.6 5.31 104.0 5.32 103.6 5.33 102.7 5.34 102.0 5.35 101.5 5.36 100.5 5.37 99.8 5.38 99.3 5.39 98.5 5.40 98.0 5.41 97.0 5.42 96.0 5.43 95.5 5.44 95.0
+ 5.45 94.0 5.46 93.5 5.47 93.0 5.48 92.2 5.49 91.5 5.50 91.1 5.51 90.4 5.52 89.7 5.53 89.0 5.54 88.2 5.55 87.8 5.56 87.4 5.57 86.8 5.58 86.2 5.59 85.8 5.60 85.3
+ 5.61 85.0 5.62 84.5 5.63 83.7 5.64 83.5 5.65 82.8 5.66 82.4 5.67 81.8 5.68 81.5 5.69 81.0 5.70 80.0 5.71 87.5 5.72 91.0 5.73 100.0 5.74 104.0 5.75 108.5 5.76 111.4
+ 5.77 114.5 5.78 116.4 5.79 118.0 5.80 119.0 5.81 119.8 5.82 119.9 5.83 120.0 5.84 119.7 5.85 119.5 5.86 119.0 5.87 118.6 5.88 117.8 5.89 116.8 5.90 117.3 5.91 113.5 5.92 111.5
+ 5.93 110.0 5.94 110.9 5.95 111.0 5.96 111.2 5.97 111.3 5.98 111.0 5.99 110.6 6.00 110.4 6.01 110.0 6.02 109.8 6.03 109.4 6.04 108.8 6.05 107.9 6.06 107.5 6.07 107.0 6.08 106.0
+ 6.09 105.5 6.10 104.6 6.11 104.0 6.12 103.6 6.13 102.7 6.14 102.0 6.15 101.5 6.16 100.5 6.17 99.8 6.18 99.3 6.19 98.5 6.20 98.0 6.21 97.0 6.22 96.0 6.23 95.5 6.24 95.0
+ 6.25 94.0 6.26 93.5 6.27 93.0 6.28 92.2 6.29 91.5 6.30 91.1 6.31 90.4 6.32 89.7 6.33 89.0 6.34 88.2 6.35 87.8 6.36 87.4 6.37 86.8 6.38 86.2 6.39 85.8 6.40 85.3
+ 6.41 85.0 6.42 84.5 6.43 83.7 6.44 83.5 6.45 82.8 6.46 82.4 6.47 81.8 6.48 81.5 6.49 81.0 6.50 80.0 6.51 87.5 6.52 91.0 6.53 100.0 6.54 104.0 6.55 108.5 6.56 111.4
+ 6.57 114.5 6.58 116.4 6.59 118.0 6.60 119.0 6.61 119.8 6.62 119.9 6.63 120.0 6.64 119.7 6.65 119.5 6.66 119.0 6.67 118.6 6.68 117.8 6.69 116.8 6.70 117.3 6.71 113.5 6.72 111.5
+ 6.73 110.0 6.74 110.9 6.75 111.0 6.76 111.2 6.77 111.3 6.78 111.0 6.79 110.6 6.80 110.4 6.81 110.0 6.82 109.8 6.83 109.4 6.84 108.8 6.85 107.9 6.86 107.5 6.87 107.0 6.88 106.0
+ 6.89 105.5 6.90 104.6 6.91 104.0 6.92 103.6 6.93 102.7 6.94 102.0 6.95 101.5 6.96 100.5 6.97 99.8 6.98 99.3 6.99 98.5 7.00 98.0 7.01 97.0 7.02 96.0 7.03 95.5 7.04 95.0
+ 7.05 94.0 7.06 93.5 7.07 93.0 7.08 92.2 7.09 91.5 7.10 91.1 7.11 90.4 7.12 89.7 7.13 89.0 7.14 88.2 7.15 87.8 7.16 87.4 7.17 86.8 7.18 86.2 7.19 85.8 7.20 85.3
+ 7.21 85.0 7.22 84.5 7.23 83.7 7.24 83.5 7.25 82.8 7.26 82.4 7.27 81.8 7.28 81.5 7.29 81.0 7.30 80.0 7.31 87.5 7.32 91.0 7.33 100.0 7.34 104.0 7.35 108.5 7.36 111.4
+ 7.37 114.5 7.38 116.4 7.39 118.0 7.40 119.0 7.41 119.8 7.42 119.9 7.43 120.0 7.44 119.7 7.45 119.5 7.46 119.0 7.47 118.6 7.48 117.8 7.49 116.8 7.50 117.3 7.51 113.5 7.52 111.5
+ 7.53 110.0 7.54 110.9 7.55 111.0 7.56 111.2 7.57 111.3 7.58 111.0 7.59 110.6 7.60 110.4 7.61 110.0 7.62 109.8 7.63 109.4 7.64 108.8 7.65 107.9 7.66 107.5 7.67 107.0 7.68 106.0
+ 7.69 105.5 7.70 104.6 7.71 104.0 7.72 103.6 7.73 102.7 7.74 102.0 7.75 101.5 7.76 100.5 7.77 99.8 7.78 99.3 7.79 98.5 7.80 98.0 7.81 97.0 7.82 96.0 7.83 95.5 7.84 95.0
+ 7.85 94.0 7.86 93.5 7.87 93.0 7.88 92.2 7.89 91.5 7.90 91.1 7.91 90.4 7.92 89.7 7.93 89.0 7.94 88.2 7.95 87.8 7.96 87.4 7.97 86.8 7.98 86.2 7.99 85.8 8.00 85.3)

r1 1 2 1.64
L1 2 3 120m
c1 3 0 6.4m

r2 3 4 1.64
L2 4 5 120m

```
c2  5 0  6.4m

r3  5 6  1.64
L3  6 7  120m
c3  7 0  6.4m

rd  7 8  2.31
Ld  8 9  79m
cd  9 0  11m
r4  9 0  53.8

rl  7 10 1.31
Ll 10 11 64m
cl 11 0  17m
r5 11 0  46.9


.tran 4 [UIC]
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Algorithm B.2. The algorithm of the coronary artery tree model for LMCA

```
fractional flow reserve computation TR analysis for left branch of the coronary artery tree
vi 1 0 pwl(0.0 85.3 0.01 85.0 0.02 84.5 0.03 83.7 0.04 83.5 0.05 82.8 0.06 82.4 0.07 81.8 0.08 81.5 0.09
81.0 0.10 80.0 0.11 87.5 0.12 91.0 0.13 100.0 0.14 104.0 0.15 108.5 0.16 111.4
+ 0.17 114.5 0.18 116.4 0.19 118.0 0.20 119.0 0.21 119.8 0.22 119.9 0.23 120.0 0.24 119.7 0.25 119.5 0.26
119.0 0.27 118.6 0.28 117.8 0.29 116.8 0.30 117.3 0.31 113.5 0.32 111.5
+ 0.33 110.0 0.34 110.9 0.35 111.0 0.36 111.2 0.37 111.3 0.38 111.0 0.39 110.6 0.40 110.4 0.41 110.0 0.42
109.8 0.43 109.4 0.44 108.8 0.45 107.9 0.46 107.5 0.47 107.0 0.48 106.0
+ 0.49 105.5 0.50 104.6 0.51 104.0 0.52 103.6 0.53 102.7 0.54 102.0 0.55 101.5 0.56 100.5 0.57 99.8 0.58
99.3 0.59 98.5 0.60 98.0 0.61 97.0 0.62 96.0 0.63 95.5 0.64 95.0
+ 0.65 94.0 0.66 93.5 0.67 93.0 0.68 92.2 0.69 91.5 0.70 91.1 0.71 90.4 0.72 89.7 0.73 89.0 0.74 88.2 0.75
87.8 0.76 87.4 0.77 86.8 0.78 86.2 0.79 85.8 0.80 85.3
+ 0.81 85.0 0.82 84.5 0.83 83.7 0.84 83.5 0.85 82.8 0.86 82.4 0.87 81.8 0.88 81.5 0.89 81.0 0.90 80.0 0.91
87.5 0.92 91.0 0.93 100.0 0.94 104.0 0.95 108.5 0.96 111.4
+ 0.97 114.5 0.98 116.4 0.99 118.0 1.00 119.0 1.01 119.8 1.02 119.9 1.03 120.0 1.04 119.7 1.05 119.5 1.06
119.0 1.07 118.6 1.08 117.8 1.09 116.8 1.10 117.3 1.11 113.5 1.12 111.5
+ 1.13 110.0 1.14 110.9 1.15 111.0 1.16 111.2 1.17 111.3 1.18 111.0 1.19 110.6 1.20 110.4 1.21 110.0 1.22
109.8 1.23 109.4 1.24 108.8 1.25 107.9 1.26 107.5 1.27 107.0 1.28 106.0
+ 1.29 105.5 1.30 104.6 1.31 104.0 1.32 103.6 1.33 102.7 1.34 102.0 1.35 101.5 1.36 100.5 1.37 99.8 1.38
99.3 1.39 98.5 1.40 98.0 1.41 97.0 1.42 96.0 1.43 95.5 1.44 95.0
+ 1.45 94.0 1.46 93.5 1.47 93.0 1.48 92.2 1.49 91.5 1.50 91.1 1.51 90.4 1.52 89.7 1.53 89.0 1.54 88.2 1.55
87.8 1.56 87.4 1.57 86.8 1.58 86.2 1.59 85.8 1.60 85.3
+ 1.61 85.0 1.62 84.5 1.63 83.7 1.64 83.5 1.65 82.8 1.66 82.4 1.67 81.8 1.68 81.5 1.69 81.0 1.70 80.0 1.71
87.5 1.72 91.0 1.73 100.0 1.74 104.0 1.75 108.5 1.76 111.4
+ 1.77 114.5 1.78 116.4 1.79 118.0 1.80 119.0 1.81 119.8 1.82 119.9 1.83 120.0 1.84 119.7 1.85 119.5 1.86
119.0 1.87 118.6 1.88 117.8 1.89 116.8 1.90 117.3 1.91 113.5 1.92 111.5
+ 1.93 110.0 1.94 110.9 1.95 111.0 1.96 111.2 1.97 111.3 1.98 111.0 1.99 110.6 2.00 110.4 2.01 110.0 2.02
109.8 2.03 109.4 2.04 108.8 2.05 107.9 2.06 107.5 2.07 107.0 2.08 106.0
+ 2.09 105.5 2.10 104.6 2.11 104.0 2.12 103.6 2.13 102.7 2.14 102.0 2.15 101.5 2.16 100.5 2.17 99.8 2.18
99.3 2.19 98.5 2.20 98.0 2.21 97.0 2.22 96.0 2.23 95.5 2.24 95.0
+ 2.25 94.0 2.26 93.5 2.27 93.0 2.28 92.2 2.29 91.5 2.30 91.1 2.31 90.4 2.32 89.7 2.33 89.0 2.34 88.2 2.35
87.8 2.36 87.4 2.37 86.8 2.38 86.2 2.39 85.8 2.40 85.3
+ 2.41 85.0 2.42 84.5 2.43 83.7 2.44 83.5 2.45 82.8 2.46 82.4 2.47 81.8 2.48 81.5 2.49 81.0 2.50 80.0 2.51
87.5 2.52 91.0 2.53 100.0 2.54 104.0 2.55 108.5 2.56 111.4
+ 2.57 114.5 2.58 116.4 2.59 118.0 2.60 119.0 2.61 119.8 2.62 119.9 2.63 120.0 2.64 119.7 2.65 119.5 2.66
119.0 2.67 118.6 2.68 117.8 2.69 116.8 2.70 117.3 2.71 113.5 2.72 111.5
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+ 2.73 110.0 2.74 110.9 2.75 111.0 2.76 111.2 2.77 111.3 2.78 111.0 2.79 110.6 2.80 110.4 2.81 110.0 2.82 109.8 2.83 109.4 2.84 108.8 2.85 107.9 2.86 107.5 2.87 107.0 2.88 106.0
+ 2.89 105.5 2.90 104.6 2.91 104.0 2.92 103.6 2.93 102.7 2.94 102.0 2.95 101.5 2.96 100.5 2.97 99.8 2.98 99.3 2.99 98.5 3.00 98.0 3.01 97.0 3.02 96.0 3.03 95.5 3.04 95.0
+ 3.05 94.0 3.06 93.5 3.07 93.0 3.08 92.2 3.09 91.5 3.10 91.1 3.11 90.4 3.12 89.7 3.13 89.0 3.14 88.2 3.15 87.8 3.16 87.4 3.17 86.8 3.18 86.2 3.19 85.8 3.20 85.3
+ 3.21 85.0 3.22 84.5 3.23 83.7 3.24 83.5 3.25 82.8 3.26 82.4 3.27 81.8 3.28 81.5 3.29 81.0 3.30 80.0 3.31 87.5 3.32 91.0 3.33 100.0 3.34 104.0 3.35 108.5 3.36 111.4
+ 3.37 114.5 3.38 116.4 3.39 118.0 3.40 119.0 3.41 119.8 3.42 119.9 3.43 120.0 3.44 119.7 3.45 119.5 3.46 119.0 3.47 118.6 3.48 117.8 3.49 116.8 3.50 117.3 3.51 113.5 3.52 111.5
+ 3.53 110.0 3.54 110.9 3.55 111.0 3.56 111.2 3.57 111.3 3.58 111.0 3.59 110.6 3.60 110.4 3.61 110.0 3.62 109.8 3.63 109.4 3.64 108.8 3.65 107.9 3.66 107.5 3.67 107.0 3.68 106.0
+ 3.69 105.5 3.70 104.6 3.71 104.0 3.72 103.6 3.73 102.7 3.74 102.0 3.75 101.5 3.76 100.5 3.77 99.8 3.78 99.3 3.79 98.5 3.80 98.0 3.81 97.0 3.82 96.0 3.83 95.5 3.84 95.0
+ 3.85 94.0 3.86 93.5 3.87 93.0 3.88 92.2 3.89 91.5 3.90 91.1 3.91 90.4 3.92 89.7 3.93 89.0 3.94 88.2 3.95 87.8 3.96 87.4 3.97 86.8 3.98 86.2 3.99 85.8 4.00 85.3
+ 4.01 85.0 4.02 84.5 4.03 83.7 4.04 83.5 4.05 82.8 4.06 82.4 4.07 81.8 4.08 81.5 4.09 81.0 4.10 80.0 4.11 87.5 4.12 91.0 4.13 100.0 4.14 104.0 4.15 108.5 4.16 111.4
+ 4.17 114.5 4.18 116.4 4.19 118.0 4.20 119.0 4.21 119.8 4.22 119.9 4.23 120.0 4.24 119.7 4.25 119.5 4.26 119.0 4.27 118.6 4.28 117.8 4.29 116.8 4.30 117.3 4.31 113.5 4.32 111.5
+ 4.33 110.0 4.34 110.9 4.35 111.0 4.36 111.2 4.37 111.3 4.38 111.0 4.39 110.6 4.40 110.4 4.41 110.0 4.42 109.8 4.43 109.4 4.44 108.8 4.45 107.9 4.46 107.5 4.47 107.0 4.48 106.0
+ 4.49 105.5 4.50 104.6 4.51 104.0 4.52 103.6 4.53 102.7 4.54 102.0 4.55 101.5 4.56 100.5 4.57 99.8 4.58 99.3 4.59 98.5 4.60 98.0 4.61 97.0 4.62 96.0 4.63 95.5 4.64 95.0
+ 4.65 94.0 4.66 93.5 4.67 93.0 4.68 92.2 4.69 91.5 4.70 91.1 4.71 90.4 4.72 89.7 4.73 89.0 4.74 88.2 4.75 87.8 4.76 87.4 4.77 86.8 4.78 86.2 4.79 85.8 4.80 85.3
+ 4.81 85.0 4.82 84.5 4.83 83.7 4.84 83.5 4.85 82.8 4.86 82.4 4.87 81.8 4.88 81.5 4.89 81.0 4.90 80.0 4.91 87.5 4.92 91.0 4.93 100.0 4.94 104.0 4.95 108.5 4.96 111.4
+ 4.97 114.5 4.98 116.4 4.99 118.0 5.00 119.0 5.01 119.8 5.02 119.9 5.03 120.0 5.04 119.7 5.05 119.5 5.06 119.0 5.07 118.6 5.08 117.8 5.09 116.8 5.10 117.3 5.11 113.5 5.12 111.5
+ 5.13 110.0 5.14 110.9 5.15 111.0 5.16 111.2 5.17 111.3 5.18 111.0 5.19 110.6 5.20 110.4 5.21 110.0 5.22 109.8 5.23 109.4 5.24 108.8 5.25 107.9 5.26 107.5 5.27 107.0 5.28 106.0
+ 5.29 105.5 5.30 104.6 5.31 104.0 5.32 103.6 5.33 102.7 5.34 102.0 5.35 101.5 5.36 100.5 5.37 99.8 5.38 99.3 5.39 98.5 5.40 98.0 5.41 97.0 5.42 96.0 5.43 95.5 5.44 95.0
+ 5.45 94.0 5.46 93.5 5.47 93.0 5.48 92.2 5.49 91.5 5.50 91.1 5.51 90.4 5.52 89.7 5.53 89.0 5.54 88.2 5.55 87.8 5.56 87.4 5.57 86.8 5.58 86.2 5.59 85.8 5.60 85.3
+ 5.61 85.0 5.62 84.5 5.63 83.7 5.64 83.5 5.65 82.8 5.66 82.4 5.67 81.8 5.68 81.5 5.69 81.0 5.70 80.0 5.71 87.5 5.72 91.0 5.73 100.0 5.74 104.0 5.75 108.5 5.76 111.4
+ 5.77 114.5 5.78 116.4 5.79 118.0 5.80 119.0 5.81 119.8 5.82 119.9 5.83 120.0 5.84 119.7 5.85 119.5 5.86 119.0 5.87 118.6 5.88 117.8 5.89 116.8 5.90 117.3 5.91 113.5 5.92 111.5
+ 5.93 110.0 5.94 110.9 5.95 111.0 5.96 111.2 5.97 111.3 5.98 111.0 5.99 110.6 6.00 110.4 6.01 110.0 6.02 109.8 6.03 109.4 6.04 108.8 6.05 107.9 6.06 107.5 6.07 107.0 6.08 106.0
+ 6.09 105.5 6.10 104.6 6.11 104.0 6.12 103.6 6.13 102.7 6.14 102.0 6.15 101.5 6.16 100.5 6.17 99.8 6.18 99.3 6.19 98.5 6.20 98.0 6.21 97.0 6.22 96.0 6.23 95.5 6.24 95.0
+ 6.25 94.0 6.26 93.5 6.27 93.0 6.28 92.2 6.29 91.5 6.30 91.1 6.31 90.4 6.32 89.7 6.33 89.0 6.34 88.2 6.35 87.8 6.36 87.4 6.37 86.8 6.38 86.2 6.39 85.8 6.40 85.3
+ 6.41 85.0 6.42 84.5 6.43 83.7 6.44 83.5 6.45 82.8 6.46 82.4 6.47 81.8 6.48 81.5 6.49 81.0 6.50 80.0 6.51 87.5 6.52 91.0 6.53 100.0 6.54 104.0 6.55 108.5 6.56 111.4
+ 6.57 114.5 6.58 116.4 6.59 118.0 6.60 119.0 6.61 119.8 6.62 119.9 6.63 120.0 6.64 119.7 6.65 119.5 6.66 119.0 6.67 118.6 6.68 117.8 6.69 116.8 6.70 117.3 6.71 113.5 6.72 111.5
+ 6.73 110.0 6.74 110.9 6.75 111.0 6.76 111.2 6.77 111.3 6.78 111.0 6.79 110.6 6.80 110.4 6.81 110.0 6.82 109.8 6.83 109.4 6.84 108.8 6.85 107.9 6.86 107.5 6.87 107.0 6.88 106.0
+ 6.89 105.5 6.90 104.6 6.91 104.0 6.92 103.6 6.93 102.7 6.94 102.0 6.95 101.5 6.96 100.5 6.97 99.8 6.98 99.3 6.99 98.5 7.00 98.0 7.01 97.0 7.02 96.0 7.03 95.5 7.04 95.0
+ 7.05 94.0 7.06 93.5 7.07 93.0 7.08 92.2 7.09 91.5 7.10 91.1 7.11 90.4 7.12 89.7 7.13 89.0 7.14 88.2 7.15 87.8 7.16 87.4 7.17 86.8 7.18 86.2 7.19 85.8 7.20 85.3
+ 7.21 85.0 7.22 84.5 7.23 83.7 7.24 83.5 7.25 82.8 7.26 82.4 7.27 81.8 7.28 81.5 7.29 81.0 7.30 80.0 7.31 87.5 7.32 91.0 7.33 100.0 7.34 104.0 7.35 108.5 7.36 111.4

+ 7.37 114.5 7.38 116.4 7.39 118.0 7.40 119.0 7.41 119.8 7.42 119.9 7.43 120.0 7.44 119.7 7.45 119.5 7.46 119.0 7.47 118.6 7.48 117.8 7.49 116.8 7.50 117.3 7.51 113.5 7.52 111.5
+ 7.53 110.0 7.54 110.9 7.55 111.0 7.56 111.2 7.57 111.3 7.58 111.0 7.59 110.6 7.60 110.4 7.61 110.0 7.62 109.8 7.63 109.4 7.64 108.8 7.65 107.9 7.66 107.5 7.67 107.0 7.68 106.0
+ 7.69 105.5 7.70 104.6 7.71 104.0 7.72 103.6 7.73 102.7 7.74 102.0 7.75 101.5 7.76 100.5 7.77 99.8 7.78 99.3 7.79 98.5 7.80 98.0 7.81 97.0 7.82 96.0 7.83 95.5 7.84 95.0
+ 7.85 94.0 7.86 93.5 7.87 93.0 7.88 92.2 7.89 91.5 7.90 91.1 7.91 90.4 7.92 89.7 7.93 89.0 7.94 88.2 7.95 87.8 7.96 87.4 7.97 86.8 7.98 86.2 7.99 85.8 8.00 85.3)

rm 1 2 140m
Lm 2 3 18m
cm 3 0 3.5m

rd 3 4 3.19
Ld 4 5 120m
cd 5 0 1.3m
r10 5 0 70.6

rad 3 6 0.5
Lad 6 7 144m
Cad 7 0 1.7m

rad1 7 8 0.24
Lad1 8 9 23m
Cad1 9 0 2.3m
r3 9 0 108.7

rad2 7 10 0.87
Lad2 10 11 67m
Cad2 11 0 4.5m

rad3 11 12 0.43
Lad3 12 13 31m
Cad3 13 0 0.18m
r4 13 0 289.8

rad4 11 14 0.63
Lad4 14 15 41m
Cad4 15 0 1.9m
r5 15 0 251.9

rx 3 16 0.17
Lx 16 17 160m
cx 17 0 1.7m

rg1 17 18 0.71
Lg1 18 19 49m
Cg1 19 0 2.7m
r6 19 0 67.4

rx1 17 20 0.14
Lx1 20 21 13m
Cx1 21 0 1.3m

rg2 21 22 1.17
Lg2 22 23 64m
Cg2 23 0 2.1m
r7 23 0 116.7

```
rx2 21 24  0.19
Lx2 24 25  17m
Cx2 25  0  0.15m

rg3 25 26  1.94
Lg3 26 27  81m
Cg3 27  0  1.6m
r8  27  0  226.3

rx3 25 28  0.38
Lx3 28 29  33m
Cx3 29  0  2.7m
r9  29  0  251.7

.tran 4 [UIC]
```

APPENDIX C: ALGORITHMS TO PLOT GRAPHS OF THE CORONARY ARTERIES BRANCHES

Algorithm C.1. Graphs of Lumped parameters without stenosis for LMCA

```
clc
clear all

[file,path] = uigetfile('*.txt', ...
'Select the Lumped parameters data file without stenosis for LMCA');
t = readtable([path,file]);
R = table2array(t);
c = t.Properties.VariableNames;
x = cell(1,14);
y = cell(1,22);

figure
for i = 3:16
    plot(R(:,1),R(:,i));
    x(1,i-2) = c(i);
    hold on
end
title('Voltage-Time Graph of LMCA without Stenosis');
ylabel('Voltage(V)'), xlabel('time(s)');
legend(x(:));

figure
for i = 17:38
    plot(R(:,1),R(:,i));
    y(1,i-16) = c(i);
    hold on
end
title('Current-Time Graph of LMCA without Stenosis');
ylabel('Current(A)'), xlabel('time(s)');
legend(y(:));
```

Algorithm C.2. Graphs of Lumped parameters without stenosis for RCA

```
clc
clear all

[file,path] = uigetfile('*.txt', ...
'Select the Lumped parameters data file without stenosis for RCA');
t = readtable([path,file]);
R = table2array(t);
c = t.Properties.VariableNames;
x = cell(1,5);
y = cell(1,7);

figure
for i = 3:7
    plot(R(:,1),R(:,i));
    x(i-2) = c(i);
    hold on
end
title('Voltage-Time Graph of RCA without Stenosis');
ylabel('Voltage(V)'), xlabel('time(s)');
legend(x(:));

figure
for i = 8:14
    plot(R(:,1),R(:,i));
    y(i-7) = c(i);
    hold on
end
title('Current-Time Graph of RCA without Stenosis');
ylabel('Current(A)'), xlabel('time(s)');
legend(y(:));
```

Algorithm C.3. Graphs of Lumped parameters with stenosis for coronary artery tree

```
clc
clear all

[file,path] = uigetfile('*.txt', ...
    'Select the data files with stenosis (0%, 30%, 60%, and 90%)',...
    'MultiSelect','on');

t0 = readtable([path,cell2mat(file(1))]);
t30 = readtable([path,cell2mat(file(2))]);
t60 = readtable([path,cell2mat(file(3))]);
t90 = readtable([path,cell2mat(file(4))]);

R0 = table2array(t0);
R30 = table2array(t30);
R60 = table2array(t60);
R90 = table2array(t90);

figure
plot(R0(:,1),R0(:,2),'b',R30(:,1),R30(:,2),'r',...
    R60(:,1),R60(:,2),'g',R90(:,1),R90(:,2),'m');
ylabel('Voltage(V)'), xlabel('time(s)'), legend('0%','30%','60%','90%')

figure
plot(R0(:,1),R0(:,3),'b',R30(:,1),R30(:,3),'r',...
    R60(:,1),R60(:,3),'g',R90(:,1),R90(:,3),'m');
ylabel('Current(A)'), xlabel('time(s)'), legend('0%','30%','60%','90%')
```

APPENDIX D: RESULTS OF STENOSIS EFFECT

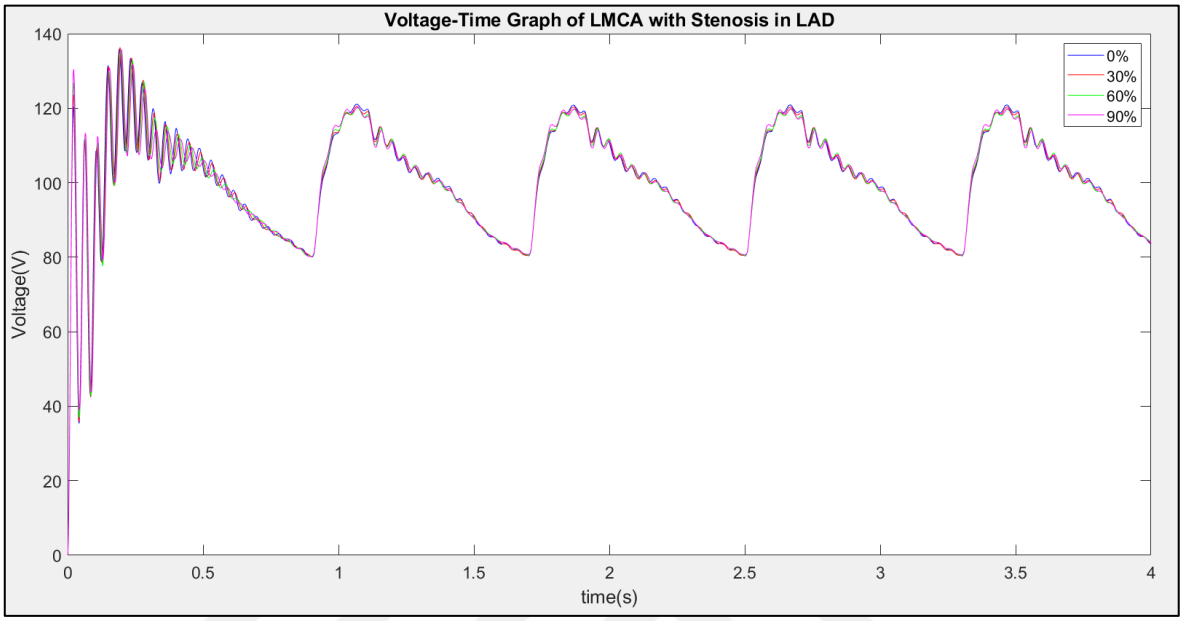

Figure D.1. Voltage versus time graph of LMCA with stenosis in LAD

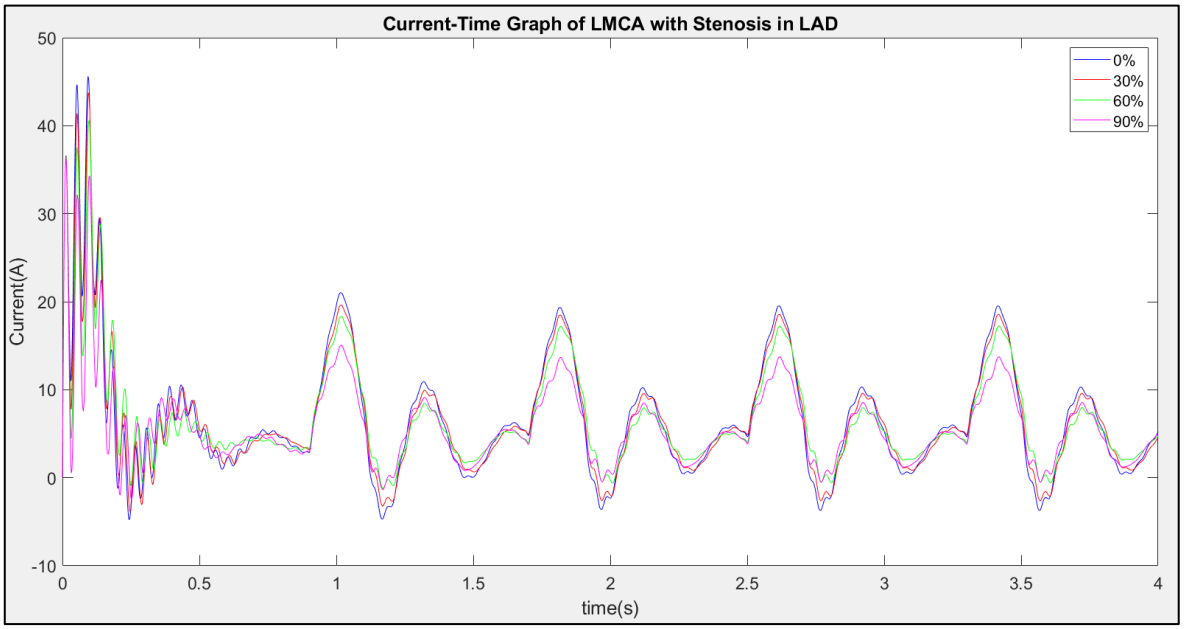

Figure D.2. Current versus time graph of LMCA with stenosis in LAD

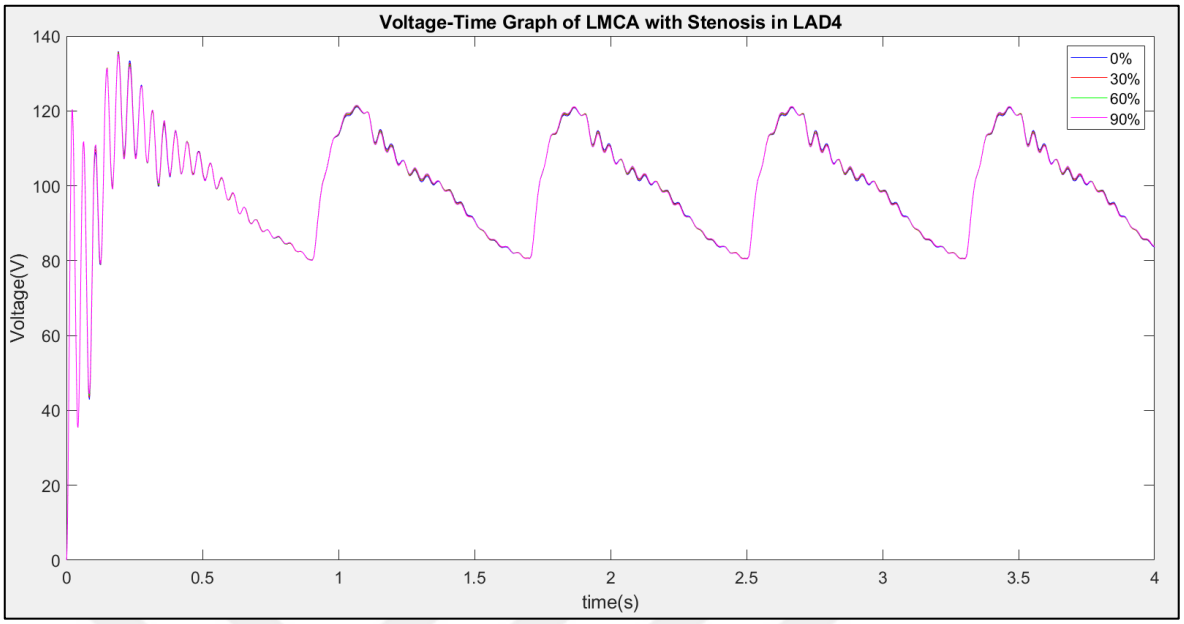

Figure D.3. Voltage versus time graph of LMCA with stenosis in LAD4

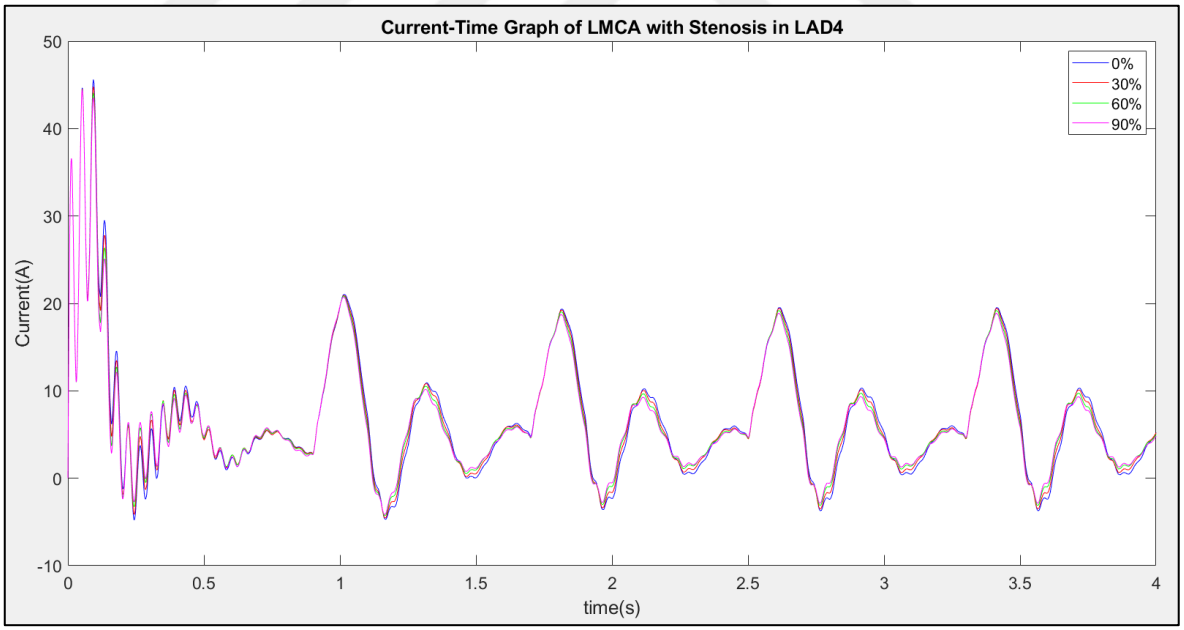

Figure D.4. Current versus time graph of LMCA with stenosis in LAD4

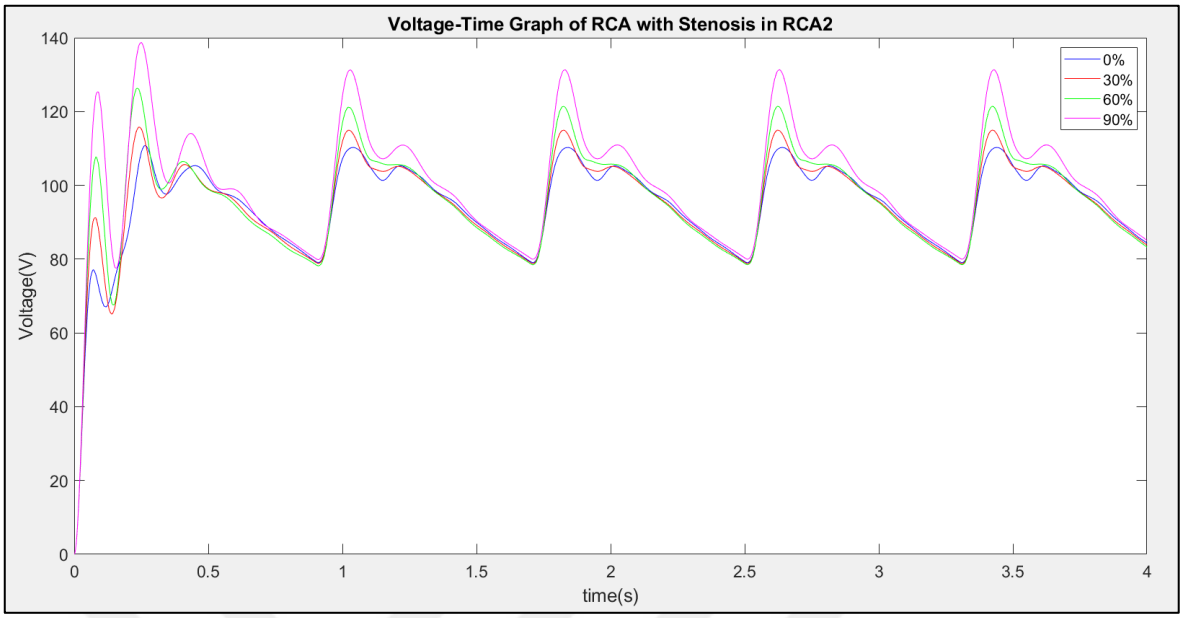

Figure D.5. Voltage versus time graph of RCA with stenosis in RCA2

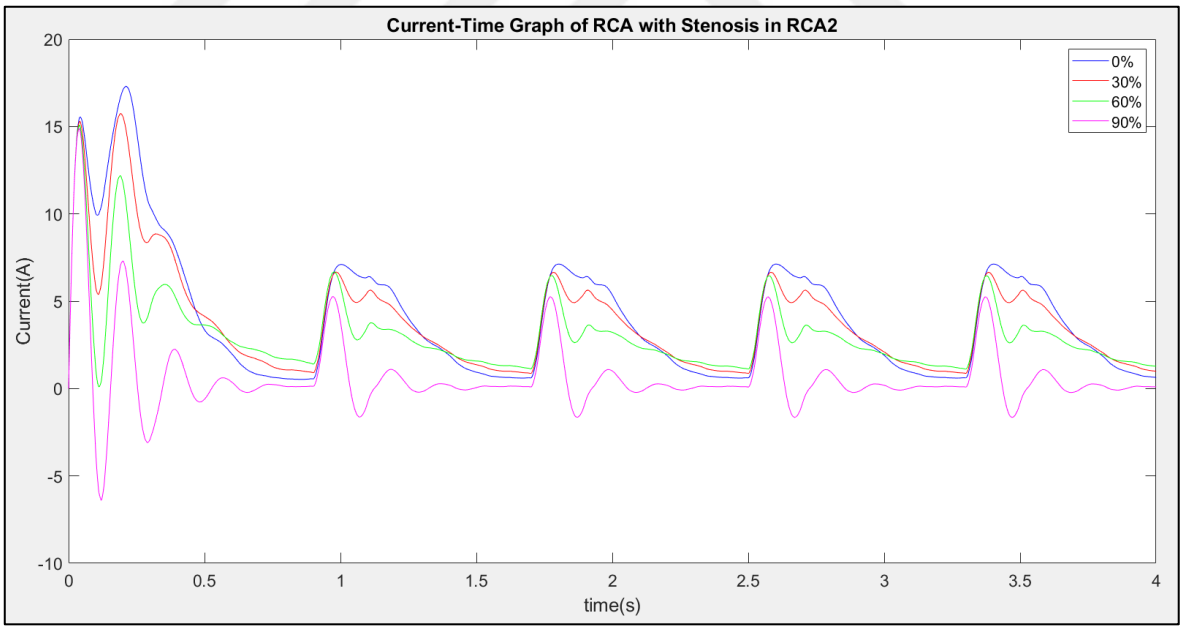

Figure D.6. Current versus time graph of RCA with stenosis in RCA2

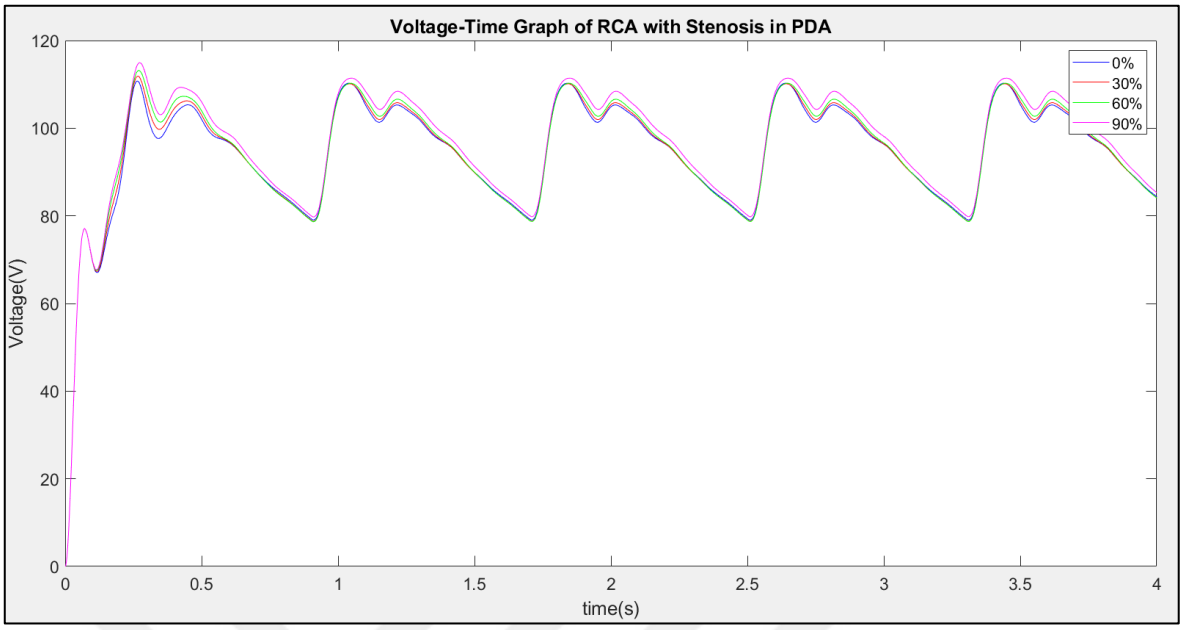

Figure D.7. Voltage versus time graph of RCA with stenosis in PDA

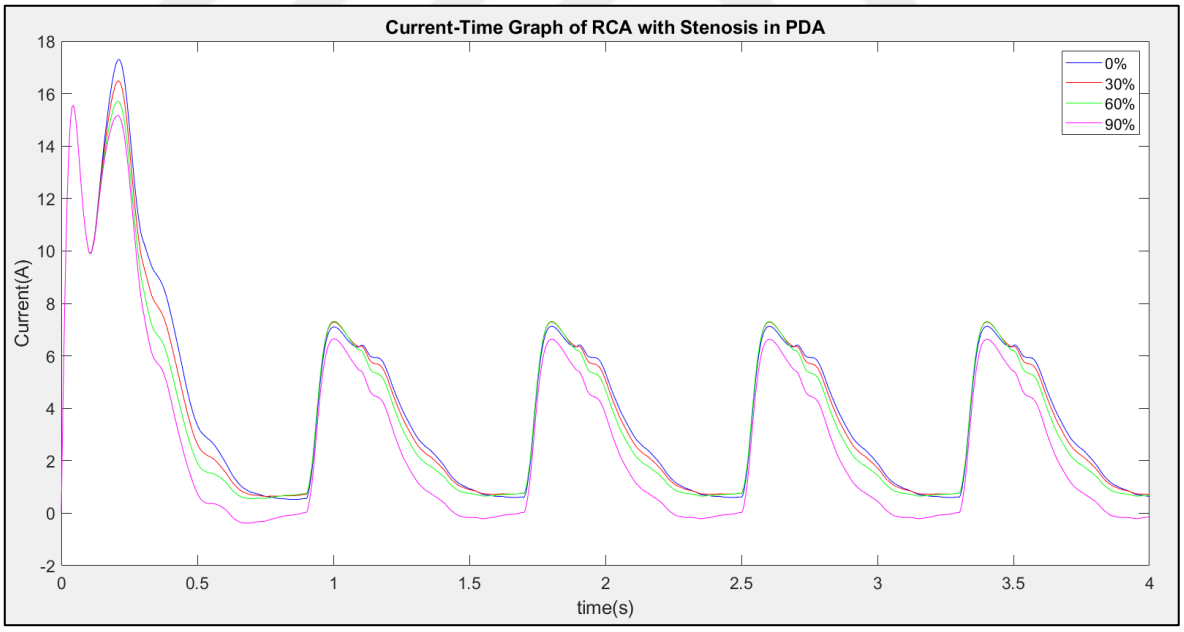

Figure D.8. Current versus time graph of RCA with stenosis in PDA