Computer Simulation of the Human Cardiovascular System in the Power BI Software Environment

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Abstract

This paper is devoted to the analytical assessment and description of mathematical model of the human cardiovascular system. The main task of paper is the creation of a computer model of blood flow. The anatomy of the cardiovascular system and various types of cardiovascular diseases as well as different characteristics of blood for male and female were studied in the paper. A mathematical model of blood flow was presented, including equations of Navier-Stocks describing the movement of fluid in 3-D space. A computer model of blood flow developed using the Python programming language. It allows to simulate the flow of blood in the cardiovascular system. The simulation model can be visualized in the interface on the Power BI program with the ability to select different types of humans with different characteristics. Thus, an interface was created for even an inexperienced user can calculate blood pressure, velocity of blood, pulsate nature of blood rhythm, and different parameters of blood as fluid - Reynolds's number, Poiseuille resistance, volumetric and linear blood velocity, pressure drop.

Keywords

Hemodynamics, blood characteristics, Power BI, Navier-Stocks equations, Reynolds's number, Poiseuille resistance, volumetric and linear blood velocity, pressure drop

1. Introduction

This paper presents a one-dimensional hemodynamics model for calculating blood flow parameters under mechanical effects on blood vessels, addressing properties related to vascular bends and pressure on vessel walls. Notably, research in this field is vital due to cardiovascular diseases being a leading cause of mortality in developed countries, with a significant impact on public health.

Sud and Sekhon [1] investigated a mathematical model of blood flow in arteries under pulsating pressure, considering the impact of physical exertion on the human body. The article "Three-dimensional numerical simulation of blood flow in the aortic arch during cardiopulmonary bypass" [2] explored stroke mechanisms during artificial circulation and the potential for computational fluid dynamics to assess individual stroke risk. In parallel, Misra and Sahu researchers in their paper [3] developed a model comparing blood flows in large vessels under varying pressure ranges, focusing on blood as a non-Newtonian fluid. In a significant part of their research, K. S. Mekeimer and M. A. Elkot [4-7] pay close attention to the study of blood flow in arteries with stenosis using Newtonian fluid models.

The articles by L. Morris, P. Delassus [8] and Marwa Selmi, Hafedh Belmabrouk and Abdullah Bajahzar [9] present a numerical study of blood flow in part of the human vascular system. In the numerical analysis, the Navier–Stokes equations were used as the governing equations of blood flow to calculate the velocity field and pressure distribution in the blood. And also, based on computational fluid dynamics methods, some authors have carried out work on non-Newtonian

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blood flow [10], pulsating flow [11-12] and even reconstructed from a realistic artery with experimental data [13-15].

Thus, an important problem of modern medicine is the creation of effective methods of treatment and prevention of cardiovascular diseases. Mathematical and computer modeling plays a huge role in their development. The methods of which, without prior intervention in the body, make it possible to predict the consequences of surgical operations and pathologies, optimize the shape of implants, and investigate their effects on hemodynamics.

2. Mathematical modeling of the process of blood movement in the human cardiovascular system

The flow of blood in the circulatory system is described by following equations:

$$divv = 0 \tag{1}$$

$$\rho \frac{\partial v}{\partial t} = \rho f + div\Sigma \tag{2}$$

where v – velocity vector, $[m/sec]$; ρ – blood density ($\rho = const$), $[kg/m^3]$; t – time $[sec]$; f – density vector of mass forces (assume $f = 0$), [N]; Σ – stress tensor, $[Pa]$.

The motion of a viscous fluid is described by the Navier-Stokes equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = \frac{1}{\rho}\frac{\partial P}{\partial x} + \eta\Delta u + g_x \tag{3}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \eta\Delta u + g_y \tag{4}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \eta\Delta u + g_z \tag{5}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{6}$$

where t – time, $[sec]$; x, y, z – coordinates of the liquid particle; $u_{i,j,k}, v_{i,j,k}, w_{i,j,k}$ – projections of its velocity, $[m/sec]$; g_x, g_y, g_z – projections of the volumetric force, $[m/sec^2]$; η – dynamic viscosity coefficient, $[Pa * sec]$; $P(x,y,z,t)$ – pressure, $[Pa]$; ρ – fluid density, $[kg/m^3]$.

Let's introduce a cylindrical coordinate system so that the axis Ox coincides with the axis of the cylinder, and the plane Oyz lies in the section separating the heart and the vessel. Blood moves under the influence of pressure created by the work of the heart. It is natural to assume that it does not depend on the angular coordinate. In this case, the deformation of the walls and the flow of blood will be axisymmetric.

Hydrodynamic resistance is the resistance to the blood flow of the vessel wall and the friction of the blood layers relative to each other. The total peripheral resistance is the resistance of all vessels of the great circle of blood circulation.

Initial conditions of displacement blood movement: $u^0_{i,j,k} = 0;\ v^0_{i,j,k} = 0;\ w^0_{i,j,k} = 0.$

Boundary conditions are:

1. The left boundary of the aorta

$In{:}\ x = 0;\ \frac{\partial f}{\partial x} = 0;\ f(u, v, w, P);\ t > 0$

$u(t, 0, y, z) = u(0,0, y, z)$

$v(t, 0, y, z) = 0$

$w(t, 0, y, z) = 0$

$P(t, 0, y, z) = P(0,0, y, z)$

2. The right boundary of the aorta

$Out\!: x = l_1;\ y = l_2;\ z = l_3;\ \frac{\partial f}{\partial x} = 0;\ f(u, v, w, P);\ t > 0$
$u(t, x, y, z) = u(0, l_1, 0,0)$
$v(t, x, y, z) = u(0,0, l_2, 0)$
$w(t, x, y, z) = u(0,0,0, l_3)$
$P(t, x, y, z) = P(0, l_1, l_2, l_3)$

3. Upper boundary of the aorta

$Top\!: z = z_1;\ \frac{\partial f}{\partial x} = 0;\ f(u, v, w, P);\ t > 0$
$u(t, x, y, z_1) = 0$
$v(t, x, y, z_1) = 0$
$w(t, x, y, z_1) = 0$
$P(t, x, y, z_1) = 0$

4. The lower boundary of the aorta

$Bottom\!: z = -z_2;\ \frac{\partial f}{\partial x} = 0;\ f(u, v, w, P);\ t > 0$
$u(t, x, y, -z_2) = 0$
$v(t, x, y, -z_2) = 0$
$w(t, x, y, -z_2) = 0$
$P(t, x, y, -z_2) = 0$

5. The upper boundary of the aorta in the plaques

$Top\ plaque\!: l = l_1;\ m = m_1;\ \frac{\partial f}{\partial x} = 0;\ f(u, v, w, P);\ t > 0$
$u(t, x, y, z) = 0$
$v(t, x, y, z) = 0$
$w(t, x, y, z) = 0$
$P(t, x, y, z) = 0$

6. The lower boundary of the aorta in the plaques

$Bottom\ plaque\!: l = l_2;\ m = m_2;\ \frac{\partial f}{\partial x} = 0;\ f(u, v, w, P);\ t > 0$
$u(t, x, y, z) = 0$
$v(t, x, y, z) = 0$
$w(t, x, y, z) = 0$
$P(t, x, y, z) = 0$

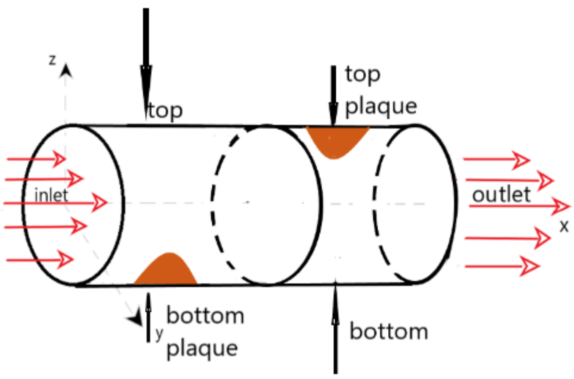

Figure 1: Simplified blood vessel geometry with boundary conditions

3. Pulsation in the laminar flow

In the field of hydrodynamics, a flow that undergoes periodic changes is referred to as pulsating flow or Womersley flow. Pulsating laminar flow is observed in major arterial vessels due to the fluctuations induced by the heartbeat. In experimental settings, this type of flow can be replicated by employing a flow with a periodically varying flow rate while keeping the flow direction constant. The pulsatile flow profile is given in a straight pipe [16]. The arrow indicating the entrance to the artery moves according to the pulsation law.

Using the smoothed particle hydrodynamics (SPH) approach, partial differential equations related to fluid flow are transformed into algebraic equations. The momentum equation can be written as:

$$\frac{\partial v_a}{\partial t} = g - \sum_b m_b \left[\frac{P_b}{(\rho_b)^2} + \frac{P_a}{(\rho_a)^2} - \frac{\xi}{\rho_a \rho_b} \frac{4\eta_a \eta_b}{(\eta_a + \eta_b)} \frac{v_{ab} r_{ab}}{r_{ab}^2 + k^2}\right] \nabla_a W_a b \tag{7}$$

where P_a – pressure of particle a; η_a – fluid viscosity of particle a; $v_{ab} = v_a - v_b$; ξ – factor associated with the viscous term; k – small parameter used to smooth out the singularity at $r_{ab} = 0$; g – the gravity vector.

It is necessary to utilize an equation of state that describes the link between particle density and fluid pressure since the Smoothed Particle Hydrodynamics (SPH) approach used here is a quasi-compressible one. An appropriate one is:

$$P = P_0 \left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \tag{8}$$

where P_0 – magnitude of the pressure; ρ_0 – reference density; for water or blood we use $\gamma = 7$. Then we get the following formula for pulsatile in flow:

$$V_{i+1} = \begin{cases} V_i + 0.5 \sin 4\pi(t + 0.0160236)\,; & t \leq 0.218 \\ 0.1; & t > 0.218 \end{cases} \tag{9}$$

where t – time, $[sec]$; $i = 0 \dots n$.

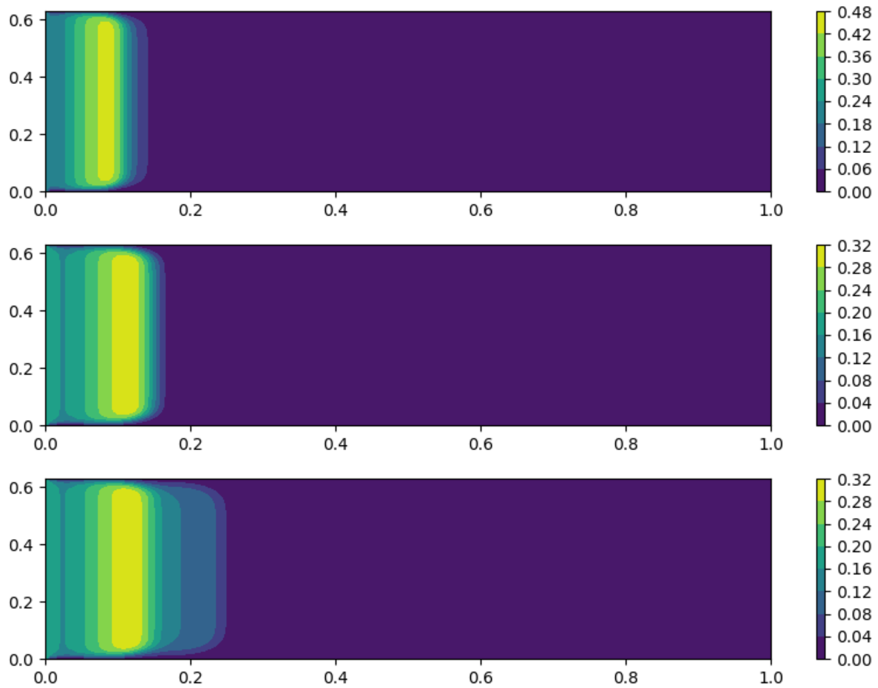

Figure 2: The change in velocity over time in the iterations of the pulsatile function from 800 to 1400

The results of the programming code are shown in Figure 2-3. The graph shows the velocity of the fluid flow in the case of a Newtonian fluid in time. 2000 iterations were launched and the graph shows every 100 iterations.

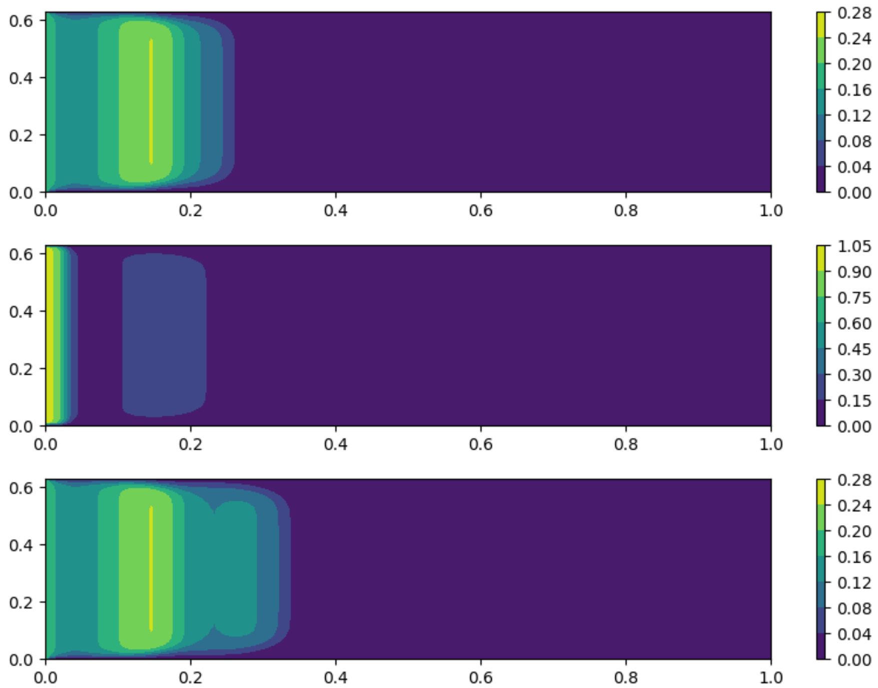

Figure 3: The change in velocity over time in the iterations of the pulsatile function from 1500 to 2000

According to the result (Figure 2-3) of the pulsation function in the form of the formula (2.33), we understand that the pulsation can happen in the range of pulsatile from 0.04 to 1.05 of a person with stable blood parameters, when density - 0.0035 $[kg/m^3]$, viscosity - 1080 $[Pa * sec]$, pressure - 11999 $[Pa]$. Its intensity reaches 0.28 at the front of its pulsation. The pulsation moves from left to right and the source of the ripple is on the left edge of this graph. It starts pulsating to the right side according to the schedule. Reaches intensity in yellow color in the graph.

Further, we will describe the progress of the implementation in the Python programming language of our numerical problem of the Navier-Stokes equation.

4. Software implementation of a numerical model in Python

To solve the numerical problem of the Navier-Stokes equation with the Gauss-Seidel method in Python.

Table shows the constant parameters of our equation for different types of humans. Based on this, we have constructed the following graphs of the ratio of the velocity of fluid movement over time:

Table 1
Hemodynamic constants

Human characteristic	Viscosity $[Pa * sec]$	Pressure $[Pa]$	Density $[kg/m^3]$	Reynold's number
Male	0,0045	15 998	1080	1200
Female	0,0053	16 665	1085	1023
Normal	0,0035	13 332	1050	1500
Sick	0,007	18 665	1200	857

The rate of blood circulation is laminar. The speed of blood circulation in the center of the blood vessel is higher than the speed of movement near the vessel wall. It follows from this that the liquid that flows next to the vessel wall is extremely sedentary, and the subsequent layer of liquid goes at some distance. Unlike all this, a portion of fluid flowing in the center of a blood vessel moves a long distance. As a result, we obtain the energy velocity distribution profile.

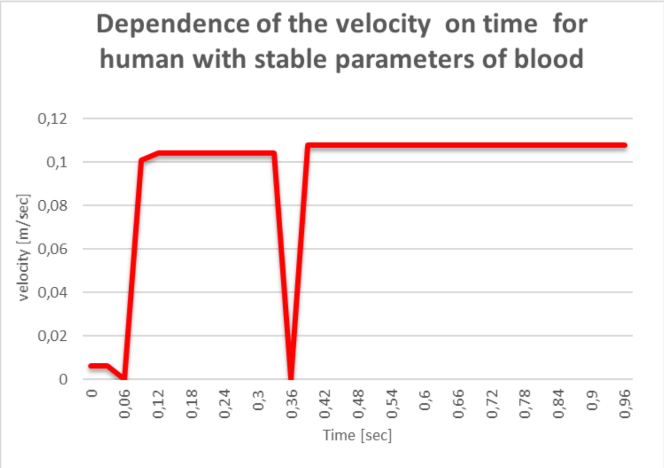

Figure 4: The graph for human with stable parameters of blood

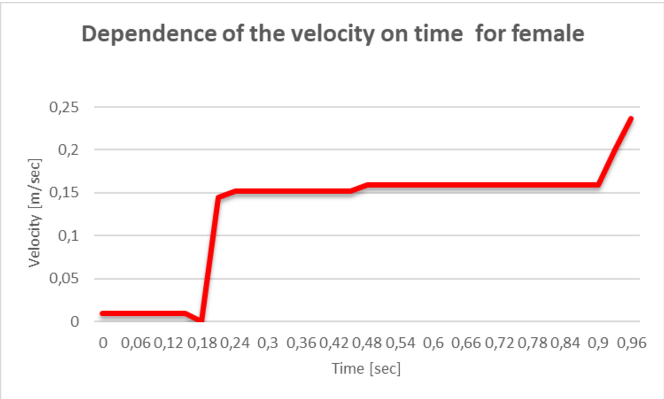

Figure 5: The graph with blood parameters for female

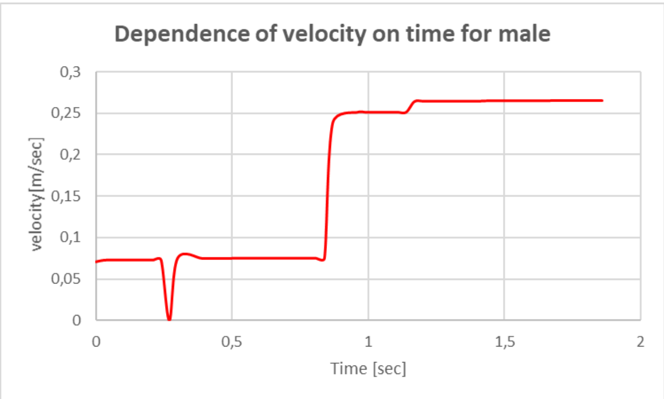

Figure 6: The graph with blood parameter for male

5. Power BI Software environment visualization results

To visualize the data we received, we used the Power BI interface. Our application in Power BI is called "Human blood". The dashboard in Power BI is presented on Figure 7. On the left side we have input data displayed as: density, viscosity and pressure in the form of a filter. Here you can choose different values depending on your condition. Also attached on top is a filter with the ability to select the gender of a person. On the right side, output parameters are described such as: Reynolds number, Poiseuille resistance, blood flow volume and linear bleeding rate and pressure drop.

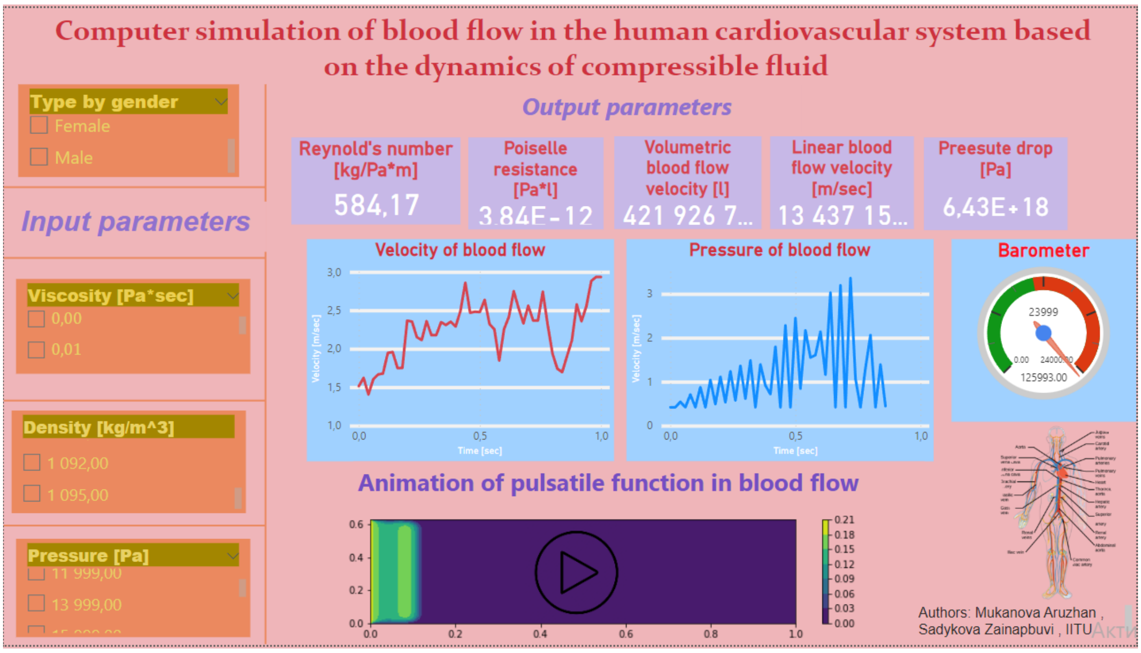

Figure 7: Visualization in Power BI

Input parameters is selected by the user, they can be different, and only after selecting, output parameters will calculate by formula and give results on the screen.

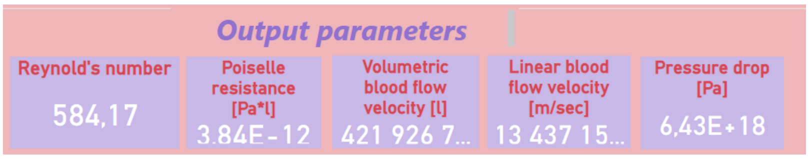

Figure 8: Output parameters of blood

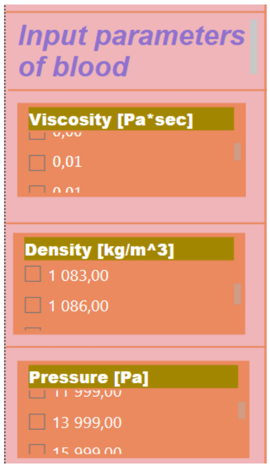

Figure 9: Input parameters of blood

As a result of the output data, the customer will be able to see the graphs below that described the dependence of blood flow velocity on time, the dependence of blood flow pressure on time.

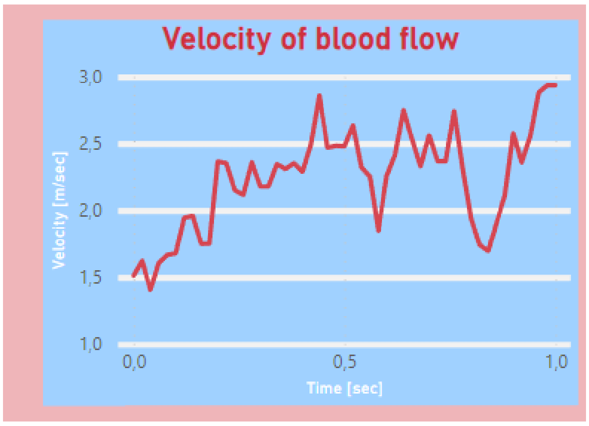

Figure 10: Dependence of velocity of blood flow on time

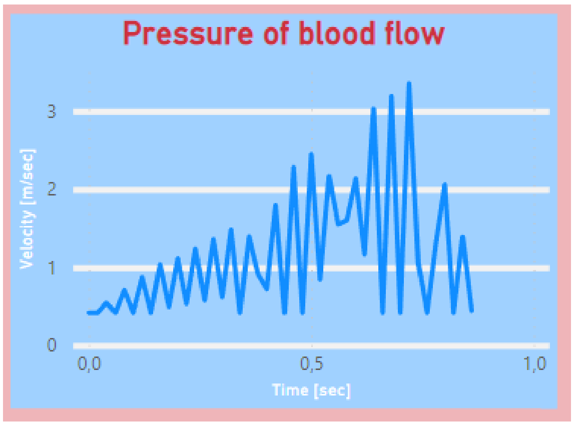

Figure 11: Dependence of pressure of blood flow on time

As a result of calculations, you will be able to see the animated graph that shows the video clips describing changes in blood flow velocity using pulsation.

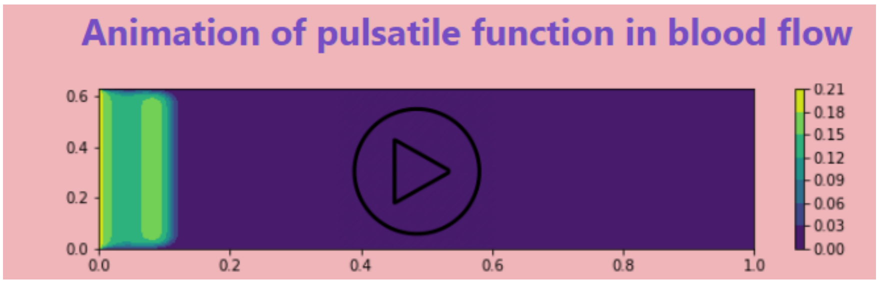

Figure 12: Changes of velocity of blood flow with pulsating function

Also we can see the attached is a pointer barometer showing the level of human pressure liquefied or elevated.

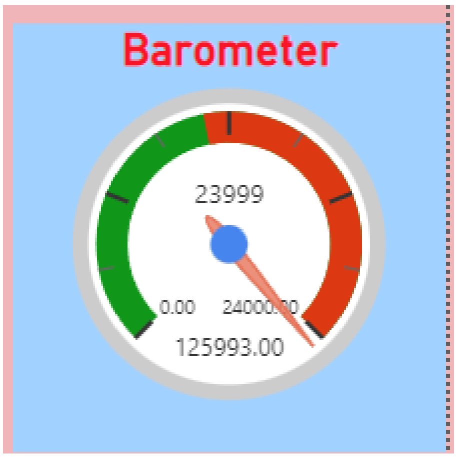

Figure 13: Barometer

Thus, we have created an interface in Power BI that allows all users to track the movement of blood and pulsation in the aorta of the cardiovascular system.

6. Conclusion

In conclusion, the use of mathematical and computer models to study the behavior of blood flow in the cardiovascular system has gained significant attention in recent years. These models provide an opportunity to conduct an almost unlimited number of numerical experiments without danger to the life and health of the subject. Various studies have been conducted to investigate blood flow in blood vessels and arteries, taking into account physical exertion on the human body, stroke during artificial circulation, and blood flows in large blood vessels experiencing a certain pressure range. As part of the research, an analytical assessment of the human cardiovascular system was carried out, and a one-dimensional model of blood flow was proposed, taking into account the Newtonian properties of blood. Based on this model, a program has been developed that allows you to simulate the flow of blood in the vascular system. Our application allows you to view the properties of the blood change by knowing the necessary values of blood characteristics. It could be done with the indication of the doctor where the "Input parameters" are indicated. After that, it is possible to see the results called "Output parameters". Overall, mathematical and computer models provide a powerful tool for understanding and analyzing complex physiological systems easy and fast in form of mobile application.

7. Acknowledgements

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