Исследование эллиптической геометрической модели сердца для компьютерной многоканальной электроимпедансной кардиографии

1st Alexey N. Tikhomirov
Bauman Moscow State Technical University
Moscow, Russia
tikhomirov.an@bmstu.ru

2nd Andrey Briko
Bauman Moscow State Technical University
Moscow, Russia
briko@bmstu.ru

3rd Nikolay Seleznev
Bauman Moscow State Technical University
Moscow, Russia
seleznev.nv@bk.ru

4th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

5th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

6th Given Name Surname
dept. name of organization (of Aff.)
name of organization (of Aff.)
City, Country
email address or ORCID

Аннотация—абстракт

Index Terms—component, formatting, style, styling, insert

I. Introduction

Stroke volume (SV), cardiac output (CO), and ejection fraction (EF) are crucial parameters for CVS assessment. These parameters highlight the circulatory dynamics of the heart.

Circulatory parameters in clinical research and practice are assessed with CT, MRI, and ultrasound. These methods provide loads of valuable diagnostic information on the heart. However, continuous monitoring is not possible with these methods for financial and dosimetric reasons.

Thermal dilution through pulmonary artery catheterization (PAC) is a golden standard of SV determination. However, a set of non- or minimally invasive procedures extensively [Kobe, Mishra 2019].

LiDCO uses the minimally invasive method: lithium chloride dilution [Linton, Band 1993]. Despite its minimal invasiveness, this method has a drawback: the system should be calibrated every 8 hours or if the hemodynamic condition has changed. Also, one of the counter-indications of LiCl dilution is intolerance to lithium. PiCCO and FloTrac use contour analysis of the pressure curve, which is accessed invasively via the catheter. Valve regurgitation, severe arrhythmia, and rapid changes in body temperature may affect the accuracy of measurements.

The reported study was funded by RFBR according to the research project No 18-29-02042.

Electrical impedance methods of the CVS study are non-invasive and inexpensive. Among them are transthoracic methods, electrical impedance tomography, and precardial impedance cardiac plethysmography.

Transthoracic electrical impedance plethysmography (TEIP) traces back to the middle of the XX century and is now used with minor changes in such apparatus as CardioScreen (Medis) and Rheo-Spectre (Neurosoft). Non-invasive methods have fewer complications to use, but not without drawbacks. The TEIP method is used to assess changes and trends in assessing blood parameters and not determine the absolute values.

Impedance cardiography (ICG) applies to both the lungs and the heart studies. The main disadvantage is low spatial resolution in terms of assessing heart hemodynamics problem.

In 2002, a precardial mapping technique was proposed to expand on electrical impedance methods for heart studies.

II. Materials and methods

A. Precardial Impedance Cardiography Methods

The precardial impedance cardiography combines several methods. Firstly, precardial radial mapping method. The electrode systems are located along the ventricle projection border onto the chest surface, perpendicular to the border. Secondly, longitudinal-transverse mapping, in which one electrode system is located on the chest's surface above the heart along the heart's anatomical axis, and the other is perpendicular to the axis.

Precardial impedance cardiography is based on the inverse problem of the electrical impedance measurements. The geometric model is built based on the a priori anatomical data, generally provided via the CT or MRI. The heart is modeled with a sphere, ellipsoid, or more complex geometry. The heart's contraction is represented by changing the parameters of the model, such as the radius of the sphere. The experimentally recorded changes in electrical impedance during the heart contraction are converted into changes in the geometric model parameters based on the solution of the inverse problem, and then the volumetric characteristics are estimated.

The complexity of the chest and heart's geometric model forms a larger number of parameters that describe the contraction of the heart in more detail. However, this requires a larger number of electrode systems to obtain data for solving the inverse problem of electrical impedance measurement.

Hence, a more complex model allows one to obtain more information and requires more electrode systems. A simpler model requires fewer electrode systems but is limited in capabilities. It is necessary to find a compromise between the model's complexity and the output information of the model.

In the monitoring of circulatory characteristics, the vanity and simplicity of the technique are often more critical. This paper compares two geometric models of a homogeneous half-space with a sphere and ellipsoid inclusions. Both models are considered for the method of precordial longitudinal-transverse cardiac mapping.

B. Ellipsoid and Sphere models

In the simulation, the heart's blood is often represented as the sphere in electrical impedance measurement problems, as well as in precordial mapping methods and electrical impedance tomography of the heart.

This model is quite simple. According to the tomography data, the sphere's parameters are determined - the radius and coordinates of the center. The heart's contraction corresponds to a change in the radius of the sphere and center's offset.

Using the ellipsoid model allows for a better approximation of blood in the heart before the onset of ventricular systole.

However, the number of model parameters increases - three semiaxes of the ellipsoid, coordinates of the center, and rotation of the ellipsoid in space compared to one radius and the center's coordinates. The heart's contraction corresponds to a change in the semiaxes of the ellipsoid and a shift in its center. Also, the ellipsoid can be spatially rotated during contraction.

The models' geometric parameters were obtained from the data of a CT of a healthy volunteer. The study of multispiral computed tomography was carried out in Pirogov Moscow City Clinical Hospital №1 with Toshiba Aquilion PRIME 160 and under the patronage of employees of both the clinic and the medical center of the BMSTU medical center.

The study was carried out with the introduction of an iodine-containing contrast agent Optiray 350 mg, 90 ml for the study on inspiration and 90 ml for the study on exhalation, 50 ml at a rate of 3.5 ml/sec, and 40 ml at a rate of 3 ml/sec.

The study was carried out on free expiration. As a result of these studies' reconstruction, sets of slices with a time resolution of 20 series per cardio cycle were obtained, which gives about 35-50 ms between the series. The distance between the axial slices was 2.5 mm. The sets of sections were used to reconstruct a 3D model of blood in the heart.

C. Sphere and Ellipsoid Approximation

The parameters of the sphere and ellipsoid were obtained by approximating 3D models of the heart's blood.

The sphere was approximated by the criterion of the least square deviation of the sphere boundaries and real 3D geometry.

Approximation criterion ??, p_i - a finite set of points on the surface of a 3D heart model, $dist(p_i, Z(f))$ - distance from the point p_i to the surface of the sphere $Z(f)$.

$$\sum_{i=1}^{q} dist(p_i, Z(f))^2 \to min \tag{1}$$

The ellipsoid was obtained according to the criterion described in . The method is peculiar because authors consider the distance from a point to the ellipsoid $dist(p_i, Z(f))$ as follows: the difference between 1) the distance from the center of the ellipsoid to the point and 2) the distance from the center of the ellipsoid to a point on its boundary. The said point is lying on the ray outgoing their center and passing through a given point. This assumption's error is estimated depending on the ratio of the ellipsoid semiaxes, and an adjustment is made. The final optimization criterion is also the least square method (2).

Analysis of the results and visualization of the approximation showed that the septa of the heart, such as the interventricular septum, the atrioventricular septum (Fig. ??) forms points that distort the approximation results, causing an increase in the average deviation of the surface of the approximating ellipse or sphere from the outer boundary of the 3D blood model. To eliminate this problem, it was decided to fill in the original 3D models of the heart partitions and internal voids. For this, the 3D model was laid out on 2D images obtained by sectioning by planes parallel to the X and Y axes (Fig. ??). Then a tangent path traversal was made of the 2D image contour with a circle radius of 20 mm (red circle), as a result of a set of obtained sections filled with septum was going to the 3D image of the heart (Fig. ??).

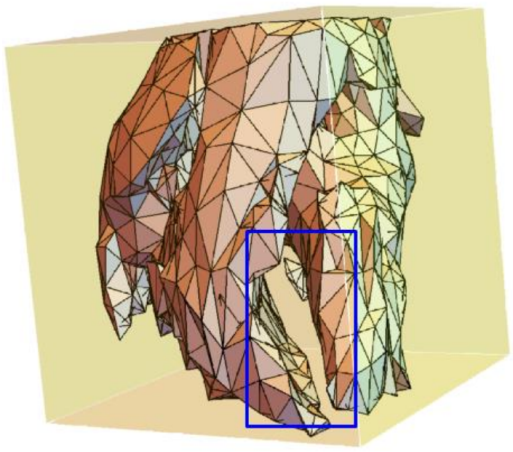

Рис. 1. 3D model of blood in the heart (interventricular septum highlighted in blue)

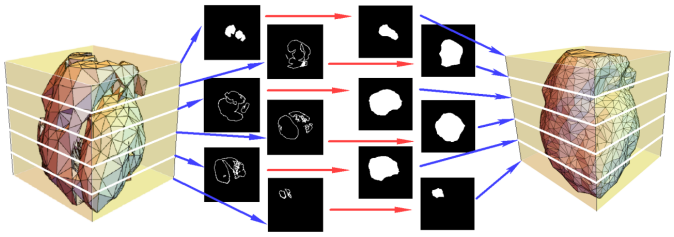

Рис. 2. Algorithm for filling the septa of the heart in the 3D model of the heart's blood (on the left - the original 3D model, on the right - the 3D model after filling the septa)

III. Modelling

IV. Electrical Impedance modelling parameters

To analyze the obtained geometric models, electrical impedance modeling was carried out in the Comsol Multiphysics CAD. The location of the electrode systems during modeling corresponded to the location of the electrode systems during longitudinal-transverse mapping. The distance between the current electrodes varied from 80 to 240 mm, and the ratio of the distance between the current electrodes to the distance between the potential ones was 2 to 1.

Values of resistivity of inclusion and homogeneous half-space are presented in the table ??.

Таблица I
Resisitivity values at 100 kHz used in the model study

Tissue	Resistivity values, $\Omega \cdot$ m	Resistivity value in simulation, $\Omega \cdot$ m
Blood (Hct=50)	1.35 [21]	1.35
Myocardium	4.6 [20]	4.2
Muscles	2.7 [20]	
	1.5 – 25 [19]	
Lung (deflated)	3.68 [20]	
Lung	1.6 – 10 [1]	
Human thorax (average)	4.63 [19]	

The averaging of the specific resistances of the lung, muscle tissue, and myocardium is possible since measurements are considered in the phase of calm expiration, and the specific resistance of the lung tissue on expiration approaches the specific resistance of muscle tissue.

A. Comparison of the 3D model with sphere and ellipsoid

Several parameters were used to compare the models themselves and the results of modeling the real 3D geometry of blood in the heart, sphere, and ellipsoid. First, a comparison of the change in the volume of blood in the heart was made. the volume of a real 3D model was compared with the volumes of the approximating sphere and ellipsoid. The volumes were estimated for each of the 20 points when the cardio cycle was split. Second, the movement of blood volume in the heart as a whole was considered, i.e. the movement of the center of mass of a real 3D model and its approximating figures. Third, the electrical impedance change dependencies during the cardiac cycle were compared for different positions and sizes of electrode systems.

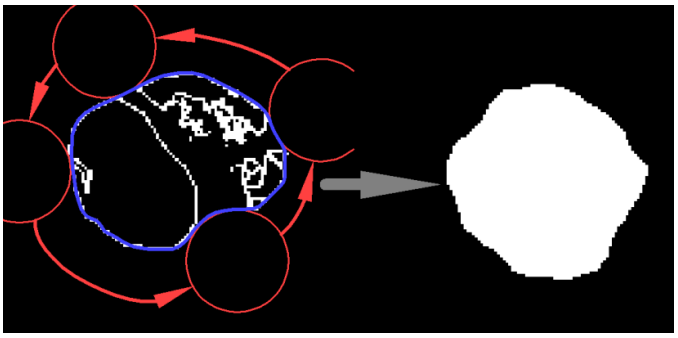

Рис. 3. Tangent path traversal of a 2D image with a circleto fill heart's semptum in the 3D models of heart's blood (on the left is white contour beforethe septum filling, on the right side - after the filling)

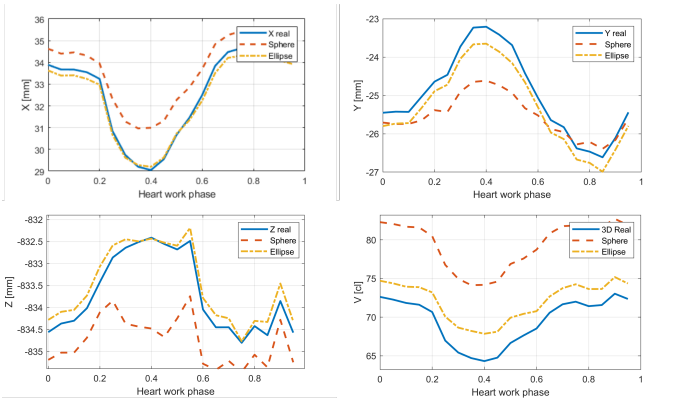

Рис. 4. Change during the cardiac cycle of the coordinates of the center of mass (X, Y, Z) and volume of the original 3D model, sphere and ellipsoid

V. Results

The dependences of the change in the volume and coordinates of the center of mass of the original 3D model, and the sphere and ellipsoid are shown in Fig. ??, where the t-axis is R-to-R interval of cardiac cycle.

The simulation results of impedance changes during the cardiac cycle are presented in Fig. ??, Fig. ??, Fig. ??. For each model, dependences are presented for the electrode system located along the heart's anatomical axis and perpendicular to it. These graphs also consider the cardiac cycle from R-wave to R-wave.

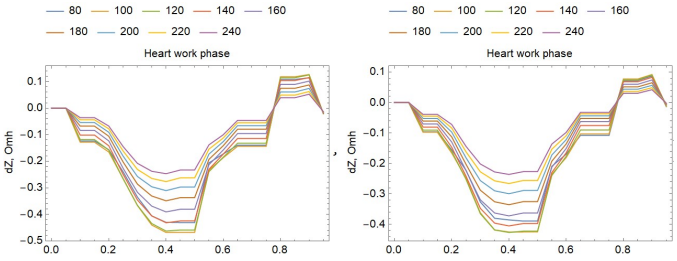

Рис. 5. Dependence of electrical impedance changes during the cardiac cycle for the initial 3D model (location of the electrode system along the heart axis - to the left, perpendicular to the heart axis - to the right)

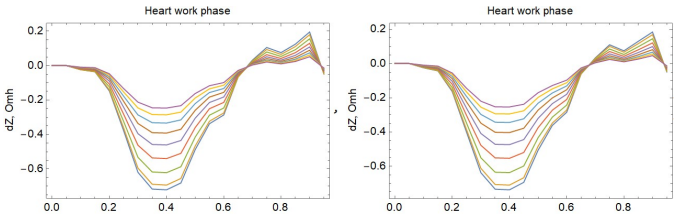

Рис. 6. Dependence of electrical impedance changes during the cardiac cycle for a spherical model (the location of the electrode system along the heart axis - to the left, perpendicular to the heart axis - to the right)

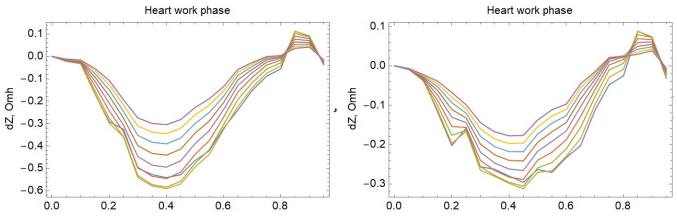

Рис. 7. Dependence of electrical impedance changes during the cardiac cycle for an elliptical model (the location of the electrode system along the heart axis - on the left, perpendicular to the heart axis - on the right)

VI. Discussion

When comparing the motion of the center of mass of the original 3D model and the approximating sphere and ellipsoid from Fig. ?? it is seen that the center of mass of the ellipsoid moves in accordance with the center of mass of the 3D model. The sphere's movement qualitatively corresponds to the movement of the 3D model, but quantitatively it differs - less amplitude. The ellipsoid volume differs by an average of 3-5% during the cardiac cycle; for a sphere, the difference reaches 12-15%. This effect can influence and introduce additional errors in assessing hemodynamic characteristics based on the sphere's geometric model.

The waveforms of the electrical impedance modeling signal for the sphere and the ellipsoid qualitatively correspond to the initial 3D model waveform but differ significantly in amplitude characteristics. For a numerical assessment of the obtained simulation results, the value of the impedance change during ventricular systole ΔZ was compared. The difference in values in Fig.?? at the time points corresponds to 0% and 40% of the cardiac cycle (beginning and end of ventricular systole). For small electrode systems (80-120 mm), ΔZ for a 3D model differs by % from ΔZ for a sphere and % from ΔZ for an ellipsoid. For large electrode systems (200-240 mm), ΔZ for a 3D model differs by % from ΔZ for a sphere and % from ΔZ for an ellipsoid.

VII. Conclusion

Studies have shown that for a given volunteer, an elliptical geometric model of the heart's blood approximates the heart's real 3D geometry with an error of 3-5% and is preferable when assessing hemodynamic parameters. Simultaneously, electrical impedance modeling showed that when using electrode systems 80-120 mm in size, it is preferable to use an elliptical geometric model, and when using large electrode systems 200-240 mm, it is preferable to use a spherical geometric model. Since electrode systems with sizes over 180 mm are usually used for precordial longitudinal-transverse mapping, it is necessary to use a spherical mathematical model.

The conclusions are valid for this volunteer. At the moment, studies are underway on three more healthy volunteers to evaluate the findings.

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