Numerical Estimation of Muscle Conductivity in Terms of Human Body Internal Resistance

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Abstract— Internal human body resistances beween hand and foot have been calculated using a numerical human model. However, the results were about two times larger than measured ones which reported by other researchers. Focused on muscle conductivity in the present study, internal human body resistances were re-calculated and were compared with the measured ones.

1. INTRODUCTION

Numerically-anatomical human models have been often used for wide band frequency electromagnetic dosimetry [1]. For the dosimetry calculation, furthermore, typical dielectric properties such as conductivity and permittivity have been used for tissues that are assigned to each voxel of the human models. In our previous study, calculated results of human body internal resistances between hand and foot were two times larger than measured results (500–700 Ω) [2]. One possible explanation for this is that there are few voxels assigned as blood, having relatively higher conductivity, because of the limitation that blood vessels with a diameter of less than 2 mm could not be included in the model. Human body impedance is given as internal impedance combined in series with skin impedance. At low frequency, the resistive components of internal impedance are more dominant than capacitive components, and skin impedance changes greatly depending on contact area and surface wetness. Hence, we focus on internal resistances at 60 Hz in the study, ignoring skin impedance and capacitive components of internal impedance. Therefore, with consideration for the fact that conductive currents in a body flow mostly through muscle, and the assumption that conductivities of blood and extracellular fluid should be mixed into the muscle conductivity, we calculate human body internal resistances between the left hand and left foot in the present paper, with changing muscle conductivity: 0.35–2.0 S/m. Here, 0.35 S/m for muscle, 0.7 S/m for blood, and 2.0 S/m for extracellular fluid have been used as the typical conductivity values at 60 Hz [3].

2. NUMERICAL PROCEDURES

2.1. Numerical Human Model

A realistic model of an adult male (Duke, 1.74 m in height, 70 kg in weight, 2 mm voxel size), comprising 77 tissues and organs, was used for the numerical calculation [4]. Both conductivity and permittivity (i.e., complex conductivity) values corresponding to a given tissue can be assigned to an individual voxel. The conductivity values, except for wholly-distributed tissues such as muscle and fat, used in the calculation at 60 Hz are based on the measurements of Gabriel et al. [3], which are commonly used in dosimetric calculations. In addition, the conductivity value of the skin was set to 0.1 S/m in the calculation of the internal resistance to ignore skin impedance.

In the numerical human model, 1.2% of blood voxels are assigned, which is very less voxels than an actual adult male. In addition, it is found in our previous study that conductive currents in a body flow mostly through muscle. Therefore, conductivities of blood and extracellular fluid should be mixed into the muscle conductivity in the calculation. According to the Gabriel report mentioned above, the typical conductivity values for muscle, blood, and extracellular fluid are 0.35, 0.7, and 2.0 S/m at 60 Hz, respectively. By referring to these values, muscle conductivity is set to 0.35–2.0 S/m in the present calculations. As another reference, furthermore, conductivity values for blood and adipose tissue are also varied from the each typical value to 2.0 S/m.

2.2. Numerical Method

The numerical method used in this study is based on the scalar potential finite difference method, which has been widely used for quasi-static magnetic field induction [5]. The detailed description and the validity of our computational code were previously reported [6]. In the voxelized model, electric fields can be expressed by dividing the potential difference between the given and adjacent voxel by the distance between their nodes. When two electrodes to which electric potentials are given in advance are attached to external surfaces of the voxelized model, current flowing between two adjacent voxels is obtained by multiplying the electric field by complex conductivity $(\sigma + i\omega\varepsilon)$ of the voxel, and further multiplying it by the cross-sectional area of the voxel. Here, σ is the electrical conductivity, and ω and ε are the angular frequency and permittivity, respectively. To determine the scalar potentials, conservation of the current that flows to a target voxel from its six adjacent voxels is applied at all nodes. Finally, the human impedance between the electrodes can be obtained by dividing the voltage across the electrodes by the total current.

2.3. Current Pathway

As typical current pathways of the human body for which resistance is measure, the study considers the pathway from the left hand to the left foot, for the numerical human model with both hands at the side. As some internal resistances have been measured in the situation [2]. As the resistances between back of left hand and top of left foot were measured in the literature [2], our calculated results for the two points would be also obtained to compare with them for validation. In the calculation, 1 V at 60 Hz is applied to the electrodes.

3. RESULTS AND DISCUSSION

Figure 1 shows the calculated human body resistance as a function of the conductivity value of each tissue. From the figure, the human body resistance does not change with higher conductivity of blood. Assuming that the blood vessels is 2 m in length and is 5 mm in diameter, the resistance can be simply calculated as 146 kΩ, which is very larger than the internal resistance between hand and foot. Therefore, change in conductivity values in the blood vessels does not influence the internal human body resistance. In contrast, it is clear from the figure that the human body resistance decreases with the higher conductivity of muscle. In addition, the internal resistance decreases gradually with the higher conductivity of adipose tissue. However, as fluid with high conductivity such as extracellular fluid is not likely to be included in the adipose tissue, the calculated result under the adipose tissue with high conductivity is clearly unrealistic.

Figure 2 shows the distribution of equipotential lines and internal electric field vector in the body. As the current flowing through the body is a fixed value, the equipotential line can be translated as the percentage of the resistance inside the human body. It is found from Figure 2 that the electric fields become higher at the joints such as wrist, elbow, knee, and ankle where the equipotential lines are short intervals. In contrast, it is clear that the electric fields in the right arm and right leg are quit small, where is not along the current path.

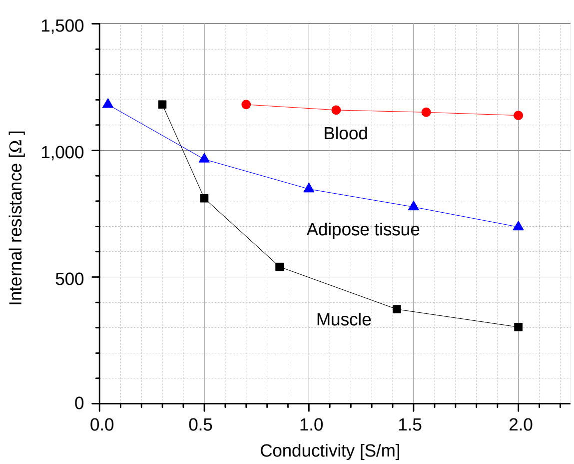

Figure 1: Calculated human body resistance as a function of the tissue conductivity.

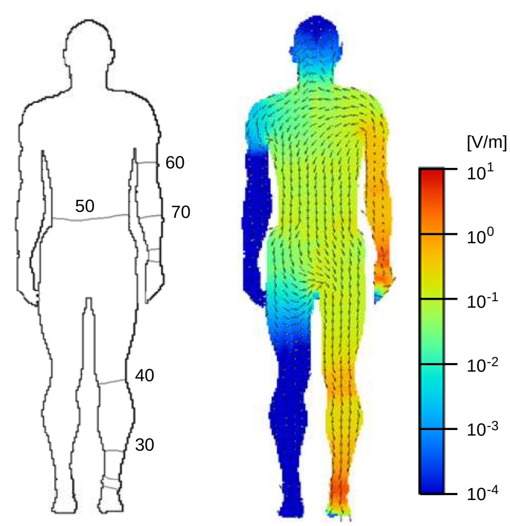

Figure 2: Distribution of equipotential lines in percentage and electric field vectors in the body.

4. CONCLUSION

It is concluded from the calculated results that the internal human resistance is reasonable compared to the measured results (500–700 Ω) when the conductivity values of muscle range from 0.7 to 1.0 S/m. More considerations including conductivity of other tissues and/or anisotropy of muscle should be further investigated.

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