VascularSim

Cardiovascular simulator

Software User Guide & Documentation

INDIAN INSTITUTE OF TECHNOLOGY

Technology of Touch
Committed to "Make in India"

TOUCH LAB, IITM

Contents

Organization of the manual-------------------------------- ---4
Downloading and Installing VascularSim---------------- ---5

CHAPTER 1 Getting Started
About VascularSim-- ---7
First Steps--- ---7
Functionalities-- ---9
Menu Bar-- ---9
Button Section--------------------------------------- ---10
Graph Section-- ---11
Parameter Section---------------------------------- ---11

CHAPTER 2 Simulation
Controlling the Parameters------------------------ ---13
Comprehending the Results----------------------- ---14

CHAPTER 3 Medical Education Aid
Learning Aid--- ---17
Current Experiments------------------------------- ---17
Simulation Guide----------------------------------- ---17

CHAPTER 4 Simulation Model
Physiology Background---------------------------- ---21
Avolio Model-- ---25
Real-time Simulation------------------------------ ---26
State Space equations---------------------------- ---26

Four-Element Windkessel--------------------------- ---27
Transmission Line Model---------------------------- ---27
Solving the Equations------------------------------- ---28
Making the Model Real-Time----------------------- ---29
Algorithms-- ---30
Peak to peak--- ---30
Pre-Ejection Period----------------------------------- ---30
Pulse Wave Velocity---------------------------------- ---31
CHAPTER 5 Software Limitations
Model Limitations------------------------------------ ---1
Software Limitations--------------------------------- ---1

CHAPTER 6 Future Updates

References

Organization of the Manual

This manual for VascularSim is organized in a way that describes the use of the software for Cardiovascular simulation as well as an insight into the development of the model and also the validation of the results with supporting literature. At the very end of the manual, future updates of the software and addition of newer models have been put.

1. Getting Started

This chapter explains all the different functionalities of the software. You'll be introduced to VascularSim and all description of each and every single functionality is provided.

2. Simulation

This section helps you to start using the software for simulation and analysis of blood pressure. Information on how to control the model parameters are given in this section.

3. Simulation Model

In this chapter, the mathematical model based on which the software is built has been detailed. Starting with the cardiovascular physiology, till the description of all the algorithm developed are described in this section.

4. Learning Objectives

Some of the learning objectives that the developers have designed the software for have been described here. If you are a medical student, or a researcher, this chapter could define the experiments that can be best simulated with this software. This section too will be frequently updated.

5. References

Al the reference articles used to develop the software are provided here.

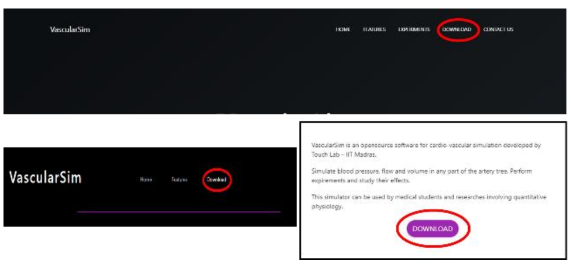
6. Future Updates

As a software with great potent, new models will be added frequently, and the updates are given in this section.

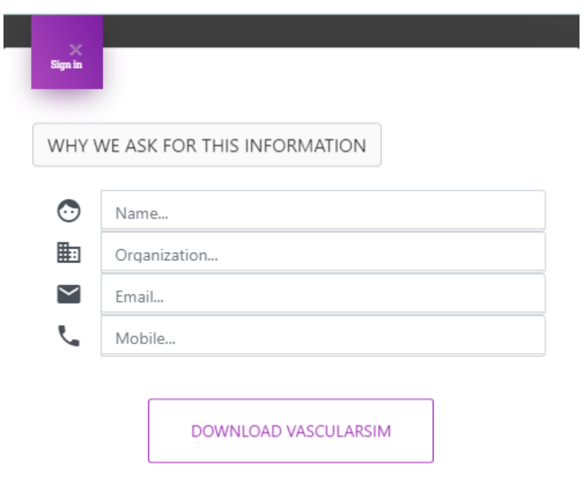
Downloading and Installing VascularSim

VascularSim can be downloaded from its official website hosted on GitHub, vascularsim.github.io.

The software can be downloaded by clicking in any of the three links in the webpage.



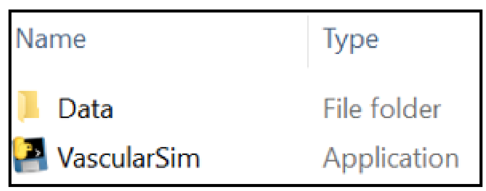
Clicking on the download button will open a modal that will ask the user to enter the following information.



We ask for this information to keep track of all the users that download our software, so that the future development of the software could be developed more to their liking.

Once the form is filled, the download button will be made active, and the software can be downloaded to a folder of your choice.

The downloaded file once extracted will look like this.



The **VascularSim.exe** is the software executable file. The software does not need any installation, and is ready to be run.

The **Resources** folder contains all the files required for running the software, such as the main program, database files, and other scripts.

CHAPTER 1

Getting Started

- **About VascularSim**
- **First Steps**
- **Functionalities**
  - **Menu Bar**
  - **Button Section**
  - **Graph Section**
  - **Parameter Section**

About VascularSim

VascularSim is an opensource software for cardio-vascular simulation developed by **Touch Lab – IIT Madras**, under **Dr. Manivannan M**.

VascularSim is developed entirely in python, and is designed to simulate the blood pressure, flow and volume in any part of the artery tree. In addition to cardio-vascular simulation, multiple experiments can be simulated.

VascularSim is a distributed parameter model of the human circulatory system and offers real time simulation. This is aimed to be used as a teaching tool for medical students and also for researches involving quantitative physiology.

This software is closely developed with feedback from renowned doctors, and thus best suited for practical applications of medical students.

This is a constantly evolving application, and a user can expect frequent updates to the software.

Developers
Dr. Manivannan M
Arvindh Swaminathan MB
Praveen Kumar S

First Steps

Once the software has been downloaded and extracted, opening the application file will open a window shown in Fig 1.

The software has three sections, the left end of the software has ten buttons of which three are colored. The middle section of the software consists of four graphs. Once the software is opened, there will be only the axes. The final section of the software is the right end, where various parameters are displayed. This is also the section where control of parameters is done.

The software is designed in a way that the user feels he/she is working on a real patient monitor system. The default simulator loaded is the human arterial simulator, which simulates the blood pressure in the entire artery tree.

The three workspace sections – button section, graph section and parameter section are separately shown in Fig 2.

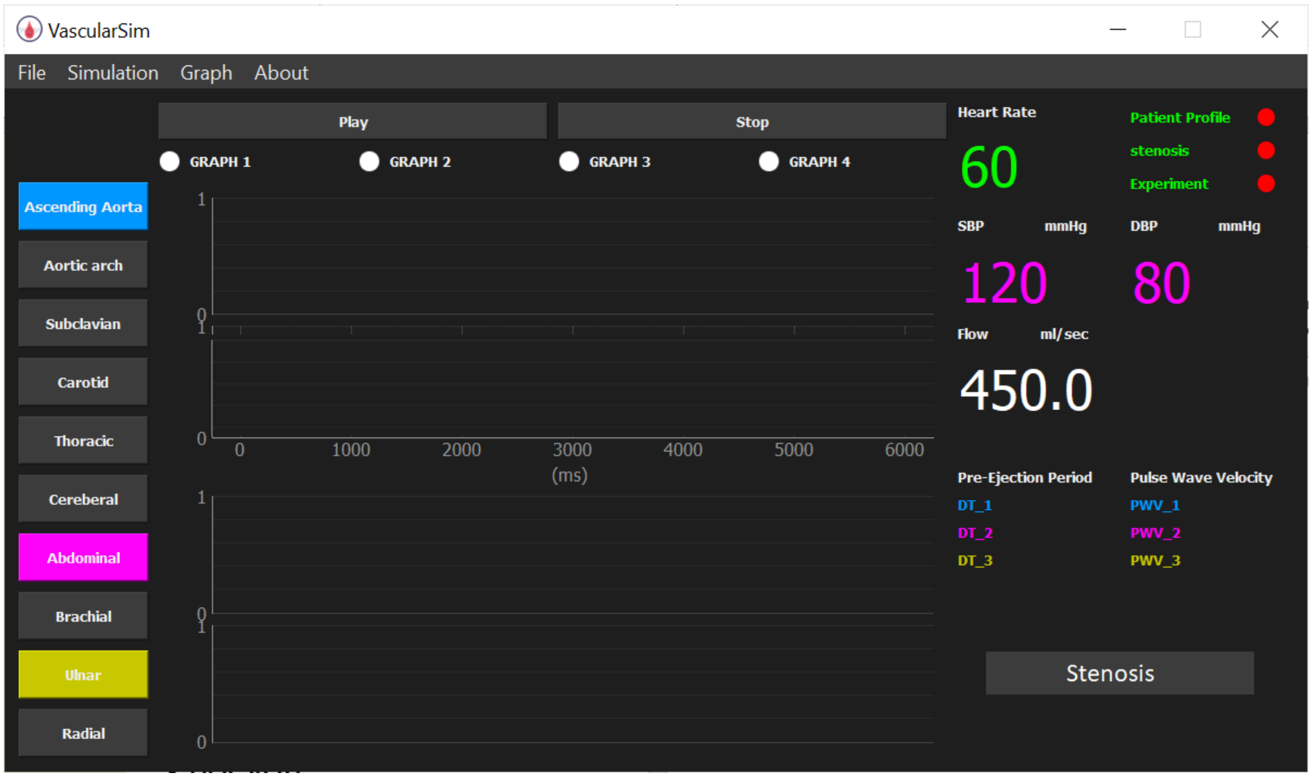


Fig -1 VascularSim Layout

Fig-2 (a) Buttons section (b) Graph sections (c) Parameter section

Functionalities

1. Menu Bar

The Menu bar has four sections – File, Simulation, Graph & About.

The **File** option has create profile, settings and quit.

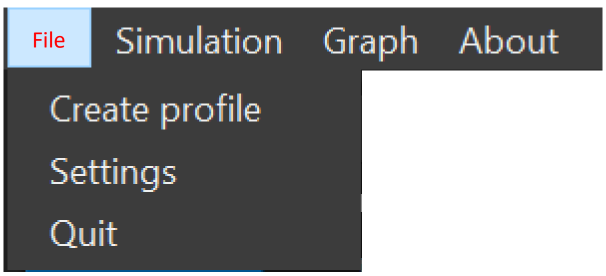


Fig 3 Menubar-File

The create profile section allows the user to create a patient profile and set parameters, which can be used anytime without having to set the parameters again.

The settings option will have options to change theme, delete patient profiles, reset the entire software and so on.

The quit option can be used to exit the software.

The **Simulation** option has the following sub labels – Human Arterial tree, Fetal circulation, Medical Simulation.

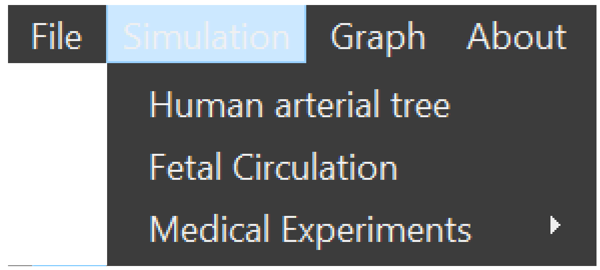


Fig 4 Menubar - Simulation

The default is Human arterial tree. This simulates blood flow in the entire circulatory system (arteries). Medical experiments option will allow the user to turn on Medical simulation, such as Effect of Stenosis, posture and gravity on blood flow. In the future more and more experiments are to be added.

The **Graph** option section allows the user to reset and clear all the graphs. Selecting clear will only remove the graphs from display, but Resetting the graph would restore all the parameters to default.

The final section on the menu bar is **About.** This section provides a video tutorial through help, and also has a option of opening the user manual.

Through this section, the user can also reach the official website.

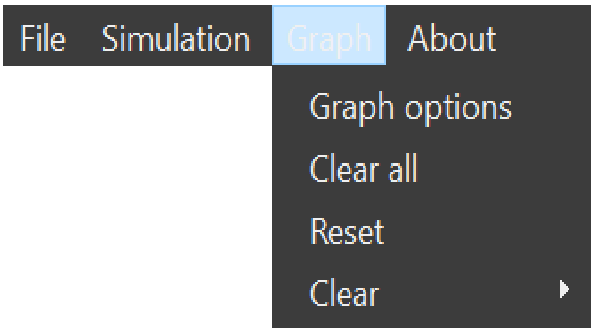


Fig 5 Menubar – Graph

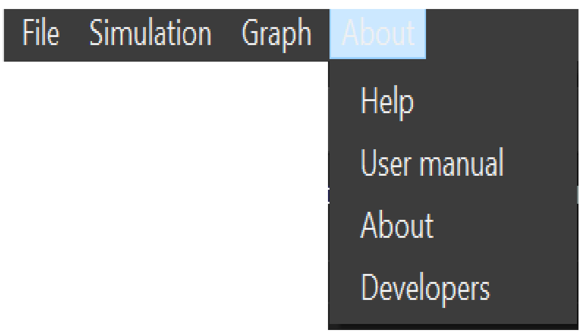


Fig 6 Menubar – About

The menu bar options are expected to be changing continuously with updates as newer and newer models are uploaded.

The newer models that are to be added will be added under the simulation option. And, based on the need, the UI would be changed, and so would this manual.

2. Button Section

This is the left most section of the software. This section contains ten buttons of which three are highlighted using the following colors – blue, pink and yellow.

This color corresponds with the graph color. For example, if the second graph (blue) is that of ascending aorta, then, the ascending aorta button will be highlighted in blue.

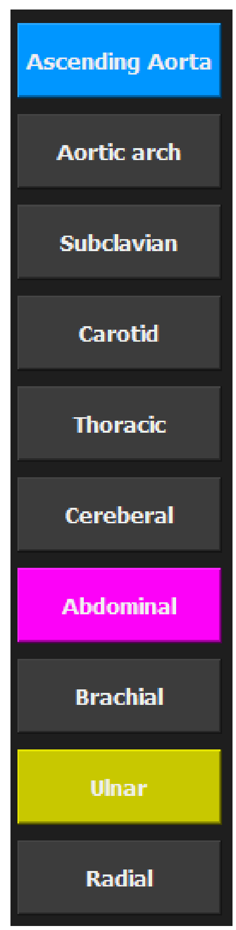


Fig 7 Buttons section

3. Graph Section

This section contains four graphs of which the second graph has an x – axis in milli seconds.

The first graph displays ECG by default and cannot be changed. The rest of the graphs are named one, two and three respectively.

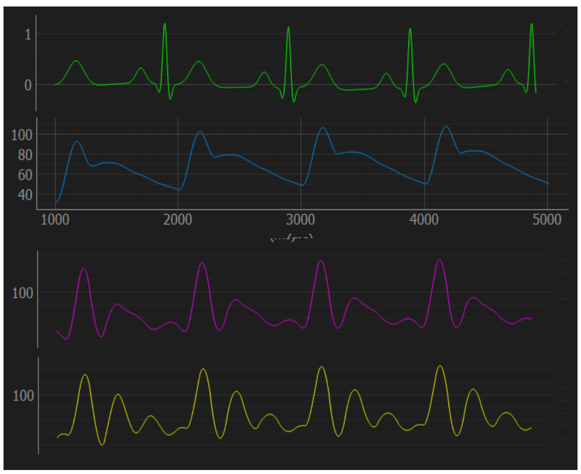


Fig 8 Graph Section

The graphs can be cleared and reset by using the graph options in menu bar.

4. Parameter Section

This section is where all the parameters are displayed as well as controlled.

In this section, the parameters such as Heart rate, systolic and diastolic blood pressures, peak flow of blood, Pre ejection period and pulse wave velocity are displayed.

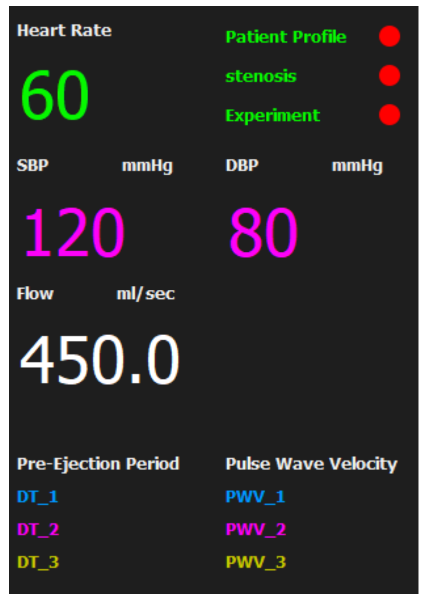


Fig 9 Parameter Section

In order to change parameters such as Heart rate and Peak flow, the user can directly change it from the display. This will prompt a dialogue box to open.

The respective text color will match the graph color. For example, blue pulse velocity means that is of the second graph.

CHAPTER 2

Simulation

- **Controlling the Parameters**
- **Comprehending the Results**

Controlling the Parameters

The simulation can be controlled by changing certain parameters in the software. Currently the software supports change of Heart rate in beats per minute and change of Peak flow of blood in ml/s. Also, stenosis can be simulated by controlling the rate of change in radius reduction of the artery. Also, more detailed parameters of the heart such as elastance and resistance of heart chambers, valves can be controlled.

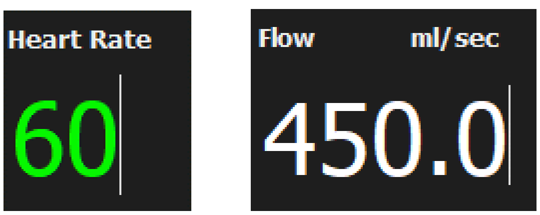


Fig 10 (a) Change in heart rate

(b) change peak flow

Once the heart rate or peak flow is changed, a dialog box will appear.

FIG 11 Dialog prompt

As more models and features are added, a newer section will be set up separately for controlling various parameters.

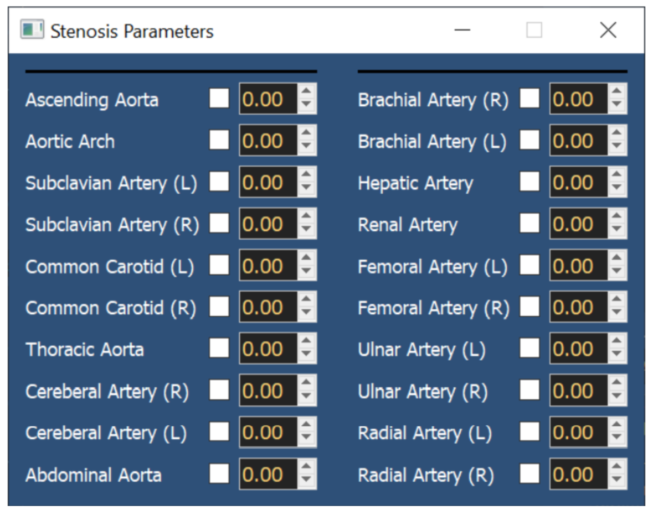


Fig 12 Set stenosis as percentage reduction in artery radius

Fig 13 Change heart parameters

Comprehending the Results

The current version supports the display of the following parameters – systolic and diastolic blood pressures, Peak flow of blood, Heart rate, peak ejection flow, pulse wave velocity. Also, display of patient profile, stenosis, and any experiment is set.

Of these sections displayed in Fig 14, The heart rate and the Peak flow of Blood can be changed. The stenosis button has to be clicked to open a new window where the parameters described in Fig 12 and 13 can be changed.

In order to start the simulation, the play button on top of the graph section has to be clicked. And the stop button will pause the simulation.

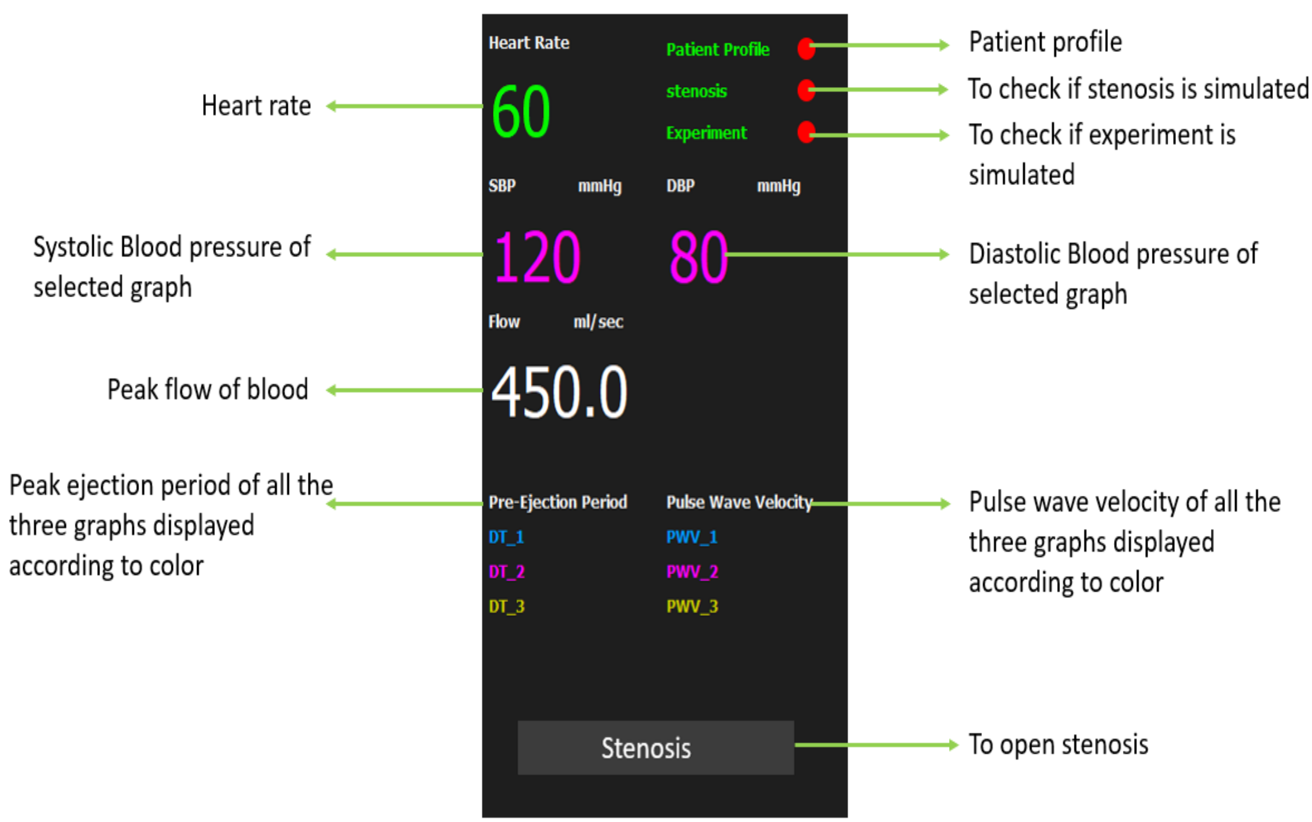


Fig 14 Parameter section

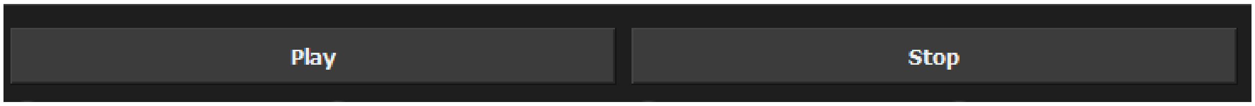


Fig 15 Play and stop buttons

Fig 15 Changing the graphs

The buttons shown in figure 15 are used to control the graphs. The first button displays ECG by default, and cannot be changed. The Following are the orders of the rest of the buttons.

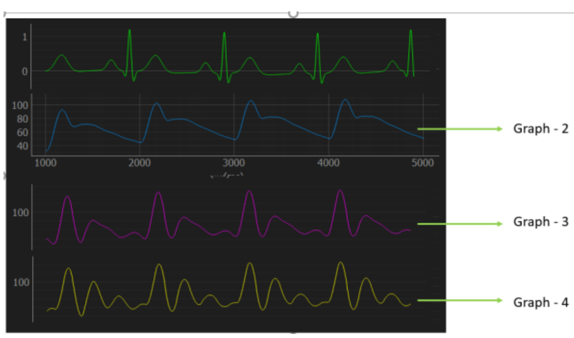


Fig 16 Graph numbers

In order to view the waveform of a different artery, the corresponding graph button has to be clicked, and then the button has to be changed as seen in Fig 17.

For example, if the second graph – the one below the ECG has to be changed to subclavian artery from Ascending aorta.

First, the radio button graph-2 has to be clicked – this is shown as step1 in Fig 17. Then the artery of choice, here subclavian, button has to be clicked – this is shown as step2 in Fig 17.

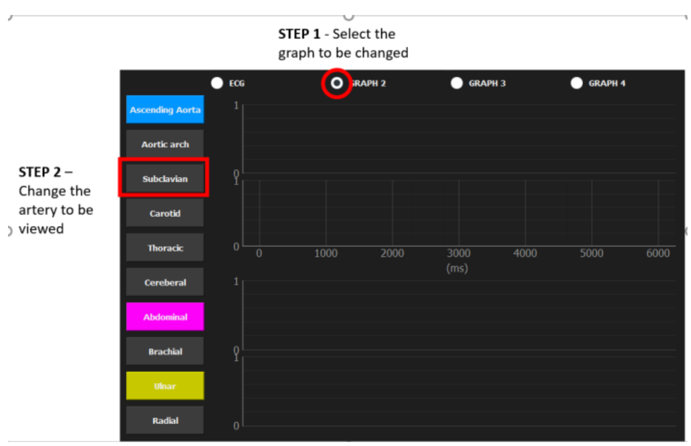


Fig 17 To change an artery

CHAPTER 3

Medical Education Aid

- **Learning Aid**
- **Current Experiments**
- **Simulation Guide**

Learning Objectives

This software has been developed in close association with doctors and a majority of experiments simulated have been developed keeping in mind their needs.

The main objective of using this software would be to visualize the effect of various parameters on blood pressure in the arteries.

Some more specific objectives are as follows

- Understand correlation between ECG and pulse.

- Appreciate pre ejection period and LVET

- Study wave properties and their propagation along the artery tree

.

- Understand Pulse wave velocity

- Study he effects of stenosis on blood pressure

The user is able to appreciate the correlation between ECG wave and the blood pressure pulse. With this software, there can be clear understanding of the electrical activity of the heart and its correlation with the mechanical activity.

Fig 18 Normal Simulator

The above image is that of a normal simulator, Here, there are no significant information to analyze ECG and blood pressure. The following image is that of VascularSim simulation.

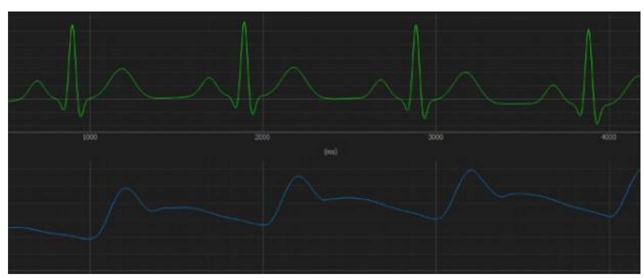


Fig 19 Realistic output

Here, the simulation is more realistic. Thus, the user is able to appreciate the PEP – pre ejection period which is displayed as dt in the above figure.

This effect has been calculated, and displayed in the parameter section described in the previous chapter.

Also, unlike most other simulators, this simulator is based on a distributed parameter model, thus opening a wider range of simulation options. The user is able to appreciate the flow of waveforms along the artery and how their velocity changes.

In the below figure, it can be seen how the waves propagate along with increasing distance.

To take a closer look, let us consider the aortic pulse, abdominal pulse, and the femoral pulse.

The blood flows from the aorta and then reaches the abdominal aorta and only then the femoral artery, this can be seen in our simulator as there can be seen a time delay in the pulse foot and also the pulse peak.

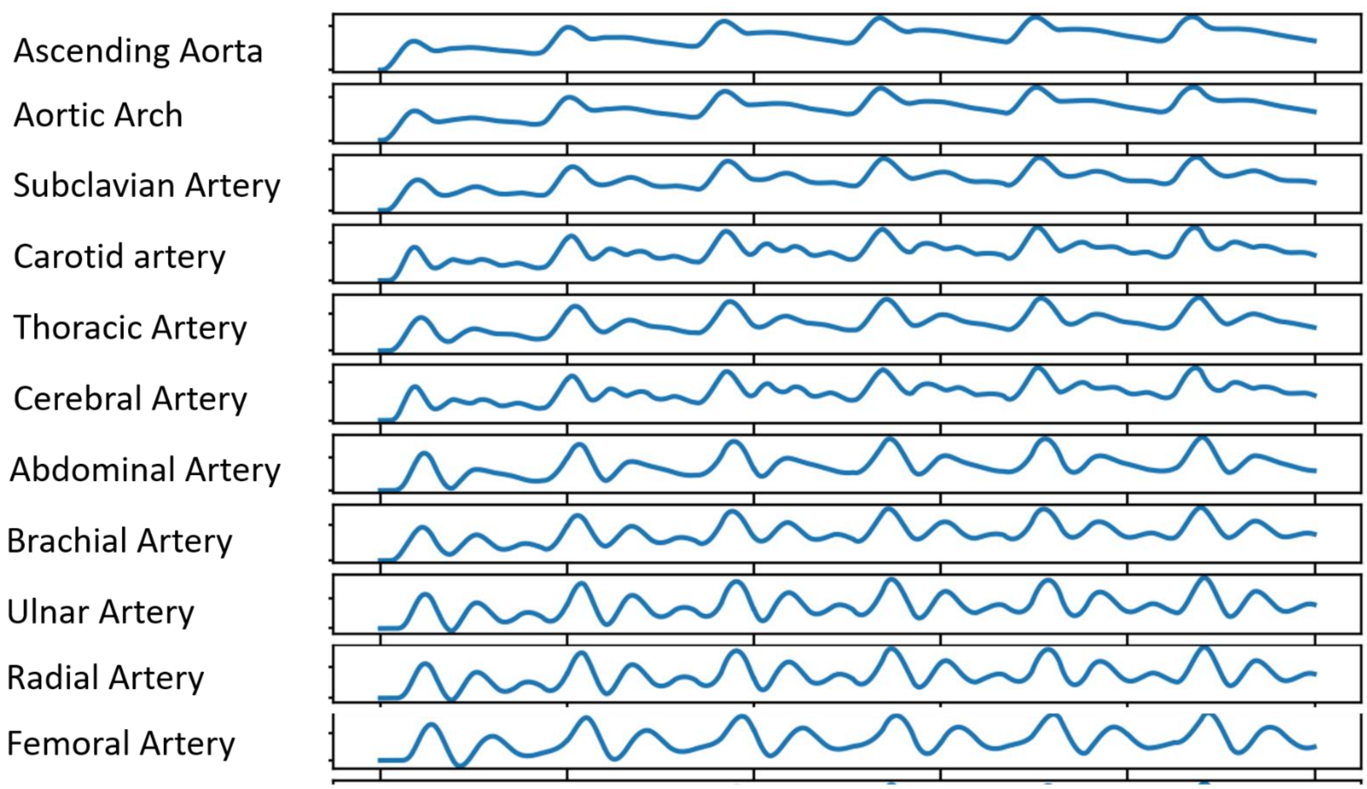


Fig 20 Pulse Transmission through the body

The following images detail the effect of distance on blood pressure peak and foot.

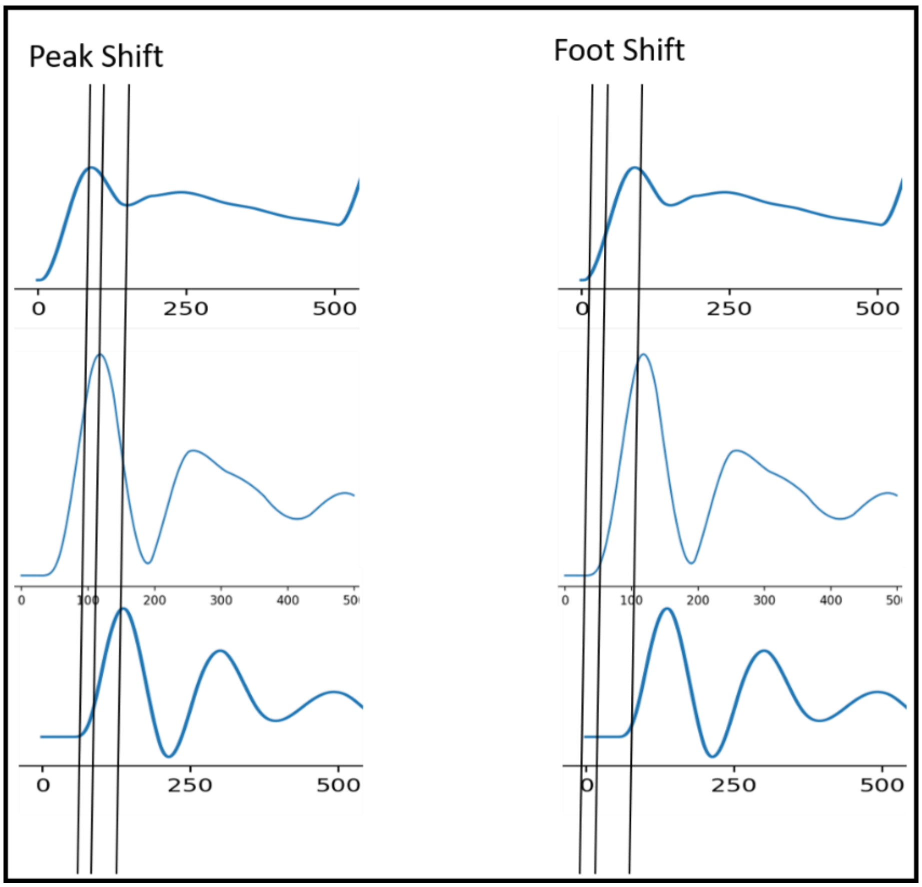


Fig 21 Shift in peaks

The next will be the effect of stenosis on the blood pressure. This has been modelled as the change in resistance, inductance and capacitance values of the arteries.

The future models once added, will be accommodated in this section.

CHAPTER 4

Simulation Model

- **Physiological Background**
- **Avolio Model**
- **Real Time Simulation**
- **Algorithms**

Physiological Background

An overview of the physiological model on which the software is based on would be

- Lumped Heart Model with properties of valves, walls, and septum
- Transmission line model of the arterial tree

The following course of the chapter would first describe the anatomy of the systems involved in the model, and then describe the previous works done to describe the model electrically and finally how the model has been converted into a PYTHON program.

1. Heart

The human heart is a mechanical pump that pumps blood throughout the body thus transporting oxygen to the organs and also responsible for pumping the deoxygenated blood to the lungs for oxygenation. It is made of specialized muscle capable of sustaining continuous beating.

The heart is anatomically separated into two halves- the left heart and right heart. The structure of the heart includes four chambers, valves, and connecting vessels. Each half consists of two chambers, 18 the atrium (upper chamber) and the ventricle (lower chamber). The atrium pumps blood to the ventricle and the ventricles pump blood to the rest of the body (systemic circulation) or the lungs (pulmonary circulation).

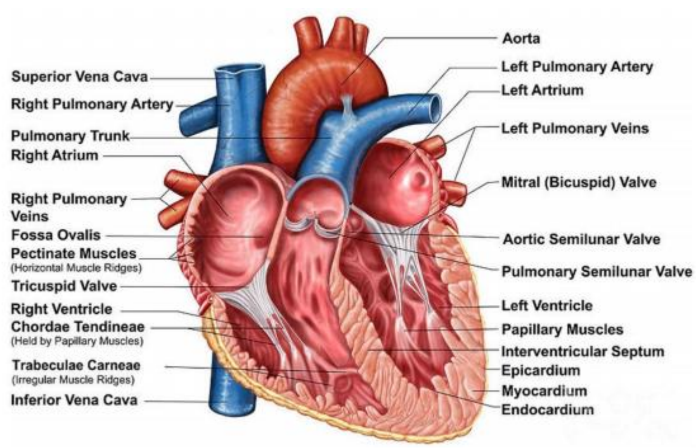


Fig 22 Anatomy of the heart

The left and right halves of the heart are separated by a septum. To prevent regurgitation of blood (backflow), there are presently four valves. The tricuspid valve separates the atrium and ventricle of the right heart, whereas the mitral valve separates the atrium and ventricle of the right heart. The pulmonic valve prevents regurgitation of blood into the right ventricle from the pulmonary artery and the aortic valve prevents the backflow from the left ventricle from the aorta. Blood flow occurs only when there is a pressure difference across the valves which causes them to open. The heart is isolated from other organs in the intrathoracic cavity by the pericardium. It is a fluid-filled sac that surrounds the heart and the proximal ends of the aorta, vena cava, and the pulmonary artery.

The pericardium keeps the heat contained in the chest cavity and also prevents the heart from over-expanding when blood volume increases. The fluid-filled in pericardium cavity is called the pericardial fluid which acts as a lubricating medium to reduce friction between the pericardial membranes. Another important anatomical structure of the heart is the septum. It is a partition that separates the right and left sides as well as the upper and lower sides of the heart. There are two separate regions of the Septum. They are the inter atria septum that separates the atriums and the interventricular septum that separates the ventricles. It prevents blood flowing from the right to the left ventricle or vice versa during contraction.

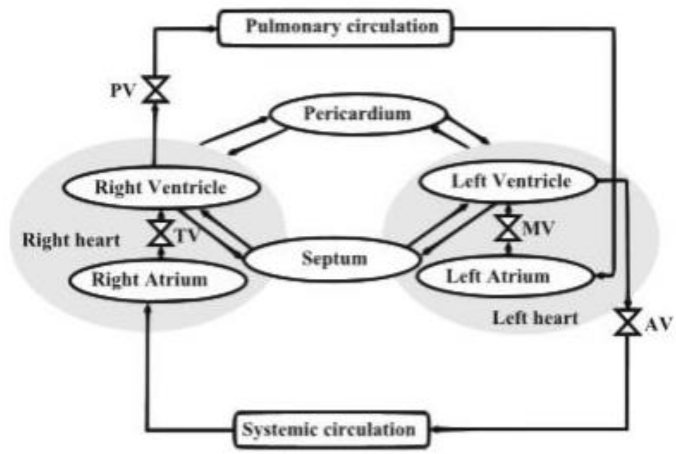
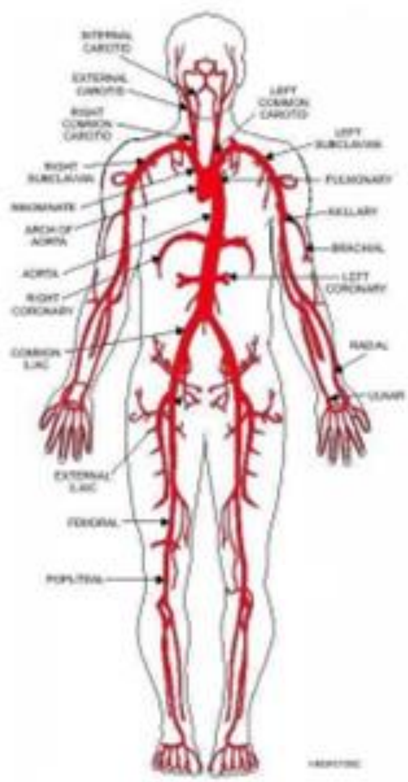


Fig 23 Schematic of cv system

2. Artery Tree

In anatomy, the arterial tree is used to refer to all arteries and/or the branching pattern of the arteries. Arteries transport blood to body tissues under high pressure, which is exerted by the pumping action of the heart. The heart forces blood into these elastic tubes, which recoil, sending blood on in pulsating waves. It is, therefore, imperative that the vessels possess strong, elastic walls to ensure fast, efficient blood flow to the tissues. The aorta is the largest vessel in the systemic circuit, arising from the left ventricle. It is commonly said to have three regions: the ascending aorta, the arch of the aorta, and the descending aorta; the latter may be further subdivided into the thoracic and the abdominal aorta. Originating from the ascending portion of the aorta are the right and left coronary arteries, which supply the heart with oxygenated blood. Branching from the arch of the aorta are three large arteries named, in order of origin from the heart, the innominate, the left common carotid, and the left subclavian. These three branches supply the head, neck, and arms with oxygenated blood. As the innominate (sometimes referred to as the brachiocephalic) artery travels upward toward the clavicle or collarbone, it divides into the right common carotid and right subclavian arteries. The two common carotid arteries, one branching from the innominate and the other directly from the aorta, then extend in a parallel fashion on either side of the neck to the top of the thyroid cartilage (the principal cartilage in the voice box, or larynx), where they divide, each to become an internal and an external carotid artery.

The two vertebral arteries, one arising as a branch of the innominate and the other as a branch of the left subclavian artery, unite at the base of the brain to form the basilar artery, which in turn divides into the posterior cerebral arteries. The blood supply to the brain is derived mainly from



vessels that may be considered as 22 branches of the circle of Willis, which is made up of the two vertebral and the two internal carotid arteries and connecting arteries between them. The arms are supplied by the subclavian artery on the left and by the continuation of the innominate on the right. At approximately the border of the first rib, both of these vessels become known as the axillary artery; this, in turn, becomes the brachial artery as it passes down the upper arm. At about the level of the elbow, the brachial artery divides into two terminal branches, the radial, and ulnar arteries, the radial passing downward on the distal (thumb) side of the forearm, the ulnar on the medial side. Interconnections (anastomoses) between the two, with branches at the level of the palm, supply the hand and wrist. The thoracic (chest) portion of the descending aorta gives off branches that supply the viscera (visceral branches) and the walls surrounding the thoracic cavity (parietal branches). The visceral branches provide blood for the pericardium, lungs, bronchi, lymph nodes, and esophagus. The parietal vessels supply the intercostal muscles (the muscles between the ribs) and the muscles of the thoracic wall; they supply blood to the membrane covering the lungs and lining the thoracic cavity, the spinal cord, the vertebral column, and a portion of the diaphragm. As the aorta descends through the diaphragm, it becomes known as the abdominal aorta and again gives off both visceral and parietal branches. Visceral vessels include the celiac, superior mesenteric, and inferior mesenteric, which are unpaired, and the renal and testicular or ovarian, which are paired. The celiac artery arises from the aorta a short distance below the diaphragm and almost immediately divides into the left gastric artery, serving part of the stomach and esophagus; the hepatic artery, which primarily serves the liver; and the splenic artery, which supplies the stomach, pancreas, and spleen. The superior mesenteric artery arises from the abdominal aorta just below the celiac artery. Its branches 23 supply the small intestine and part of the large intestine. Arising several centimeters above the termination of the aorta is the inferior mesenteric artery, which branches to supply the lower part of the colon. The renal arteries pass to the kidneys. The testicular or ovarian arteries supply the testes in the male and the ovaries in the female, respectively. Parietal branches of the abdominal aorta include the inferior phrenic, serving the suprarenal (adrenal) glands, the lumbar, and the middle sacral arteries. The lumbar arteries are arranged in four pairs and supply the muscles of the abdominal wall, the skin, the lumbar vertebrae, the spinal cord, and the meninges (spinal cord coverings). The abdominal aorta divides into two common iliac arteries, each of which descends laterally and gives rise to external and internal branches. The right and left external iliac arteries are direct continuations of the common iliac and become known as the femoral arteries after passing through the inguinal region, giving off branches that supply structures of the abdomen and lower extremities. At a point just above the knee, the femoral artery continues as the popliteal artery; from this arise the posterior and anterior tibial arteries. The posterior tibial artery is a direct continuation of the popliteal, passing down the lower leg to supply structures of the posterior portion of the leg and foot. Arising from the posterior tibial artery a short distance below the knee is the peroneal artery; this gives off branches that nourish the lower leg muscles and the fibula (the smaller of the two bones in the lower leg) and terminate in the foot.

Avolio Model

This is the transmission line model of the systemic circulation and is built up of Windkessel elements and transmission line elements. This model includes the multibranched configuration of the arterial system and models the distributed nature of the arterial properties. This model was first described by Avolio (1980). This model represents the architecture of the human arterial tree encompassing bifurcations and physical properties of the arterial segments. The systemic vasculature is divided into a multi-segment branching structure consisting of 128 arterial segments arranged according to the anatomical 26 architecture of the human arterial tree. This configuration includes all the central vessels and principal arteries supplying the extremities with each segment having realistic dimensions and arterial properties. The current and voltage in each segment are described by equations (3.1) and (3.2).

$$-(\partial V/\partial x) = IR + L(\partial I/\partial t) \text{ ---------} 3.1$$

$$-(\partial I/\partial x) = VG + C(\partial V/\partial t) \text{ --------} 3.2$$

Using these equations, a hydraulic system can be modeled as an electrical circuit and compliant tubes can be modeled as small segments of the transmission line.

The RLC values can be calculated from the mechanical parameters of compliant tubes using the following relations

$$R = (8\mu) / (\pi r^4) \text{ -----------------} (3.3)$$

$$L = \rho / (\pi r^2) \text{ ----------------------} (3.4)$$

$$C = (3 \pi r^3) / 2Eh \text{ ----------------} (3.5)$$

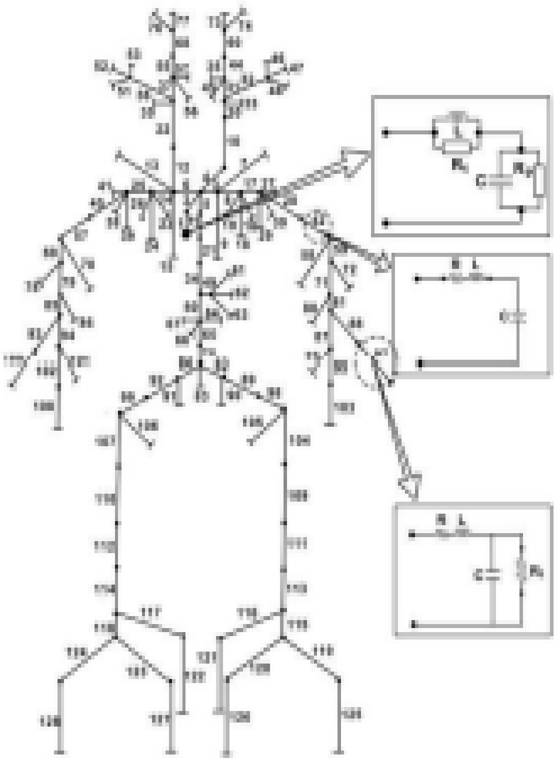


Fig 25 Schematic model of human Arterial tree. (Avolio)

The terminal resistance Rt of the terminating segment can be calculated using the given relation

$$Rt = (1/\pi r^2)(\rho Eh / 2r)^{0.5}((1 + R) / (1- R)) \text{ ---------------------(3.6)}$$

All these relations are adapted from Suganthi et al (2014).

Real Time Simulation

First, the electrical model of various physiological systems from literature is taken and converted to the state-space model. Thus, multiple ODEs are obtained and are separated into pressure and flow equations. These equations are solved simultaneously using Runge-Kutta 4 th order algorithm.

1. State Space Equations

The mathematical equations are derived from the electrical model by representing them as state-space variables. In this project, we have considered the state variables as voltage (V) and current (I). These space variables correspond to blood pressure and flow respectively. The electrical models comprise of basic units which are repetitive throughout the physiological system. Thus, modelling these systems is described in the following section.

2. Four Element Windkessel model

The four-element Windkessel model consists of four components or elements namely, Vascular resistance R, arterial compliance C, characteristic impedance Z (Rp is used to denote this element in this project), and a fourth element Inertance L, placed in parallel with R_p .

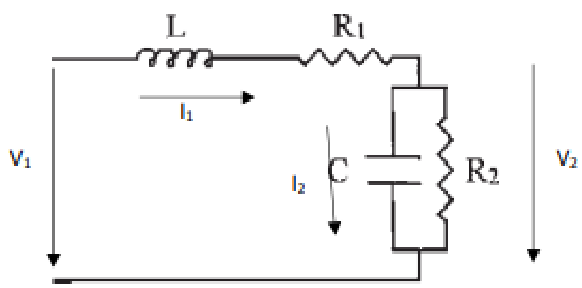


Fig 26 Electrical equivalent of 4 element model

The state space variables are voltage which represents pressure and current which denotes the flow. The first order ordinary differential equations are then derived as follows,

d(I1)/dt = (V1 / L) – {(I1*R1) / L} – (V2/ L)(3.6)

d(V2)/dt = -I2 / C – V2/ (R2* C)-----(3.7)

3. Transmission Line Model

The other element present in the arterial tree circuit is the transmission line model, which has three elements namely resistance R, inductance L, and capacitance C. The entire arterial tree is made up of the two sets of models.

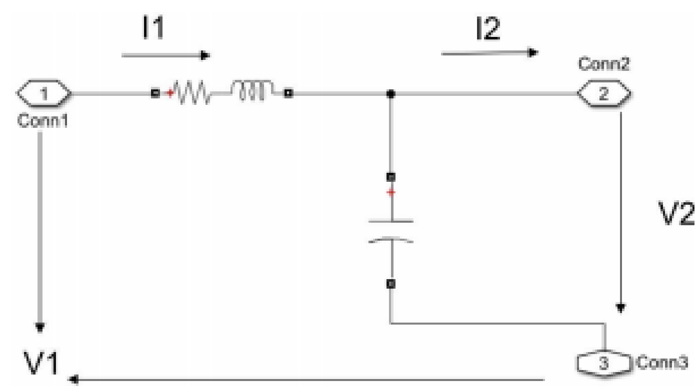


Fig 27 Transmission Line model

The state space equations are as follows,

d (I1)/dt = V1 / L – (I1 * R1) / L – V2 / L ------------------------------(3.8)

d (V2)/dt = - I2 / C + I1 / C ---(3.9)

From the above derivation's different sets of first-order ordinary differential equations have been derived. The number of ODEs obtained vary on the model, and a common approach of all the voltages corresponds to blood pressure and the currents correspond to blood flow have been used. The distributed

parameter model of the arterial tree corresponds to 256 first-order ordinary differential equations. The model comprises of 128 segments, and each segment models a voltage and current state-space variable. Thus, in total there are 256 pressure and flow equations.

4. Solving the Equations

The different sets of equations are solved over a time scale T. The time scale used in this project ranges from 0 to 15 seconds. The step size is taken as 0.02. It is to be noted that the step size and the Time T can be changed according to the application. The equations are solved over T using the 4th order Runge Kutta algorithm.

Runge–Kutta methods are a family of implicit and explicit iterative methods, which include the well-known routine called the Euler Method, used in temporal discretization for the approximate solutions of ordinary differential equations. The flowchart of RK4 algorithm is as given in figure 3.11. The RK4 algorithm is used to solve initial value problems. These are a set of equations to be solved over a time T, where the initial value of the equations at time T = 0 is known. This algorithm involves iterative methods. The step size is defined as the interval between two adjacent points in the time axis. For example, a time scale of 0 to 15 seconds with a step size of 0.001 would have 15,000 points in between. The Runge-Kutta 4th order algorithm involves the use of four temporary variables and the algorithm is as follows.

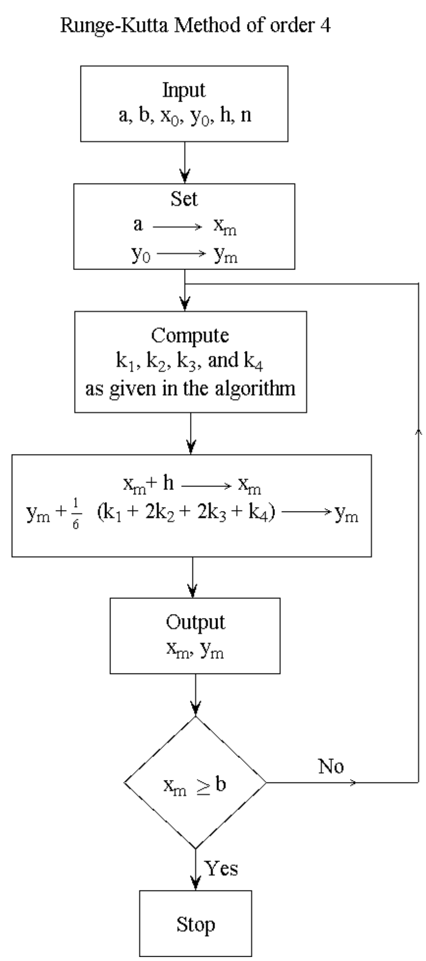


Fig 28 RK4 flowchart

$k1 = h * f(xn, yn)$

$k2 = h * f(xn + h/2, yn + k1/2)$

$k3 = h * f(xn + h/2, yn + k2/2)$

$k4 = h * f(xn + h, yn + k3)$

Once the four variables are calculated the function y and x are defined as,

$yn+1 = yn + (1/6) (k1 + 2k2 + 2k3 + k4)$

$xn+1 = xn + h$

where h is the step size. The function x, here time, increases by h. The RK4 algorithm, in case of too many equations, becomes expensive and the time taken by the algorithm to complete increases exponentially with an increase in the number of equations and a decrease in the step size.

These are carried out by the use of NUMPY and SCIPY libraries in python.

4. Making the Model Real Time

The described above model is static, and can be solved for over a period of time. But the real potent of the software could be brought out only if the software offered a real time simulation with continuously changing parameters.

In order to achieve this, a new algorithm was developed. This algorithm, makes use of the fact that the model is an initial value problem (IVP). First, the model is solved for a time of 1 second with the step size of 0.02. For this step, the initial value is given as zero. Solving this will result in an output array of size 500 X 256. Of this, the last column i.e. The 256th column is taken as the initial value for the next iteration.

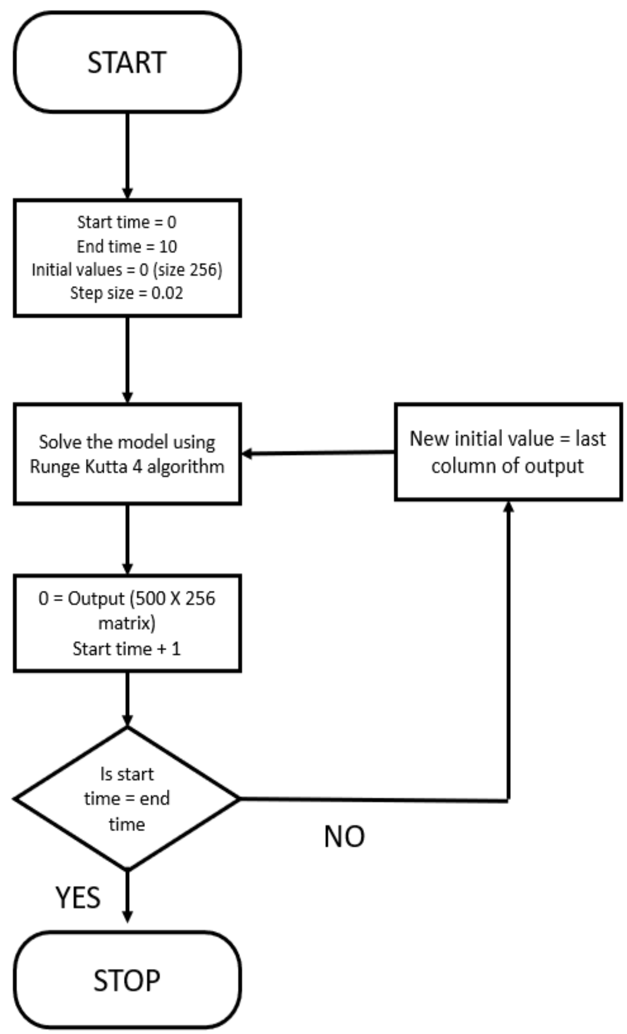


Fig 29 Real time simulation – flowchart

Algorithms

This section contains all the algorithms used to calculate various attributes from the model simulation.

3. Peak to Peak Distance

The peak to peak distance of all the graphs are calculated using the concept of maxima and minima using the slope of the graphs. The peak of 1st wave is identified and its index. Similarly, for the second wave. The difference between the two indexes will give the number of samples between the two peaks. As the sampling rate is 500, the peak to peak in seconds would be the number of samples multiplied by 0.002 seconds.

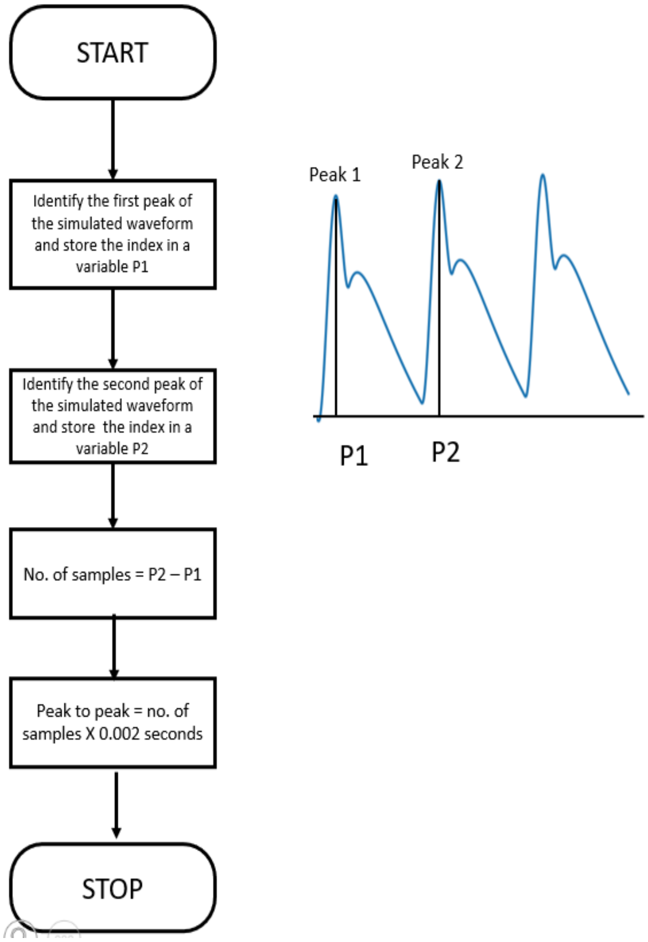


Fig 30 Peak to peak detection - flowchart

4. Pre-Ejection Period

The pre ejection period (PEP) is the time elapsed between the electrical depolarization of the left ventricle (QRS on the ECG) and the beginning of ventricular ejection and represents the period of left ventricular contraction with the cardiac valves closed.

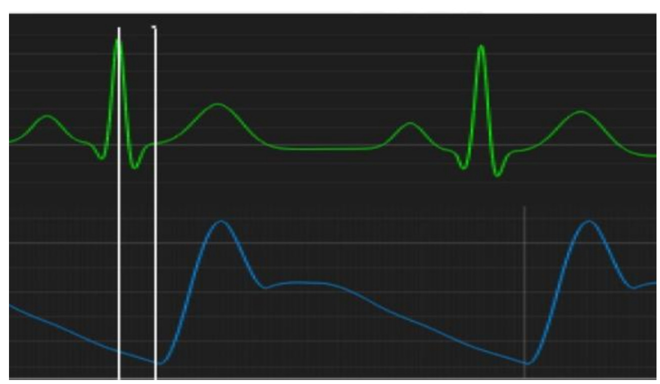


Fig 31 PEP

The PEP is calculated by using the above explained algorithm. The peak of the ECG wave is identified, and the index is stored in P1. Similarly, the peak of the pressure pulse is identified and stored in P2. The difference between the two will give the PEP in seconds or milli seconds.

5. Pulse Wave Velocity

Pulse wave velocity (PWV) is the velocity at which the blood pressure pulse propagates through the circulatory system, usually an artery or a combined length of arteries.

The widely accepted equation for calculation of pulse wave velocity is the Moens-Korteweg equation.

$$\mathrm{PWV} = \sqrt{\frac{E_{\mathrm{inc}} \cdot h}{2 \cdot r \cdot \rho}},$$

In this equation,

E is the Young's modulus of the artery,

H is the thickness of the artery wall,

R is the radius of the artery,

P (rho) is the density of blood flowing through the artery.

From the graph, the PWV can be calculated as follows,

Velocity = distance / time

i.e. the pulse wave velocity can be calculated as the ratio of the distance of the artery from the aorta to that of the time taken for the pulse to reach the artery.

The distance can be taken from reference articles, and the time taken for the artery to reach the artery can be calculated using the following algorithm developed.

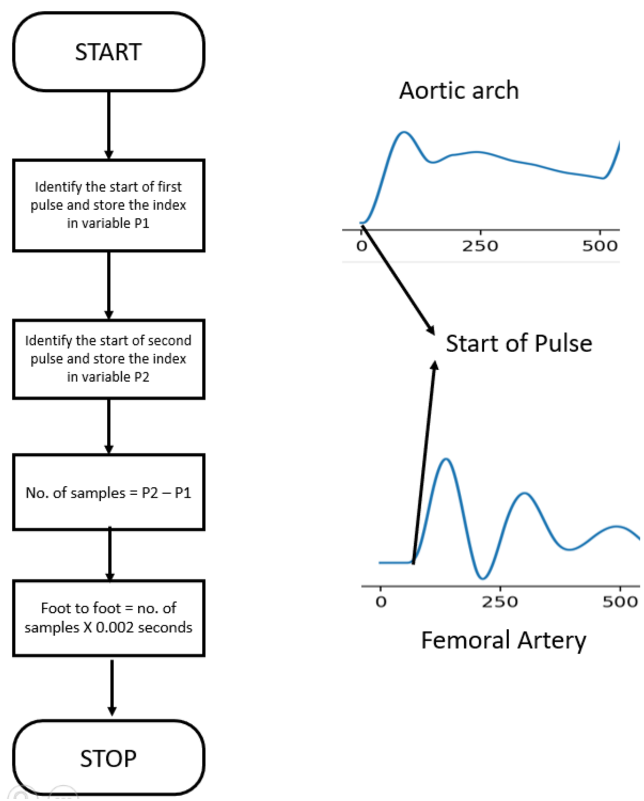


FIG 32 Foot to foot – Algorithm

CHAPTER 5

Software Limitations

- **Model Limitations**
- **Software Limitations**
- **Comparison with Current Software**

Model Limitations

This section describes some of the limitations of the model that exist in the current version of the software.

The following limitations are those models that are to be added soon, but are not currently supported in the current software version.

- Cardiopulmonary reflex and chemo reflex are not considered in the model.
- Respiratory effects are not considered in the model.
- Gravitational effects are not considered in the model.

As new models are being added to the software, the above limitations will be overcome. The following limitations owe to the model itself.

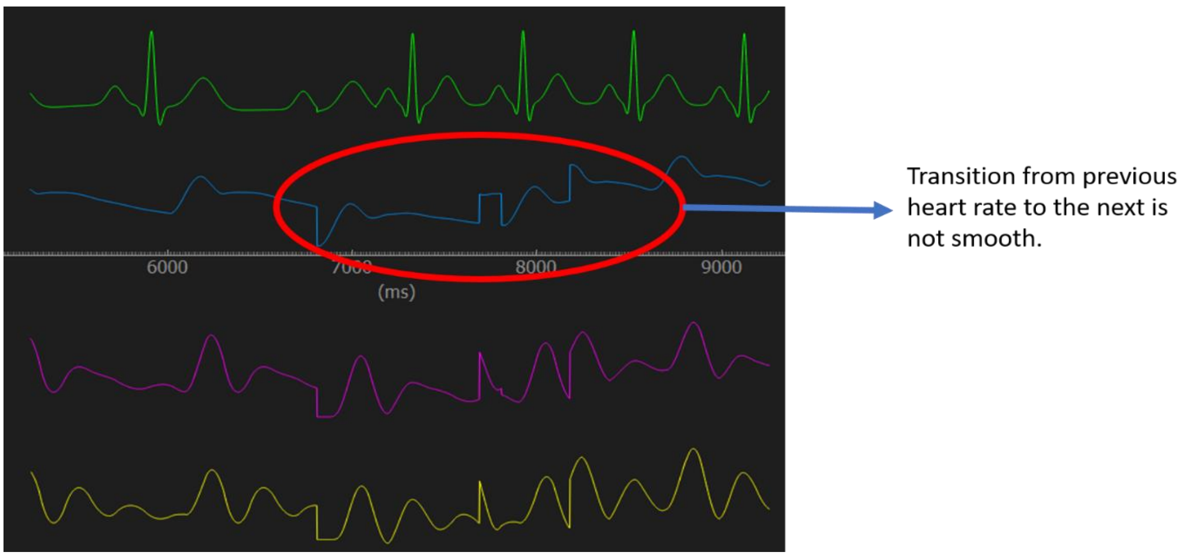
- The model parameters are not verified with clinically derived parameters using the invasive measurements of those patients' parameters.

- The height of subjects is not matched with the length of segments
- The local parameters such as radial artery stiffness and resistance play vital role in determining the pattern of radial artery pressure pulse and hence amplitude and time factors and they change from subject to subject. Though our model has the facility to tune those parameters to get exact patient specific radial artery pulse, the present model studies are not focused to implement those factors because of the complicated experimental procedure involved in collection arterial properties.

Software Limitations

This section describes some of the limitations of VascularSim. While the previous section described limitations with respect to the model, this section lists out the limitations with respect to the software UI.

- This software is computation heavy and requires to be run in a modern system. The system requirements are given in the website.



- The software is currently only for Windows 7 and above. This is yet to be made compatible for MAC os and android.
- The model has been made real time by repeated solving over a period of time. This means that whenever the heart rate or any other parameters are changed, the next iteration will affect the change, and thus the transition will not be smooth. This is shown in Fig 33

CHAPTER 6

Future Updates

As this is a software with a great potential, many more models are to be added on a regular basis.

The set of models that are going to be added immediately are as follows,

1. Effect of gravity on Blood pressure

2. Effect of Muscular Exercise on blood pressure.

3. Fetal circulation

References

Avolio. A. P. (1980). Multi-branched model of the human arterial system. Medical and Biological Engineering and Computing, 18(6), 709-718

John, L. R. (2004). Forward electrical transmission line model of the human arterial system. Medical and Biological Engineering and Computing, 42(3), 312- 321.

Hemalatha, K., Suganthi, L., & Manivannan, M. (2010). Hybrid cardiopulmonary model for analysis of Valsalva maneuver with radial artery pulse. Annals of biomedical engineering, 38(10), 3151-3161

Suganthi, L., Manivannan, M., Kunwar, B. K.,Joseph, G., & Danda, D. (2015). Morphological analysis of peripheral arterial signals in Takayasu's arteritis. Journal of clinical monitoring and computing, 29(1), 87-95

Sun, Ying, Mazen Beshara, Richard J. Lucariello, and

Salvatore A. hiaramida. A comprehensive model for right-left heart interaction under the influence of pericardium and baroreflex. Am. J.

Physiol. 272 (Heart Circ. Physiol. 41): H1499-H1515, 1997

Sergey S. Simakov* Lumped parameter heart model with valve dynamics https://doi.org/10.1515/rnam-2019-0025

John K-J Li DYNAMICS of the VASCULAR SYSTEM (Vol - 1)

Mark Summerfield - Rapid GUI Programming with Python and Qt. Definitive Guide to PyQt-Prentice (2007).

https://scipy.org(TheSciPy ecosystem, a collection of open source software for scientific computing in Python)

https://www.riverbankcomputing.com/static/Docs/PyQt5/ 60

Shai Vaingast - Beginning Python visualization crafting visual transformation scripts (2009, Apress)

Sandro Tosi - Matplotlib for Python Developers (2009)

https://www.geeksforgeeks.org/python-programming-language

.
http://www.pyqtgraph.org/documentation

https://physionet.org/content/cvsim/1.0.0/

https://www.python.org/

https://commons.wikimedia.org

https://en.wikipedia.org/wiki/Arteriosclerosis

https://ccrma.stanford.edu/~jos/NumericalInt/Lumped_vs_Distributed_Syste ms.html

https://ccrma.stanford.edu/~jos/NumericalInt/Lumped_vs_Distributed_Syste ms.html

https://en.wikipedia.org/wiki/Windkessel_effect

https://www.gettyimages.in/detail/illustration/anatomy-of-heart-interiorfrontal-section-royalty-free-illustration/188057943

https://slide-share.ru/heart-s-anatomy-and-physiology-175409

https://www.chegg.com/homework-help/questions-and-answers/solve-fourelement-windkessel-model-terms-variables-given-q25508336

https://en.wikipedia.org/wiki/Runge%E2%80%93Kutta_methods