Development of a Software Package for Analysis of Heart Muscle Activity

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Abstract. Cardiac examinations are becoming increasingly common among all segments of the population. For a more accurate diagnosis, such tools as an electrocardiogram, ultrasound of the heart muscle, as well as computed tomography are used. To understand the processes that occur when a pathology occurs, it was decided to implement the mathematical and 3D models of the heart muscle that are interconnected. These models are individualized. The work of the heart is presented without a hemodynamic system, so the contraction processes are set using programmable spring pistons. The mathematical model was implemented in the MatLab software package. The paper describes the main problems that arose when creating a 3D model of the heart, and how to solve them. The development of the 3D model was carried out in the 3ds Max program, with the help of which not only the model was built, but also the parameterization of the model was considered according to the calculations. This experimental software aims to facilitate the diagnosis and detection of cardiac diseases.

1. Introduction
There are many different methods of diagnosing the state of the human body nowadays, including the diagnosis of individual systems and organs. In addition to medical equipment of various complexity, different computerized diagnostic systems have also been used for diagnostic purposes. Many of them are based on the analysis of data from sensors mounted on the patient's body and the construction of various types of models based on the results of this analysis. Visual analysis, which is based on 3D and 2D models and processing of collected data received with the help of various medical devices (MRI, ECG, EEG, etc.), occupies a large part of diagnostics [1, 6].

In the represented work the software complex for diagnostics of cardiac muscle efficiency has been developed. It is based on the construction of mathematical and 3D models of the organ, and also on the processing of electrocardiogram (ECG) data in MatLab software environment. Processing and further analysis of the ECG signal makes it possible to determine the heart rate (HRF) and to identify the appropriate time intervals, which are required to visualize heart muscle contractions. The mathematical model allows to estimate the pumping function of the heart, atrial and ventricular pressures, as well as their mass and volume. The 3D model of the heart makes it possible to visualize the data of the mathematical model and the contractile function of the heart muscle at the same time.

Because of the foregoing, the aim of this work is the creation of a program complex for the analysis of heart muscle activity. To achieve this aim it is necessary to solve the following objects: to process the ECG signal; to develop a mathematical model of the heart based on pre-determined equations and
required parameters; to develop a 3D model of the heart; to evaluate the functioning of the obtained software complex.

2. Mathematical model of the heart
The main parameters that are necessary for the construction of models are such parameters as atrial and ventricular masses, valve diameters, and average heart muscle sizes. The analysis of the electrocardiogram requires knowledge about the structure of the ECG signal, its main waves, and intervals.

Mathematical models are built on the base of these parameters and the principles of how heart muscle is working. These math models are represented by systems of equations [2]. With the help of these models, it is possible to conduct studies of cardiac muscle activity in order to detect abnormalities.

Several assumptions and simplifications have been made to draw up a cardiac design:

- to consider the stiffness of the heart muscle to be constant;
- to consider the valve opening areas to be constant;
- to consider the mass of fluid moved at valve opening as constant;
- to consider the blood viscosity constant;
- to consider the valves inertial;
- to consider the valve diameter constant;
- to take all physiological parameters close to normal.

Having studied the work of the simulated biological object, i.e. the heart muscle, a scheme reflecting the main parameters was developed. From the technical point of view, the heart is a four-chamber pump with low-pressure atrium pumps and high-pressure ventricular pumps. These pumps are controlled by an autoregulation system represented by a sinus node, atrial node, beam, and Gisa legs [1].

The pumps described above are presented in the form of pistons, due to the lack of hemodynamic system, with two types of valves: suction and discharge [14]. The valve pistons are affected by pulses that cause a reduction in the volume of chambers at intervals compared to the physiology of the heart. The elasticity of vessels associated with atria and ventricles is modeled by cylinders with spring pistons, i.e. elastic chambers of variable volume [5, 16].

This model works as follows: the patient gives his individual data to the doctor, in our case it is the weight. The masses of the heart chambers are calculated, based on these parameters. The program already contains parameters such as piston areas, valve diameters, piston stroke, maximum volumes of heart chambers, and spring stiffness coefficients, which was calculated before diagnostic began [3].

The results are used to calculate piston movement and vessel stiffness. The blood flow rate through the valves is then calculated, which will depend on the ratio of pressure in the heart chambers. After that, the pressure in the veins and arteries is calculated, as well as the pressure in the heart chambers, which allows you to get the final value of blood flow [16, 17]. All the data obtained are individual for each patient, which will further allow using this model for diagnostics. The data also serves as the basis for parameterization and individualization of the 3D model of the heart muscle [5].

Mass of heart has been accepted from a parity 1/220 to the weight of a person's body. The average weight of the heart of men is 332 g, of women - 253 g. Thanks to the task taking into account the given parity it is possible to achieve more exact calculation further. Also for the equations, it will be necessary to determine the masses of ventricles and atria. As the basic part of a heart is in the left half of a body, we accept their weights according to a parity that masses of atria make 1/3 from masses of corresponding halves [15]. The masses of pulmonary artery pistons, aorta, pulmonary vein and hollow vein piston are also included in the mass parameters [1].

The piston areas of the heart chambers in this paper were assumed to be 10 cm² and the piston areas of the veins and arteries to be 10 times larger than the piston areas of the heart chambers. The main parameters also include piston displacement, i.e. their stroke, piston spring stiffness coefficients. Valve diameters were assumed to be 0.02 m. Specific blood density was assumed to be 1060 kg/m³.
The maximum volumes of heart, vein and artery chambers were accepted according to the main parameters of heart physiology [1].

To calculate the basic values, it was assumed that the total mass of the heart is approximately 300 g, which is calculated taking into account the fact that the mass of a person will be 65-70 kg. In this case, the mass of the left half of the heart can be assumed to be 175 g, and the mass of the right half - equal to 125 g, so the ratio of the halves is about 7/12 and 5/12 [13]. The same ratio will be used in the future. To determine the volume of blood ejection it is necessary to calculate the average values of finite-systolic and finite-diastolic volume [1].

Modeling of influence from the side of electric regulation system is represented by the equation of motion of the upper piston and looks like it:

$$ m_1 \frac{d^2 x_1(t)}{dt^2} + h \frac{dx_1(t)}{dt} + k_1 x_1(t) = F_1(t) - P_{RV}(t) \times S_1 \quad (1) $$

where $m_1$ corresponds to the mass of the right ventricle piston;
$x_1$ corresponds to the piston stroke of the right ventricle piston;
$h$ corresponds to the mass flow rate;
$k_1$ corresponds to the stiffness coefficient of the springs responsible for the impact on the piston;
$F_1$ corresponds to the force of the heart’s autoregulation system on the chamber of the heart;
$P_{RV}$ corresponds to the pressure in the right ventricle;
$S_1$ corresponds to the area of the chamber’s piston [7].

Description of vessel stiffness is presented by the equation of piston movement:

$$ m_5 \frac{d^2 x_5(t)}{dt^2} + h \frac{dx_5(t)}{dt} + k_5 x_5(t) = P_{PA}(t) \times S_1 \quad (2) $$

where $m_5$ corresponds to the mass of the pulmonary artery piston;
$x_5$ corresponds to the piston stroke of the pulmonary artery piston;
$h$ corresponds to the mass flow rate;
$k_5$ corresponds to the stiffness coefficient of the springs responsible for the impact on the piston;
$F_3$ corresponds to the force of the heart’s autoregulation system on the chamber of the heart;
$P_{PA}$ corresponds to the pressure in the pulmonary artery;
$S_1$ corresponds to the area of the vein’s piston [8].

For this model, it was decided to neglect the pressure change, as the blood is considered as incompressible liquid [9, 11]. Thus, the equation of chamber volume changes takes the form:

$$ \frac{dV}{dt} = \sum Q_1 - \sum Q_2 \quad (3) $$

where $\frac{dV}{dt}$ corresponds to the volume change over time;
$\sum Q_1 - \sum Q_2$ corresponds to the volumetric flow.

so the fluid flow equation takes the form:

$$ G = \frac{1}{4} \pi d^2 \sqrt{2\rho(P_1 - P_2)} \quad (4) $$

where $G$ corresponds to the blood flow rate;
$d^2$ corresponds to the bore diameter;
$\rho$ corresponds to the blood viscosity;
$P_1, P_2$ corresponds to the pressure in the heart’s chamber.

According to the law of energy conservation, all the useful work of the heart goes into the energy of the blood. Thus, the full work of the heart behind the systole can be expressed as the sum of kinetic and potential blood energy. However, in the calculations, it was decided to neglect the kinetic part, as it is only 2-5% [1].
Therefore, the equations that describe the change in pressure in the right ventricle and pulmonary artery will take the following form:

Equation of pressure in the right ventricle:

\[
\frac{dP_{RV}(t)}{dt} = \frac{P_{RV}(t)K}{S_1|x_01-x_1(t)|} \times \left\{ \frac{1}{\rho} \left[ G_1(t) - G_2(t) \right] + S_1 \frac{dx_1(t)}{dt} \right\};
\]

where \( K \) corresponds to the correction factor;
\( x_01 \) corresponds to the maximum volume of the heart’s chamber.

Equation of pressure in the pulmonary artery:

\[
\frac{dP_{PA}(t)}{dt} = \frac{P_{PA}(t)K}{S_5|x_05-x_5(t)|} \times \left\{ \frac{1}{\rho} \left[ G_2(t) - G_3(t) \right] + S_5 \frac{dx_5(t)}{dt} \right\};
\]

where \( K \) corresponds to the correction factor;
\( x_05 \) corresponds to the maximum volume of the artery.

Equations for all heart chambers are made similarly.

The results are used to calculate piston movement and vessel stiffness. Blood flow through the valves is then calculated, which will depend on the ratio of pressure in the heart chambers. The pressure in the veins and arteries is then calculated, and the pressure in the heart chambers is calculated to obtain the final blood flow rate. All the data obtained are individual for each patient, which in the future will allow using this model for diagnosis. The data also serves as a basis for parameterization and individualization of the 3D-model of the heart muscle.

Figure 1. Principle of data exchange between models.

3. 3D-model of the heart
In this paper, we consider the construction of a 3D model of the heart muscle in the 3ds Max software from Autodesk. This program was selected based on several criteria, based on what is most convenient for building.

The first and main stage of building a three-dimensional model of the heart is the study of the anatomical structure of the organ. Having considered the structure of the organ, it is fashionable to divide it into several parts theoretically for the convenience of construction: the outer shell of the heart - the pericardium is divided into myocardium and epicardium, which allows you to break the construction of the model into two large parts, it is also necessary to visualize the large veins and arteries coming out of their hearts, and several small veins and arteries on the surface of the organ. As a result, the structure of the organ is divided into four main parts:
• myocardial imaging;
• visualization of the epicardium;
• visualization of large arteries and veins;
• visualization of small veins and arteries on the pericardium surface [1].

In this paper, we used a polygonal model of heart construction. The basis for the construction was the plane from which the myocardium was built [9, 10]. After building the plane, it was squeezed out, which allowed you to create a three-dimensional base figure. By breaking up large polygons into smaller ones and changing their shape to and location, a fragment similar to a myocardium in shape was built.

Then on the basis of the received figure surfaces of atria together with left and right ears are constructed. Atrial planes are relatively simple to construct because they do not have a large number of complex inflections. Left and right ears, in turn, are completed on the atrial surface as a complex part, with the use of offset polygons, without smoothing, has an angular shape, so to increase accuracy, they are divided into smaller asymmetric polygons [2].

After the pericardium is built, large arteries and veins are built on its surface [16, 17]. For them, a part of the surface polygons at the base of the vessel is combined, which is transformed into a rounded polygon of the required diameter. This polygon is stretched out to the size we need, and it is also shaped by shifting and modifying the planes.

After that, smaller vessels are completed on the surface, including the crown sinus, without the use of smoothing they have a complex broken shape.

Then additional partitioning and smoothing will be applied to obtain the required surface shape and increase the accuracy of the construction.

![Polygonal Heart Model](image)

**Figure 2.** Polygonal heart model general view for printing.

4. **Benefits of the model**
The developed model can be parameterized according to the individual parameters obtained during the examination of the patient, which will allow to visualize the organ for a more detailed analysis of the disease, or so that the doctor could explain the cause of the disease to the patient in a more accessible way, showing the patient the difference between the activity of the heart muscle in normal condition and in case of illness. Also, this model can be printed on a 3D printer both in general view and in parameterized form. Printing of the parameterized organ will give an opportunity to perform "test" surgical intervention, if it is necessary for the patient, in complex clinical cases in cardiac surgery. Parameterization of the model is carried out according to the data calculated in the MatLab program at construction and calculation of mathematical model of heart.
5. Conclusions
Active research is currently underway in the field of printing of donor internal organs. This development will allow to print an organ with the most suitable dimensional parameters for the patient, which in turn will allow us to solve the problem of internal organs transplantation.

As a result of the work, a model was created that not only displays the pumping function of the heart, but also reflects the output values such as blood flow in the veins and arteries, and the level of pressure in the chambers of the heart. This model allows to calculate parameters such as heart weight, weight of heart chambers individually for each person. The resulting mathematical and 3D models of the heart muscle can be used in various fields of science and education. For example, to calculate and visualize organ resistance to various external influences, or as a teaching aid in biology and anatomy.

References
[1] Alexandrov S, Lyamina E and Date D 2018 Journal of Physics: Conference Series 1063(1):12012
[2] Swan E S and Nemushchenkova N I 2005 Ventriclelular and atrial models Biotekhn, medical and ecological systems, and complexes
[3] Petrova L 2018 Journal of Physics: Conference Series vol 1051 012025 p 1–8
[4] Stadnik N E and Dats E P 2018 Journal of Physics: Conference Series vol 991 p 012075
[5] D Paul, R Velmurugan, R Jayaganthan et al 2018 Journal of Physics: Conference Series vol 991 p 012064
[6] Michael J Shea 2017 Electrocardiography (University of Michigan) https://www.msdmanuals.com/professional/cardiovascular-disorders/cardiovascular-tests-and-procedures/electrocardiography
[7] Barabanov S V, Evlakhov V I, edited by Tkachenko B I 2014 Heart Physiology: Manual by edition of St. Petersburg SpesialLitt
[8] Litvin AV and Ananchenko V N 2012 Computer analysis of biomedical signals and images: textbook DSTU Rostov-on-Don: IC DSTU p 190
[9] Nikanorov B A and Indyukhin A F 2010 Mathematical modeling of biotechnological systems: manual for universities TSU Tula: Publishing house of TulSU p 113
[10] Omelchenko V P Kurbatova E V and Tsybri I K 2015 Biophysical foundations of living systems: textbook. manual DSTU Rostov-on-Don: IC DSTU p 148
[11] Amosov N M 1968 Modeling of complex systems: textbook for universities Kiev Naukova Dumka p 392
[12] Barabanov S V and Evlakhov V I et al edited by Tkachenko B I 2001 Heart Physiology: Manual St. Petersburg: SpetsLit p 143
[13] Julia Tian, Asif Uddin, and Philippe Akhrass 2019 Creative Commons Attribution License, USA https://doi.org/10.1155/2019/5637638
[14] Ali Jalali, Gerard F. Jones, Daniel J. Licht and C. Nataraj 2015 Research Article Application of Mathematical Modeling for Simulation and Analysis of Hypoplastic Left Heart Syndrome (HLHS) in Pre- and Postsurgery Conditions (Creative Commons Attribution License, USA), Retrieved from http://dx.doi.org/10.1155/2015/987293
[15] A. Quarteroni, A. Manzoni and C. Vergara 2017 The cardiovascular system: Mathematical modelling, numerical algorithms and clinical applications (Cambridge University Press) https://doi.org/10.1017/S0962492917000046
[16] Francisco J Chorro Gasco 2005 Mathematical Modeling and Simulations to Study Cardiac Arrhythmias (Cardiology service, University Clinical Hospital) https://www.revespcardiol.org/en-mathematical-modeling-simulations-study-cardiac-articulo-13070826
[17] VladimirTregubov andSvetlana Rutkina 2018 Mathematical modelling of pulsative blood flow in deformable arteries https://cyberleninka.ru/article/n/mathematical-modelling-of-pulsative-blood-flow-in-deformable-arteries