Sensitivity field distributions for segmental bioelectrical impedance analysis based on real human anatomy

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Abstract. In this work, an adaptive unstructured tetrahedral mesh generation technology is applied for simulation of segmental bioimpedance measurements using high-resolution whole-body model of the Visible Human Project man. Sensitivity field distributions for a conventional tetrapolar, as well as eight- and ten-electrode measurement configurations are obtained. Based on the ten-electrode configuration, we suggest an algorithm for monitoring changes in the upper lung area.

1. Introduction

Segmental bioelectrical impedance analysis (segmental BIA) is commonly used for various purposes such as the assessment of body composition and abdominal adiposity, as well as for monitoring of body fluids redistribution under various physiological and pathological conditions [1-4]. Available equipment is produced by a number of manufacturers including InBody (Korea), Omron (Japan), RJL Systems (USA), Tanita (Japan), Medas (Russia) and other (see, e.g., [5,6]). For validation of existing measurement schemes, the development of new ones and for accurate data interpretation, it is important to know relative contribution of tissues and organs to the result of bioimpedance measurements of the particular body segment. Here, we aimed at the construction and visualization of sensitivity field distributions for segmental BIA using anatomically accurate 3D model of the human body. Similar approach has already been used before with partially segmented models of the human body, e.g., in impedance cardiography [7,8].

2. Methods

The segmented model of the Visible Human Project (VHP) man [9] containing 30 materials was constructed. For this, partially segmented model of the VHP man torso [10] was initially used with the subsequent improvements as described in details in [11,12] and with the addition of segmented head and extremities.
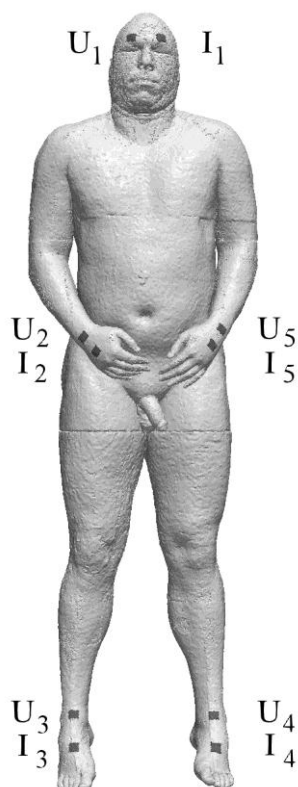
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Fig. 1. A scheme of current (I) and potential (U) electrodes location on the geometrical model of the VHP man for simulation segmental BIA measurements.

Along with conventional tetrapolar wrist-to-ankle measurement configuration, two schemes of segmental BIA were considered: an eight-electrode one with the placement of current and potential electrodes 5 cm apart on the dorsal surfaces of the wrists and ankles, and also ten-electrode scheme with an additional electrode pair located on the forehead as shown in Fig.1. Accordingly, five pairs of thin bilayer square objects 23×23 mm in size simulating electrode properties were added on the forehead and distal parts of arms and legs of the segmented model. Possibilities for the assessment of body regions using various combinations of current and voltage electrode pairs as depicted in Fig. 1 are shown in Table 1. A thin nonconducting layer was added between arms and torso surfaces of the model to avoid tissue contacts. Clearly, the considered 8- and 10-electrode configurations enable measurement of at least 5 (arms, legs, torso) and 6 (arms, legs, torso, and head-neck-upper torso area) body segments, respectively.

After the addition of electrodes, an adaptive unstructured tetrahedral mesh was generated and post-processed in order to improve its quality using mesh cosmetics algorithms from the Ani3D library [13]. The resulted mesh contained 470 thousands vertices and 2.7 millions tetrahedra. In it, most anatomical features of the human body were preserved while keeping a feasible number of mesh elements. BIA measurements at the electrical current frequency 50 kHz were simulated using finite element mathematical model (for details, see [11]). The electrical conductivity parameters for labeled tissues were taken from [14] and the references therein. Sensitivity field distributions were obtained according to Geselowitz formula [15].

Table 1. Some combinations of current (I) and potential (U) electrodes used for the assessment of various body regions in segmental BIA according to the 10-electrode measurement configuration.

Body region	Combination of electrodes	
	I	U
Right arm, right leg, torso	2, 3	2, 3
Torso	5, 4	2, 3
Torso	5, 3	2, 4
Head, neck, upper torso	1, 2	1, 5
Right arm	2, 3	2, 1
Right arm	2, 3	2, 5
Left arm	5, 1	5, 4
Left arm	5, 4	5, 2
Right leg	3, 4	3, 2
Left leg	4, 5	4, 3
Head, neck, torso	1, 4	1, 3

3. Results

Current density fields were calculated from the finite-element model, and the corresponding sensitivity field distributions were obtained for various configurations of electrode sites. Figure 2 shows body regions providing 98% of measurement sensitivity for various schemes of electrodes placement: a conventional tetrapolar scheme (a) and some of those provided by the eight- (c) and ten-electrode configurations (d). (The integral of the sensitivity over the volume area represented in Figures 2a, 2c, and 2d is equal to 98% of the total integral of the sensitivity.) Also, an integral projection of sensitivity field for the tetrapolar scheme can be seen in Figure 2b: the higher values of the projection correspond to the more intense color.
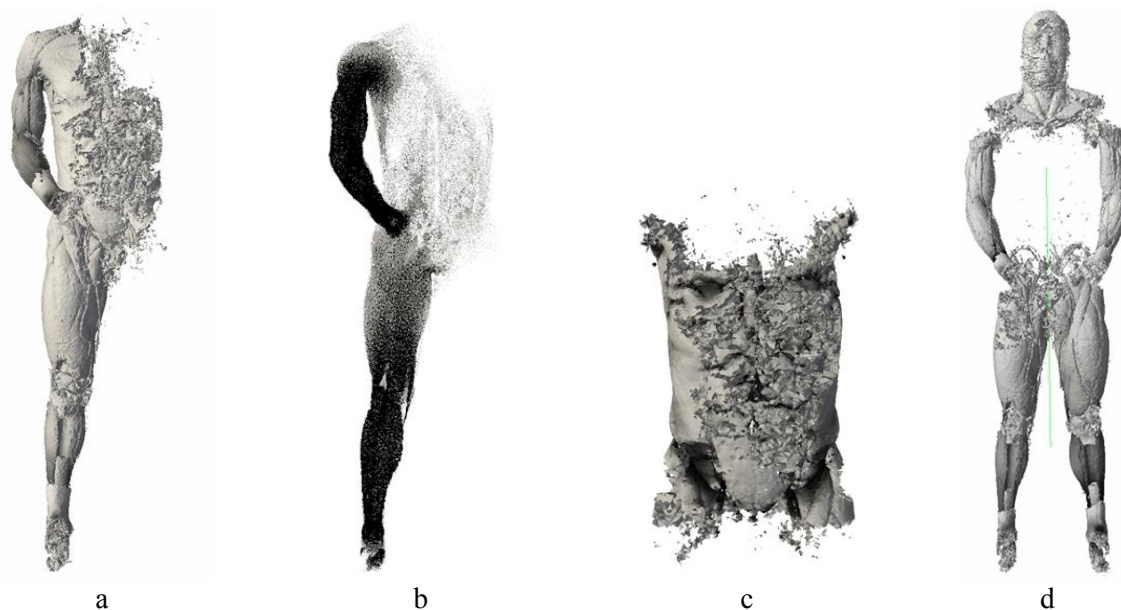

Fig. 2. (a) The regions of high sensitivity and (b) the frontal integral projection of sensitivity density function for a conventional tetrapolar measurement scheme; (c) the regions of high sensitivity for the eight-electrode configuration, torso measurements; (d) a sum of high sensitivity regions for the ten-electrode configuration, measurements of head-neck-upper torso area and of extremities.

The regions of high sensitivity for the parallel and crosswise schemes of torso measurements according to Table 1 were essentially the same with the difference lying within 1%. The same applies to measurements according to 10-electrode configuration providing the volume difference within 1.5% compared to the above-mentioned schemes. Our data show that, given the considered electrodes configuration and body position, about 95-96% of its volume can be assessed, with the exception of distal parts of foots and hands, as well as lateral parts of shoulders (Fig. 2d). The latter feature is explained by the uncommon, from the viewpoint of the conventional BIA measurements, position of arms of the VHP man, and is expected to be eliminated with the recommended body position. The specific position of the anatomical model of the body, in particular the location of the hands, is prescribed by the position of male cadaver during VHP data acquisition. Some future work is planned to create a model with the conventional hands location.

Figure 3 demonstrates a sufficiently wide space present between the non-intersecting regions of high sensitivity of torso and head-neck-upper torso area measurements with the body contours depicted in light gray, and lungs and heart shown in dark grey as a reference. The subtraction of the impedances of torso and head-neck-upper torso region from the total impedance of head, neck and torso (we can define it for any appropriate electrode placement, e.g., according to $I_1I_4U_1U_3$ scheme, see Table 1) provides the impedance of intermediate space that involves upper lung region. Therefore, theoretically, application of the ten-electrode measurement scheme provides a method for the

assessment hydration changes of this important area. Experimental testing of this assumption gave the impedance values in the range between 3 and 7 Ohms.

a   b

Fig. 3. The regions of high sensitivity of torso and head-neck-upper torso area measurements as provided by the ten-electrode configuration: a - frontal view, b - rear view.

4. Conclusion

In this study, sensitivity field distributions for the conventional tetrapolar measurement scheme as well as for the segmental BIA as represented by the eight- and ten-electrode configurations are constructed using high-resolution 3D model of the VHP man. Our data provide accurate interpretation of the results of segmental BIA. The advanced mesh generation approach along with numerical modeling procedure can serve as a valuable tool for evidence-based approach to the development and validation of novel BIA techniques and measurement schemes.

Acknowledgements

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