Solving direct and indirect tasks of tissue modelling in the precardiac area

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Abstract — Medicine is going to use noninvasive instrumental methods where they are possible. Precardiac rheocardiogram technique could be considered as an additional tool for ultrasound or even as a self-dependent procedure for the determination of heart’s functionality. In precardiac rheography method’s development it is essential to solve several tasks: direct task and indirect task. Solving direct and indirect tasks in the precardiac rheocardiography (preRCG) and calculating parameters of the heart’s model, we can estimate location of the heart and also determine its biomechanical parameters.

Keywords— Precardiac rheocardiography, impedance monitoring, tissue modelling

1. Introduction

It is difficult to overestimate the importance of state-of-the-art and precise heart diagnostics, such as the determination of disorders in the hemodynamic function of a cardiovascular system. It is associated with a large number of lethal outcomes as a result of heart diseases. It is significant that heart diseases rank among the world’s most dangerous diseases. Stress and bad ecology aggravate the situation. Hence, it is necessary to develop some medicotechnological solutions which could allow us to control hemodynamic parameters for a long time.

There are a lot of invasive and noninvasive methods to determine the cardiovascular system’s functioning parameters. Nowadays medicine is going to use noninvasive instrumental methods where they are possible. Thus, the precardiac rheocardiogram technique could be considered as an additional tool for ultrasound or even as a self-dependent procedure for the determination of heart’s functionality. In precardiac rheography method’s development it is essential to solve several tasks, one of these being the distribution of electric potentials modeling in the precardiac area (direct task) and the other one being the determination of model parameters by means of these distributions (indirect task).

Thereby, solving direct and indirect tasks in the precardiac rheocardiography (preRCG) and calculating parameters of the heart’s model, we can estimate the location of the heart and also determine its biomechanical parameters, such as stroke volume, heart-rate etc.

2. Precardiac rheocardiography technique

Examinations carried out are connected with tool elaboration to determine cardiovascular system’s functioning parameters by using impedance methods. At the same time measurements are realized in the precardiac area, since such allocation of current and measuring electrodes allows increasing method’s precision.

The essence of this technique is that for measurement purposes 4 electrodes usually have to be applied to the body surface. Two electrodes (usually called current electrodes) are used to pass a constant alternating current with a high frequency (60 - 100 kHz) and very low amplitude (1 mA). The current is imperceptible to the patient and does not cause any physiological reactions. The other two electrodes (usually called measuring electrodes) are placed between the current electrodes and measure the voltage which is caused by the current flowing through the body segment. This voltage corresponds to the impedance of the body segment and changes in blood volume variations. On this basis the blood flow can be measured and analyzed.

Two biological tissue models are used for solving direct and indirect task in precardiac rheography method:

- Precardiac area is considered as horizontally layered medium with two layers: upper layer (thickness \( h_1 \) and specific resistance \( \rho_1 \)) and lower layer (semi-infinite layer with specific resistance \( \rho_2 \)) – two-layered model
- Precardiac area is considered as horizontally layered medium with three layers: upper layer (thickness \( h_1 \) and specific resistance \( \rho_1 \)), middle layer (thickness \( h_2 \) and specific resistance \( \rho_2 \)) and lower layer (semi-infinite layer with specific resistance \( \rho_3 \)) – three-layered model

Besides, we take into the following considerations for polylayer model’s construction:

- Electrical properties of each layer are invariant under direction
- Employed electrodes are dotty and they are placed on the surface of the upper layer
- Field function caused by the current electrodes meets the Laplace's equation everywhere, excepting placement of the current electrodes.
2.1. Direct task

Provided poly-layer model using we consider tissue compound, which contains muscle tissue \((\rho_{\text{muscle}} = 5 \text{ Ohm} \cdot \text{m})\), pulmonary tissue \((\rho_{\text{pulm}} = 8 \text{ Ohm} \cdot \text{m})\), myocardium \((\rho_{\text{myo}} = 5 \text{ Ohm} \cdot \text{m}, h_{\text{myo}} = 0.02 \text{ m})\) and bone tissue \((\rho_{\text{bone}} = 10 \text{ Ohm} \cdot \text{m})\). In case of two-layered model this compound is replaced by effective specific resistance \(\rho_{i}\), upper layer’s thickness is determined by occurrence depth of the heart, \(h_{i} = 0.1 \text{ m}\), and specific resistance of lower layer corresponds with specific resistance of blood \((\rho_{\text{blood}} = 1.0-1.5 \text{ Ohm} \cdot \text{m})\). In case of three-layered model we consider myocardium layer as separate layer.

The major mathematical modeling of preRCG involves calculation of the forward and inverse problems. In the forward problem the governing equations in the preRCG field are derivable from Laplace’s Equation (electrostatic approximation for low frequency).

A three-layered model will be considered in this section, because such mould imitates precardiac area properties very well. A three-layered heart’s model is shown in Fig.1. In points A and B current electrodes are placed, measuring electrodes are placed in points M and N, respectively.

![Fig.1. Three-layered heart’s model](image)

In case of cylindrical symmetry of the model, Laplace’s Equation is written as:

\[
\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (2.1.1)
\]

To solve equation (2.1.1) we can make use of the boundary conditions, i.e. the potential’s continuity and current density’s normal component’s continuity at the bedding interface. Besides, we take into consideration that air is not a good electrical conductor and potential at infinity must be equal to 0 (2.1.2)

\[
\phi|_{z=h} = \phi_{i+1}|_{z=h} \quad (2.1.2)
\]

By using these boundary conditions the expression for impedance on the body’s surface is:

\[
R(a, b) = \frac{D_1}{\pi} \left[ \frac{1}{a^2 - b^2} + \int A_1(m) \cdot J_0[m \cdot (a - b)] \, dm - \int A_1(m) \cdot J_0[m \cdot (a + b)] \, dm \right]
\]

\[
A_1(m) = \frac{N}{D_1 + D_2}
\]

\[
N = (\rho_2 - \rho_1) \cdot (\rho_3 + \rho_2) \cdot e^{-4m \cdot h_1} + (\rho_2 + \rho_1) \cdot (\rho_3 - \rho_2) \cdot e^{-4m \cdot h_i - 2m \cdot h_2}
\]

\[
D_1 = (\rho_1 + \rho_2) \cdot (\rho_3 + \rho_2) \cdot e^{-2m \cdot h_1} + (\rho_2 - \rho_1) \cdot (\rho_3 - \rho_2) \cdot e^{-2m \cdot h_i - 2m \cdot h_2}
\]

\[
D_2 = (\rho_1 - \rho_2) \cdot (\rho_3 + \rho_2) \cdot e^{-4m \cdot h_i} + (\rho_1 + \rho_2) \cdot (\rho_2 - \rho_3) \cdot e^{-4m \cdot h_i - 2m \cdot h_2}
\]

Final impedance vs. range between current electrodes relationship is shown in Fig.2 (range between measuring electrodes is 0.05 m).
2.2. Indirect task. Apparent resistivity conception.

For homogeneous half-space with specific resistance $\rho(r)$ relationship looks:

$$\rho(r) = \frac{2 \pi r^2}{I} \frac{\partial \Phi_1(r, 0)}{\partial r}$$  \hspace{2cm} (2.1.5)

In case of tetrapolar gradient electrode system (Fig.1), provided $MN \ll AC$:

$$\rho \approx \frac{\pi AM \cdot AN}{MN} = \frac{\pi (a - b)(a + b)}{2b} \cdot R_{MN}$$  \hspace{2cm} (2.1.6)

If medium is not homogeneous $\rho$ is called apparent resistivity. It is denoted $\rho_k$. For two-layered model:

$$\rho_k = \rho_1 \left[ 1 + 2 \sum \frac{K_{n, r}^2}{\left(r^2 + 2n \cdot h_1 \right)^{1/2}} \right]$$  \hspace{2cm} (2.1.7)

If $r \ll h_1 \rho_k \approx \rho_1$, and so if $r \to \infty \rho_k \to \rho_2$.

Apparent resistivity vs. half-range between current electrodes dependence is shown in Fig.3 ($\rho_2$ variable) and Fig.4 (h1 variable).

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Fig.2 Impedance vs. range between current electrodes (distance between measuring electrodes equals 5 cm)

Fig.3. Set of dependencies apparent resistivity vs. half-range between current electrodes (three-layered model, $\rho_1 = 8 \text{ Ohm} \cdot \text{m}, \rho_2 = 400-600 \text{ Ohm} \cdot \text{m}, \rho_3 = 1.35 \text{ Ohm} \cdot \text{m}, h_1 = 0.09 \text{ m}, h_2 = 0.02 \text{ m}$).
Thus, the indirect task is the determination of model parameters by means of impedance distributions. In order to determine the model’s parameters by using impedance distribution we make use of the apparent resistivity conception. We need to determine 3 parameters ($\rho_1$, $\rho_2$, $h_1$) of two-layered model and 5 parameters ($\rho_1$, $\rho_2$, $\rho_3$, $h_1$, $h_2$) of three-layered model. Having measured the apparent resistance we can determine electrical specific resistance of one of the layers. Also, by using the demonstrated application it is possible to define the layer’s thicknesses.

In order to automatize determination of parameters we have developed application. It allows us to calculate impedance distributions by using model parameters and otherwise: it calculates model parameters by using set of impedance values. The precision of calculation you can see in Table 1.

Table 1. Precision of model parameter’s determination in case of solution of indirect task by using apparent resistivity conception.

<table>
<thead>
<tr>
<th>N</th>
<th>$\rho_{1\text{gen}}$, Ohm cm</th>
<th>$h_{1\text{gen}}$, cm</th>
<th>$\rho_{2\text{gen}}$, Ohm cm</th>
<th>$h_{1\text{calc}}$, cm</th>
<th>$\rho_{2\text{calc}}$, Ohm cm</th>
<th>$\delta\rho_1$, %</th>
<th>$\delta h_1$, %</th>
<th>$\delta\rho_2$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>5</td>
<td>120</td>
<td>749</td>
<td>4.9</td>
<td>131</td>
<td>&lt; 0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>820</td>
<td>7</td>
<td>110</td>
<td>819</td>
<td>6.8</td>
<td>134</td>
<td>&lt; 0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>760</td>
<td>11</td>
<td>130</td>
<td>760</td>
<td>10.7</td>
<td>160</td>
<td>&lt; 0.5</td>
<td>2.7</td>
</tr>
<tr>
<td>4</td>
<td>750</td>
<td>9</td>
<td>140</td>
<td>750</td>
<td>8.9</td>
<td>150</td>
<td>&lt; 0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>5</td>
<td>770</td>
<td>10</td>
<td>150</td>
<td>770</td>
<td>9.9</td>
<td>159</td>
<td>&lt; 0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

In this table with index “gen” genuine parameters is shown and with index “calc” calculated parameters is shown. Besides, we display miscalculation of model's parameters determination for every parameter.

3. Conclusions

In this paper we took up main features of the precardiac rheography technique and examined general poly-layer models to simulate the precardiac area tissues. Solutions for direct tasks (by solving Laplace’s equation by using the boundary conditions) and determination of model’s parameters by solving indirect task (using apparent resistivity method) are presented. As is shown the miscalculation of the model’s parameters determination is less than 1% for parameter $\rho_1$, about 2-3% for parameter $h_1$ and about 20% for parameter $\rho_2$. The lessening of the miscalculation is considered as the future step of presented work to implement this method in order to determine human’s biomechanical heart parameters.

4. References