SIMULATION OF BIOIMPEDANCE MEASUREMENT METHOD ON A CROSS SECTION OF A HUMAN UPPER ARM

T. Žagar and D. Križaj

Faculty of electrical engineering, University of Ljubljana

tomaz.zagar@fe.uni-lj.si

Abstract: A 2D finite element model for simulation of a bioimpedance measurement of a human upper arm in a transverse direction is presented. The simulations are made for different configurations of two electrodes and the relative contribution of m. Biceps Brachii (BB) region to the measured impedance is examined. Simulation is extended to 3-electrode and 4-electrode measurement and the effect of 25% increase in conductance of BB region to measured bioimpedance on circumference of an arm is examined.

Introduction

A localized measurement of bioimpedance can be used to show skeletal muscle changes following prolonged intensive exercise [1] or to detect changes due to various neuromuscular diseases [2]. An application of bioimpedance measurement in a transverse direction is e.g. determination of upper arm muscle and fat areas [3]. The obtained results are affected by a variety of factors among which the variations in location of current injecting and voltage measurement electrodes play a significant role [1]. The localized bioimpedance measurements are performed by passing a high frequency current into the body while measuring a corresponding voltage response over a selected muscle or muscle group [1].

A 2D finite element model (FEM) for simulation of a bioimpedance measurement of a human upper arm in a transverse direction is presented. The model is based on a simplified anatomic cross section of an upper arm and the effects of a different electrode configuration on measured bioimpedance are examined. A numerical simulation of bioimpedance measurement method enables study of various effects under controlled conditions.

Materials and Methods

A simplified 2D geometric model (Figure 1, right) derived from a geometric model of a human upper arm cross section based on an anatomical atlas (Figure 1, left) was developed. The FEM simulation was performed using FEMLAB (version 2.3) software. Test voltage of 1 V was applied to the current injecting electrodes while the remaining boundary was assigned to Neumann boundary condition. A Laplace's equation for complex electric potential (1) was solved. Electric field and current density were calculated from the obtained potentials.

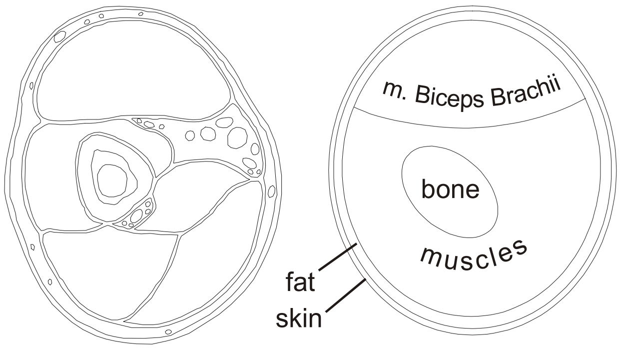

Figure 1: Cross section of a human upper arm (left) and its simplification used for FEM (right).

The simulation was made for the frequency of 50 kHz which is commonly used in bioimpedance measurement [1, 2, 3].

$$\vec{\nabla} \cdot \left[\left(\sigma + j\omega\varepsilon_r\varepsilon_0 \right) \nabla \vec{V} \right] = 0 \qquad (1)$$

The conductivity and the relative permittivity values used in the equation (1) were compiled from the mathematical models [4] and are presented in Table 1.

Table 1: Electrical properties of FEM for 50 kHz

Tissue	σ (S/m)	ε_r
bone	0.02	260
muscle	0.35	10000
fat	0.03	170
skin	0.04	21000

A relative contribution of BB region to the measured impedance for 2-electrode measurement (current injecting and voltage measuring electrodes were the same) for 9 possible electrode positions (Figure 2) on the circumference of an arm was calculated. In this way 36 different electrode combinations are possible. The electrodes in Figure 2 are drawn for visualisation purpose only in the model they were modelled as boundaries with constant voltage. The first electrode in

 ISSN: 1727-1983

every possible combination was assigned a potential of 1V and the second electrode was ground.

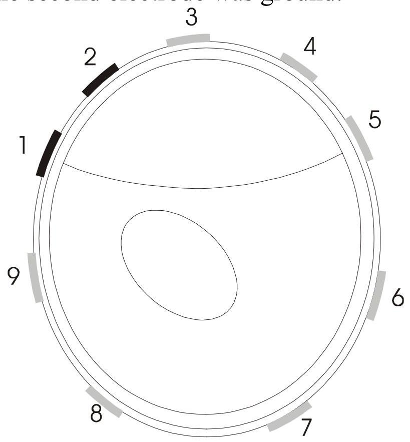

Figure 2: Geometric model with possible electrode positions.

The relative contribution (C_r) of BB region was calculated as

$$C_r = \frac{Z_{BB}}{Z} \cdot 100\% , \qquad (2)$$

where Z_{BB} is a contribution of BB region to measured impedance and Z is measured impedance between the electrodes.

A contribution Z_R of region R to the measured impedance between the electrodes was calculated according to equation (3) which is a special case of a general expression [5].

$$Z_R = \frac{1}{\sigma_R} \int_R \left| \vec{J}_L \right|^2 dR \qquad (3)$$

σ_R is a conductivity of the region and J_L is a current density for unit current applied through the electrodes. For the 2-electrode measurement this is the same for voltage measurement and current feeding electrodes.

For the combination of electrodes 1-2 and 1-5 with approximately the same C_r of BB region an arbitrary change of 25% to complex conductivity of that region was introduced and relative change in measured impedance with 3-electrode system calculated. The current injecting electrodes were left in place, a voltage reference electrode was the same as the second current electrode and voltage sensing electrode was moved around the circumference of a limb. It was not modelled with a boundary like the other electrodes as it was supposed to have an ability to measure voltage in a point. The measured impedance was calculated as the ratio between the voltage on the circumference and the injected current which was obtained by integrating current density on the current leaving electrode boundary.

Additionally, 3 experiments with 4-electrode measuring system were performed.

Results

The C_r for different electrode combinations is presented in Figure 3. The electrodes are marked from N = 1 to 8 according to Figure 2. Each k^th bar in an electrode group N represents a sensitivity value for electrode combination N and N+k, e.g. the 2^nd bar (k = 2) in the 3^rd (N = 3) electrode group represents a sensitivity value obtained if electrode combination 3 (N) and 5 (N+k) is used.

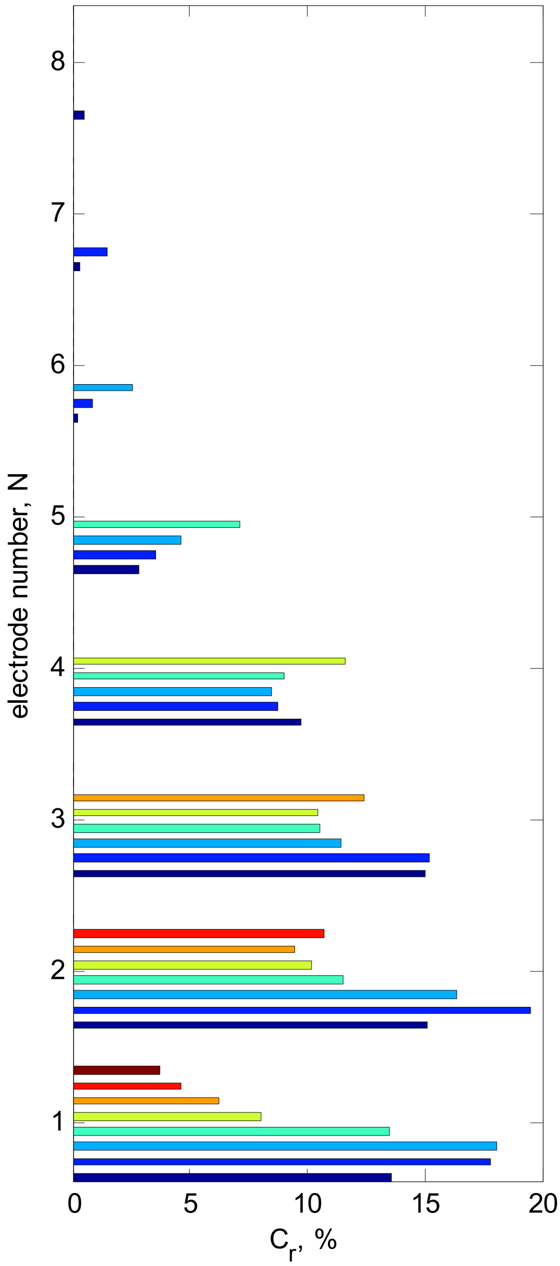

Figure 3: A relative contribution of BB region to measured impedance for all combinations of 9 possible electrode positions.

ISSN: 1727-1983 © 2005 IFMBE

It is interesting to note that almost equally large C_r values are obtained when the electrodes are close together (combination 1-2) and when they are approximately 3-times more separated (combination 1-5). Figures 4 and 5 show a modulus and a phase angle of measured impedance for current electrode combination 1-2 and 1-5 and Figures 6 and 7 present relative changes in measured impedance at increase of a specific conductivity in BB region for 25%. Bold numbers in figures 4 and 5 represent a position of the electrodes. The voltage sensing electrode was moved clockwise from left edge of the electrode number 1. The phase angle values in Figure 5 and relative change in Figure 6 and 7 are omitted in the region of the second current electrode since the voltage was measured relative to this electrode and thus an impedance modulus is zero and a phase angle is undetermined.

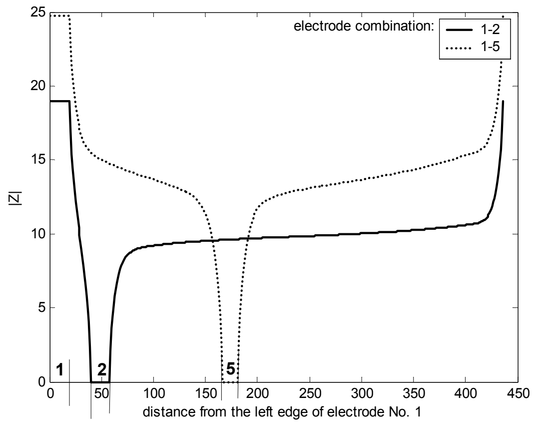

Figure 4: Impedance modulus measured along the circumference with 3-electrode measuring system for two current feeding electrode combinations.

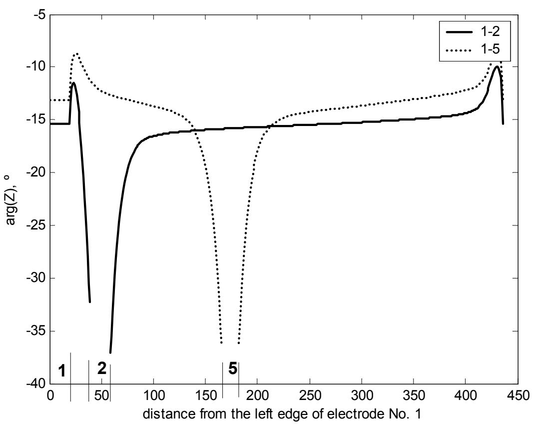

Figure 5: Impedance phase angle measured along the circumference with 3-electrode measuring system for two current feeding electrode combinations.

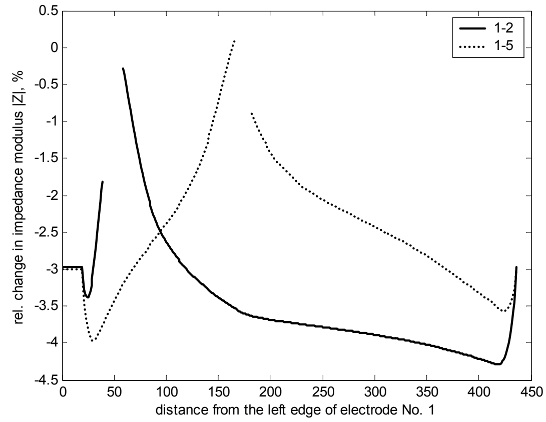

Figure 6: Relative change in impedance modulus provoked by a 25% change in BB region conductivity. Simulation was performed with 3-electrode system. The voltage sensing electrode was moved along the circumference.

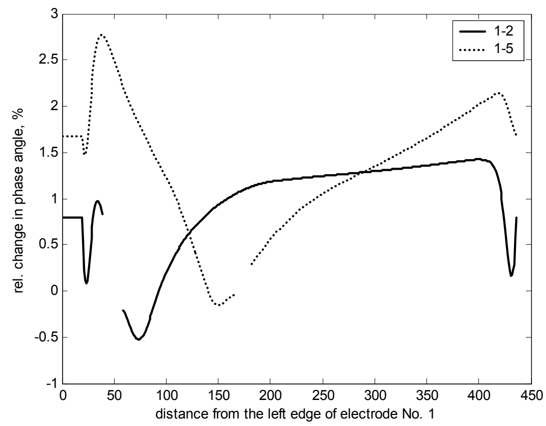

Figure 7: Relative change in impedance phase angle provoked by a 25% change in BB region conductivity. Simulation was performed with 3-electrode system. The voltage sensing electrode was moved along the circumference.

In Figure 8 an experiment with 4-electrode measuring system is presented. A current is injected through electrodes 2 and 4 and voltage is measured in three different configurations. The changes in calculated impedance modulus because of an increase in BB region conductivity for 25% are ΔZ_1 = -4.98%, ΔZ_2 = -15.7% and ΔZ_3 = -19.2%.

ISSN: 1727-1983

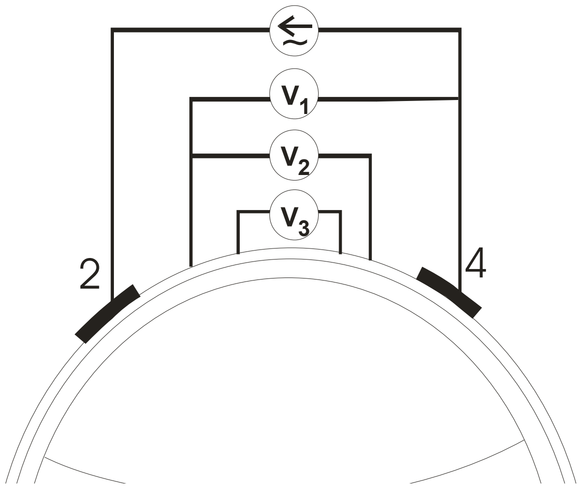

Figure 8: Experiment with four electrodes.

Discussion

For the simulated model with a 2-electrode system the highest C_r is obtained for the electrode combination 2-4. A contribution of specific region to the measured impedance for the 2-electrode system is proportional to current density in that region as it is evident from the equation (3), hence with this configuration the current density in BB region is the highest. However, in general expression with 3 or 4-electrode system a current density field of current feeding and voltage measuring electrodes are not the same and a dot product of them is to be calculated [5].

The highest sensitivity for 3-electrode measuring system in response to 25% increase in BB region conductivity can be seen when voltage measuring electrode is near the current injecting electrode. One could expect that the same holds for the 4-electrode measuring system, however this is not true as it is shown in experiment presented in Figure 8 where the highest sensitivity is obtained when voltage measuring electrodes are close together. This is not always achievable in practical measurement due to sensitivity and resolution limitations of a voltage measuring device.

Conclusions

Simulation has shown that in order to detect the largest changes in bioimpedance as a result of change in underlying muscle properties the current injecting electrodes have to be placed above this muscle encompassing only the specific muscle as wide as possible. For the 3-electrode measuring system the voltage sensing electrode should be close to current injecting electrode and for 4-electrode measuring system the voltage sensing electrodes should be close to each other. The measured changes of impedance on the surface are in general smaller than the changes inside the limb that provoked them.

References

[1] ELLEBY B., KNUDESN L. F., BROWN B. H., CROFTS C. E., WOODS M. J., TROWBRIDGE E. A. (1990): ‘Electrical impedance assessment of muscle changes following exercise’, *Clinical physics and physiological measurement*, **11 (2)**, pp. 159-166

[2] RUTKOVE S. B., PARTIDA R. A., ESPER G. J., AARON R., SHIFFMAN C. A. (2005): ‘Electrode position and size in electrical impedance myography’, *Clinical Neurophysiology,* **116 (2)**: pp. 290-299

[3] BROWN B. H., KARATZAS T., NAKIELNY R.., CLARKE R. G. (1988): ‘Determination of upper arm muscle and fat areas using electrical impedance measurements’, *Clinical physics and physiological measurement*, **9 (1)**, pp. 47-55

[4] Italian National Research Council Institute For Applied Physics "Nello Carrara" - Florence (Italy). An internet resource for the calculation of the Dielectric Properties of Body Tissues in the frequency range 10 Hz – 100 GHz. Internet site address: **http://niremf.ifac.cnr.it/tissprop/**

[5] GESELOWITZ D. B. (1971): ’Application of Electrocardiographic Lead Theory to Impedance Plethysmography’, *IEEE Transactions On Biomedical Engineering,* **18 (1)**, pp. 38-41

ISSN: 1727-1983