Sensitivity Analysis of Polysegmental BIA Parameters for Estimation of Body Composition and Systemic Hydrohemodynamics

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Abstract—**Indirect polysegmental methods of bioimpedance analysis enable to minimize the number of electrodes placed on biological objects with complex geometry (such as human body). However, the borders of investigated regions and their anatomical structure have to be accurately described. For this, the mathematical method of sensitivity analysis for various body regions and visualization of their borders using 7-segment BIA analysis with electrode placements at distal zones of the head and extremities is suggested. The model enables to visualize sensitivity of various body segments using flat projection of the human body. Graphical examples are shown for the sensitivity distribution of impedance parameters in torso, abdominal and aortal regions, as well as in arms, legs, and head. Also, the results of the central blood flow visualization in thoracic region by Kubicek are represented. In general, sensitivity analysis can be used as a valuable tool for the substantiating the various diagnostic purposes in polysegmental and whole-body bioimpedance analysis.**

Keywords—**polysegmental BIA, sensitivity analysis.**

I. Introduction

Polysegmental tetrapolar BIA has been a widely used method of body composition analysis. Further developments of polysegmental technologies involve the studies of hemodynamics and redistribution of venous blood and interstitial liquids between extremities and torso under pharmacological tests, physiotherapeutic procedures, and surgical interventions. The aim of this paper is to determine the borders of body regions for our suggested seven-segments measurement scheme as well as the spatial distribution of impendance measurements sensitivity for the thoracic and abdominal regions by means of mathematical modeling [1, 2, 3].

II. Methods

The static, isotropic, flat, and square matrix having 1600 (40×40) cells is used as a model of the human body. Each cell of the matrix within the schematic contour of the human body is considered as having four resistors of value R. The resistors are placed on the square sides of each cell, with the ends connected to 3 other resistors from the adjacent cells.

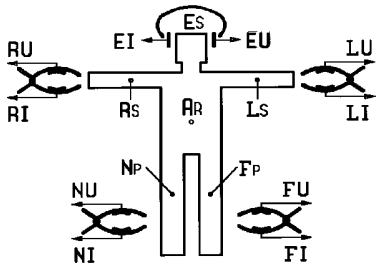

Fig. 1 Positioning of electrode pairs on patient's body. Electrodes RU, RI are placed on right wrist, LU, LI – on left wrist, NU, NI – on right ankle, FU, FI – on left ankle, EU, EI – on temples

The resistors of cells from the outside of the body contour are assumed to have infinite resistances. The polysegmental measurement procedure using five current (RI, LI, NI, FI, EI) and five potential (RU, LU, NU, FU, EU) electrodes is modeled with the electrodes pairs placed on distal parts of extremities and head (Fig. 1).

It is assumed that the electrodes commutate automatically in the following order: (RU-NU, RI-EI), (NU-RU, NI-FI), (FU-LU, FI-NI), (LU-FU, LI-EI), (EU-LU, EI-RI), (EU-NU, EI-FI), (RU-NU, LI-FI). These commutations enable to calculate and visualize impedance of extremities, head (including neck), abdominal and thoracic regions.

The resulting formula for BIA measurements sensitivity was obtained using conventional electrotechnical equations. Surface plots of impedance sensitivity for various body regions were obtained using Mathlab 7 software.

III. Results

In general, to determine electrical field inside the object we need to have analytical description of its surface, a law of resistivity change, the coordinates of electrode placements, and a resistivity distribution outside the object.

When the current source is applied, an electrical field arises in the object and external medium. Current density vector j in a given point is directed along the vector of

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electrical field E: $j = E/\rho$, where $\rho = \rho(x,y,z)$ – resistivity in a point (x,y,z).

The output voltage U_{OUT} is defined by the curvilinear integral of field intensity along the line L connecting the potential electrodes:

$$U_{OUT} = \int_L \mathbf{E}d\mathbf{l} = \int_L E_X dx + E_Y dy + E_Z dz = \\ = \int_L \rho j_x dx + \rho j_y dy + \rho j_z dz. \quad (1)$$

The vector of field intensity in a given point depends on the current density and resistivity. Function of the output voltage sensitivity to resistivity a point is defined by the expression

$$S(x,y,z) = \frac{dU_{OUT}}{d\rho} = \rho(x,y,z)\left(\frac{j_x}{\rho'_x} + \frac{j_y}{\rho'_y} + \frac{j_z}{\rho'_z}\right). \quad (2)$$

Areas with greater values of sensitivity provide the greater impact to the output voltage change. The change in specific resistance by $\Delta r(x,y,z)$ causes the change in output voltage

$$\Delta U_{OUT} = \int_V S(x,y,z)\cdot\rho(x,y,z)dv. \quad (3)$$

If the sensitivity function is normalized, then its integration over volume gives 100% change of the output voltage:

$$S_n(x,y,z) = 100\cdot\frac{S(x,y,z)}{\Delta U_{OUT}}. \quad (4)$$

Consider K surfaces of equal sensitivity in a scalar field S_n:

$$S_n(x,y,z) = k\cdot\delta + S_n(x,y,z)_{MIN},$$

where $k = 0,\ldots,K-1$,

$$\delta = \frac{S_n(x,y,z)_{MAX} - S_n(x,y,z)_{MIN}}{K-1},$$

and $S_n(x,y,z)_{MIN}$, $S_n(x,y,z)_{MAX}$ – the minimal and maximal values of sensitivity function, respectively. Area between i-th and $(i+1)$-th surfaces gives percentage contribution to the general output signal change.

To combine areas with the greatest contributions, it is possible to define area that gives n% contribution to general output voltage change.

Assume that one system of assignments on active area V_1 gives an output signal

$$\Delta U_{OUT1} = \int_{V_1} S_1(x,y,z)\cdot\Delta\rho(x,y,z)dv_1. \quad (5)$$

Also assume that another system of assignments at active area V_2 gives a signal U_{OUT2}. If an area V_2 contains V_1, i.e. $V_2 = V_1 + V_3$, then

$$\Delta U_{OUT2} = \int_{V_2} S_2(x,y,z)\cdot\Delta\rho(x,y,z)dv_2 = \\ = \int_{V_1} S_2(x,y,z)\cdot\Delta\rho(x,y,z)dv_1 + \\ + \int_{V_3} S_2(x,y,z)\cdot\Delta\rho(x,y,z)dv_3.$$

Determine the scale factor N:

$$N = \frac{\int_{V_1} S_2(x,y,z)\cdot\Delta\rho(x,y,z)dv_1}{\int_{V_1} S_1(x,y,z)\cdot\Delta\rho(x,y,z)dv_1}, \quad (6)$$

and write the expression

$$\Delta U_{OUT3} = \Delta U_{OUT2} - N\Delta U_{OUT1} = \\ = \int_{V_3} S_2(x,y,z)\cdot\Delta\rho(x,y,z)dv_3.$$

The value ΔU_{OUT3} describes an output voltage change provided by the active area V_3 only which can not be estimated through the conventional electrode placements.

Example 1: The results of modeling impedance sensitivity for the right leg region which corresponds to electrodes system commutation (NU-RU, NI-FI) are represented in Fig. 2. The vertical scale on this and the following figures is conditional, with lighter colors corresponding to higher impedance sensitivity. Low informative zones were neglected. Impedance sensitivity for the left leg results from modeling the similar (symmetric) commutation scheme of the electrode pairs (FU-LU, FI-NI).

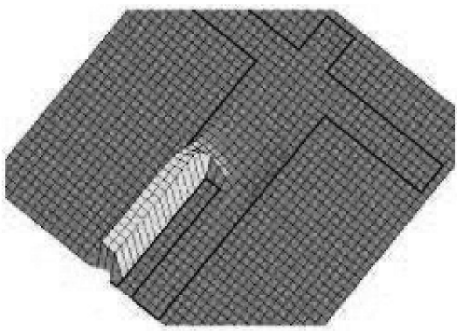


Fig. 2 Surface plot of impedance sensitivity for the right leg region

Fig. 3 Surface plot of impedance sensitivity for the right arm region

Example 2: Commutation schemes (RU-NU, RI-EI) and (LU-FU, LI-EI) provide impedance sensitivity plots for the right (Fig. 3) and left arms, respectively. A plot for the head region can also be obtained using electrodes commutation scheme (EU-LU, EI-RI).

Example 3: The results of modeling the abdominal region impedance sensitivity using electrodes system commutation (RU-NU, LI-FI) are shown in Fig. 4.

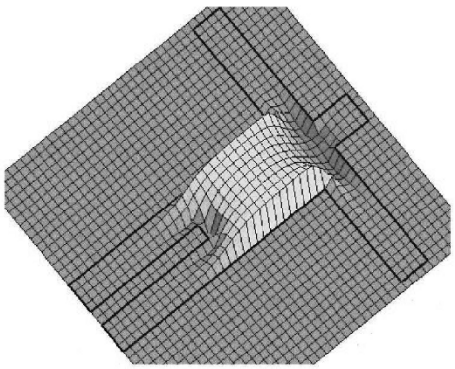


Fig. 4 Surface plot of impedance sensitivity for the abdominal region

Impedance sensitivity plot for the whole torso from neck to inguinal region (Fig. 5) was obtained by the subtraction of the correspondent plots for the head and torso (commutation scheme EU-NU, EI-FI), and for the head only (commutation scheme EU-LU, EI-RI).

Subtracting a plot for the abdominal region from that for the whole torso results in a plot for the thoracic region (Fig. 6), which is of primary importance for the investigations of central hemodynamics and hydration.

Equipotential lines of impedance sensitivity for the thoracic region having an ellipse-like form with the center in an intercept of the vertical axis of symmetry and the central line of horizontally placed arms are shown as a 2-D plot (Fig. 7).

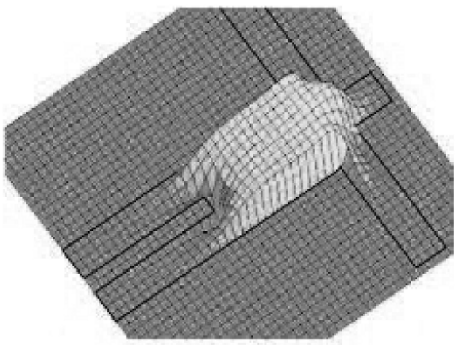


Fig. 5 Surface plot of impedance sensitivity for the trunk

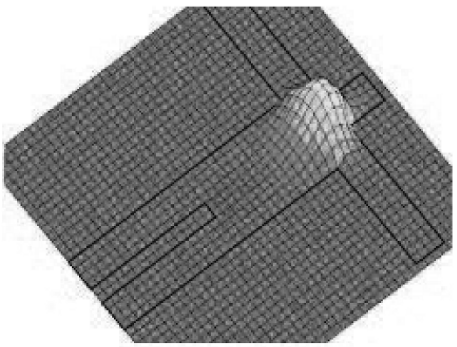
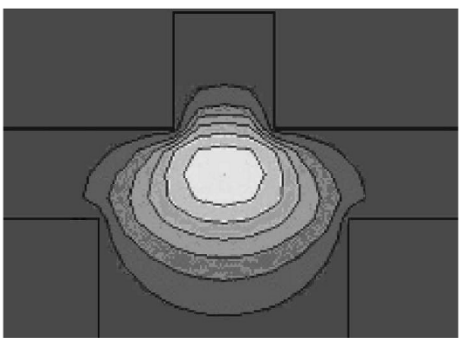


Fig. 6 Surface plot of impedance sensitivity for the thoracic region



F ig. 7 2-D projection of the surface plot of impedance sensitivity for the thoracic region

IV. Discussion

Despite the use of low-resolution flat model of the human body, the results of modeling impedance sensitivity of various body regions with our suggested polysegmental measurement procedure showed qualitative agreement with the results obtained previously using the method of electric equipotential lines density [4]. In view of investigations of central hemodynamics and hydration, the most important are the results of modeling thoracic region sensitivity (Figs. 6, 7) which differ significantly from that obtained by the Kubicek method (Fig. 8).

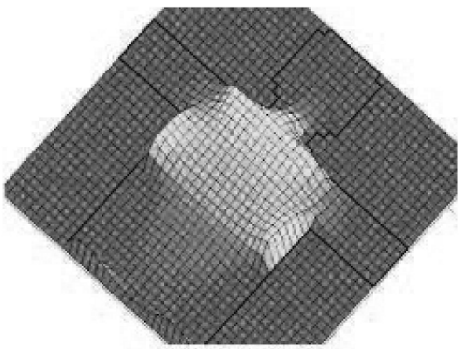


Fig. 8 Surface plot of impedance sensitivity in thorax by Kubicek

Clear advantage of our measurement procedure compared to conventional methods consists in the location of the zone of maximal impedance sensitivity directly over an aortal region. This suggests an opportunity to get more comparable estimates of cardiac output in regard to direct (invasive) measurements.

V. Conclusion

Our theoretical results indicate that the suggested polysegmental BIA can be used in impedance cardiography and for the analysis of body regions hydration. Another area of possible applications is the thoracal and abdominal surgery.

References

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