Mathematical Model of Tissue Characteristics in Human-Body Communication

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Abstract. In this study, electric parameters of human tissues are used to build the simplified numerical solution model of the research object with the software COMSOL Multiphysics. During modeling, potential distribution of electric signal in two models are analyzed on the basis of isotropy and anisotropy of human tissues respectively. It is concluded that, at a low frequency and near the electrodes, two models' potential errors are approximately 0.05-0.07V and the error ratio is about twenty percent. However, as the communication distance is increased, signal attenuation becomes greater so that the signal collected by the receiving electrode is very weak; therefore, a little potential error will lead to a great error ratio. In the high frequency mode, the capacitance effect of the tissues becomes more and more obvious, so the effect of human tissues' characteristics is not obvious.

Introduction

The intra-body communication technology [1, 2] is a short-distance wireless communication mode. It plays an important role in the modern medical monitoring [3]. In this communication, human tissue is used as the communication medium so as to avoid complicated wire jointing and injury to human tissue in the process of establishing the system; therefore, it will become a significant component in future medical monitoring [4]. According to different signal coupling modes, the intra-body communication may be classified into two categories, the galvanic coupling intra-body communication and the capacitive coupling intra-body communication. In the latter communication, human body is considered to be a capacitor, namely an integral whole, and signal transmission is achieved through detecting variation of the field; so effects of human tissues on the channel is not required be considered too much. In the galvanic coupling intra-body communication technology, the transmitter couples the information carrier of the alternating current in human body, and the signal flows into human tissue in the mode of differential current [5], so as to achieve signal transmission by detecting variation of the potential. In order to explain signal's distribution in human tissues, from the point of view of model simplification, human tissues (bone, muscle, fat and skin) generally are regarded as volume conductors [6, 7] and considered to be isotropic; the channel model is built based on the volume conductor theory and Maxwell equation [8,9]. However, the effects of human tissues on the channel are neglected. It is learned from anatomy that human tissue is not completely isotropic. Some tissues have different parallel and transverse growth characteristics, and their parallel and transverse electric characteristics are greatly different as shown in Fig. 1. For this reason, in order to analyze the effects of human tissues' characteristics on model precision, in this study, human tissues' characteristics are considered, the volume conductor theory and Maxwell equation are applied to build the isotropic and the anisotropic analytical solution models under the quasi-static mode; distribution of surface potentials are analyzed under different frequencies to judge effects of human tissues' characteristics on the model.

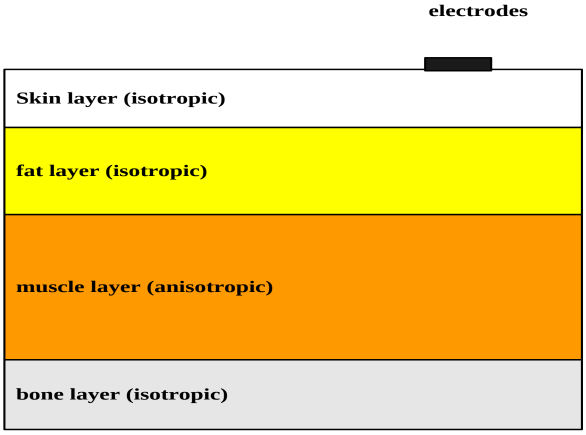

Figure 1. Nonuniform and anisotropic volume conductor model consists of four layers, namely bone (isotropic), muscle (anisotropic), fat (isotropic) and skin (isotropic), which form an integrated conductor model.

Model Theory

In order to simplify modeling in the galvanic coupling intra-body communication, the research object such as arm and leg are firstly abstracted as a standard multilayer cylinder structure; and two pairs of electrodes are used as the signal transmitting terminal and the signal receiving terminal. In Fig. 2, human forearm with the length of h is made equivalent to a multilayer concentric cylinder with bone, muscle, fat and skin according to anatomical characteristics, $(r_1, r_2, \cdots r_n)$ represents circumscribed radiuses of all tissues on the tangent plane, $(\varepsilon_{t1}, \varepsilon_{t2}, \cdots \varepsilon_{tn})$ and $(\varepsilon_{l1}, \varepsilon_{l2}, \cdots \varepsilon_{ln})$ represent the tangential dielectric constant and the lateral one of all tissues respectively, $(\delta_{t1}, \delta_{t2}, \cdots \delta_{tn})$ and $(\delta_{l1}, \delta_{l2}, \cdots \delta_{ln})$ indicate the tangential electric conductivity and the lateral one of all tissues respectively.

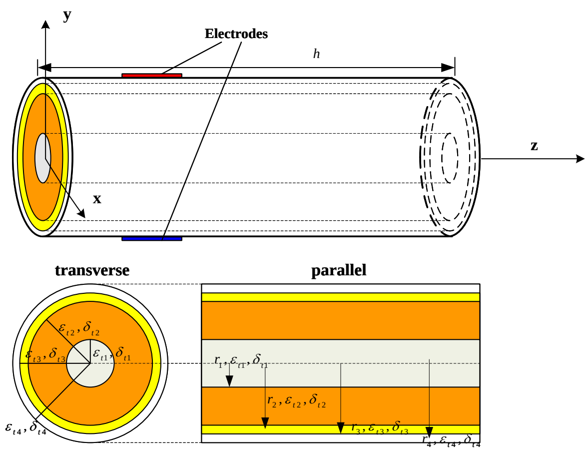

Figure 2. IBC model of human anisotropic forearm

It is concluded from research results of M. Wegmueller [5] and PUN.S.H [9] that, in the galvanic coupling intra-body communication, when the electric signal's frequency in the input electrode is less than 1MHz, the propagation effect, the inductive effect and the irradiation effect from the skin to air throughout the channel may be basically ignored. With the increase of the frequency, the capacitance effect of human tissues become more and more obvious; therefore its impact on the overall system shall be taken into account in building the tissue model. The abbreviated equation [10] of the tissues' potential distribution can be approximately derived in the cylindrical coordinate system through the Maxwell's equation under the quasi static approximation condition [9, 15-17]:

$$\nabla \bullet \delta_{Eq(s)}(f)\nabla V \approx 0 \;\; s=1,2,\cdots N \tag{1}$$

where V represents the interior electric potential in the tissue of human forearm, $\delta_{Eq(s)}(f)$ indicates the composite conductivity of the tissue in the s-th layer at the frequency of f, $\delta_{Eq(s)}(f)$ only has difference between the lateral and the longitudinal electrical characteristics, namely different conductivity, so the following can be derived:

$$\delta_{Eq(s)}(f)=\begin{bmatrix} \delta_{st}(f) & 0 & 0 \\ 0 & \delta_{st}(f) & 0 \\ 0 & 0 & \delta_{sl}(f) \end{bmatrix} \tag{2}$$

where $\delta_{st}(f)$ and $\delta_{sl}(f)$ represent the tangential and the lateral composite conductivity of the tissue *in the* s*-th layer* at the frequency of f respectively, they are expressed as follows:

$$\delta_{st}(f)=\delta_{it}(f)+j\omega\varepsilon_{rit}(f)\varepsilon_0 \tag{3}$$

$s=1,2,\cdots N$, $i=1,2,\cdots N$

$$\delta_{sl}(f)=\delta_{il}(f)+j\omega\varepsilon_{ril}(f)\varepsilon_0 \tag{4}$$

$s=1,2,\cdots N$, $i=1,2,\cdots N$

where $\delta_{it}(f)$ and $\delta_{il}(f)$ indicate the tangential and the lateral conductivity of the tissue *in the* i*-th layer* at the frequency of f respectively, $\varepsilon_{rit}(f)$ and $\varepsilon_{ril}(f)$ indicate the tangential and the lateral relative dielectric constants of the tissue *in the* i*-th layer* at the frequency of f respectively, and ε_0 represents the dielectric constant in the vacuum.

Numerical Solution of the Model

Human tissue parameters obtained by S.Gabriel [14] are used and the alternating current signal $J_n(\theta,z)$ is inputted in the model, where

$$J_n(\theta,z)=\begin{cases} J & if\ -0.615<\theta<0.615 \\ -J & if\ \pi-0.615<\theta<\pi+0.615 \\ 0 & otherwise \end{cases}; \tag{5}$$

Isotropic model

Assume the tangential composite electric conductivity $\delta_{st}(f)$ and the lateral one $\delta_{sl}(f)$ of the tissue *in the* s*-th layer* at the frequency of f are equal, namely

$$\delta_{st}(f)=\delta_{sl}(f) \tag{6}$$

So the abbreviated equation [9] of the tissue's potential distribution is

$$\nabla^2 V \approx 0 \qquad s=1,2,\cdots N \tag{7}$$

Because the communication channel is isotropic, we build a simplified numerical solution model of the research object with the software COMSOL Multiphysics. When the alternating current signal $J_n(\theta,z)$ is inputted in the model, potential distribution of the simplified research object at different frequencies can be derived:

Anisotropic model

However, in the actual research process, the tangential composite electric conductivity $\delta_{st}(f)$ and the lateral one $\delta_{sl}(f)$ of the tissue *in the* s*-th layer* at the frequency of f are not equal, namely:

$$\delta_{st}(f) \neq \delta_{sl}(f) \tag{8}$$

For the anisotropic communication channel, we build a numerical solution model of the simplified research object with the software COMSOL Multiphysics. When the alternating current signal $J_n(\theta, z)$ is inputted in the model, potential distribution of the simplified research object at different frequencies can be also derived:

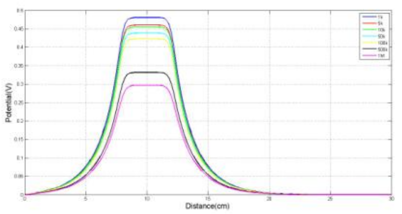

Figure 3. Potential distribution of isotropic tissue communication channel at different frequencies

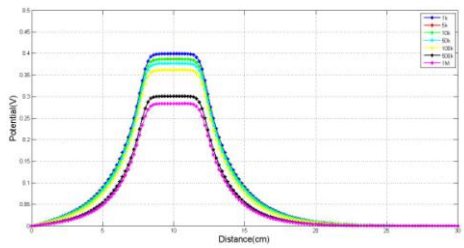

Figure 4. Potential distribution of anisotropic tissue communication channel at different frequencies

Result Analysis

By comparing the isotopic and the anisotropic results (see Fig. 4), it is not difficult to find that there is a certain error between the isotopic and the anisotropic model solutions; the more the frequency is the larger the model error.

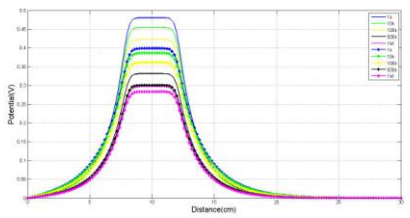

Figure 5. Potential distribution comparison of the isotropic and the anisotropic tissue communication channels at different frequencies

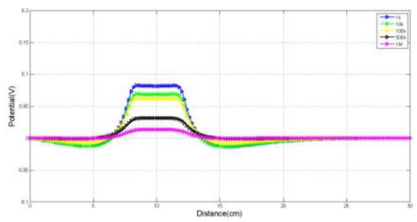

Figure 6. Potential error of the isotropic and the anisotropic tissue communication channels at different frequencies

At a low frequency and near the electrodes, the potential error between the isotropic and the anisotropic models is about 0.05-0.07V. However, as the frequency rises, the capacitance effect of human tissues become more and more obvious and the potential error near the electrodes becomes smaller and smaller. With the increase of the communication distance, signal attenuation is aggravated and the electric signal gathered by the receiving electrode becomes weaker and weaker, so the error is less and less obvious (see Fig. 4).

In order to analyze potential error in terms of the communication distance at different frequencies, we use the error judgment function:

$$k_{eeror} = \left| \frac{V_{Isotropic} - V_{Anisotropic}}{V_{Anisotropic}} \right| \times 100\% \tag{9}$$

By analyzing the error function, it is not difficult to find that the potential difference is not distinct at a further communication distance, but the gathered electric signal is very weak, so a minor difference will cause a great error. Therefore, in the future study, the effect of human tissues' electric characteristics on the communication channel cannot be neglected.

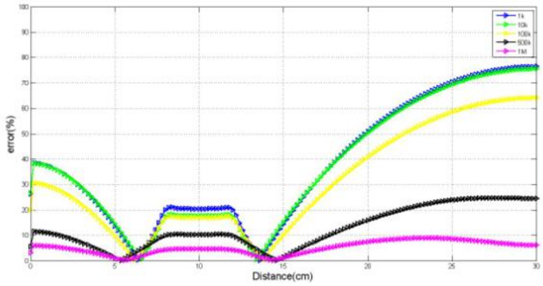

Figure 7. Potential error ratio of the isotropic and the anisotropic tissue communication channels at different frequencies

Conclusion

By building the isotropic and the anisotropic tissue communication channel models and analyzing potential distribution of the communication channels at different frequencies, it is concluded that, at a low frequency and near the electrodes, the potential error of the two models is approximately 0.05-0.07V, and the error ratio is roughly twenty percent. However, as the communication rises, the potential error becomes smaller and smaller, and the error ratio is gradually increased. This is because signal attenuation becomes larger and larger as the communication distance is increased, so that the signal gathered by the receiving electrode is very weak, but so small potential error will cause great error ratio as well. In the high frequency mode, the capacitance effect of human tissues is more and more obvious, while the effect of human tissues is not so obvious.

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