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Galvanic coupling intra-body communication channel model based on anisotropic muscular tissue

Abstract*. *Background: *Characteristics of human tissues have direct effects on transmission property of the current signal in human tissues. It is learned from anatomy that, characteristics of all human tissues are not identical, and some like skin and fat are isotropic, while others like muscle are anisotropic. Muscular tissue has a great effect on transmission and distribution of the current signal in human body.* ***Method:*** *based on human tissue's characteristics and boundary conditions under the quasi-static condition, the channel model based on human tissue's characteristics is built in the cylindrical coordinate system by means of Maxwell equation. Furthermore, the model is verified through model calculation and experiments on human body.* ***Results:*** *in combination with electric parameters of human anisotropic tissue (muscle), the derived channel model is used to obtain computed results of the channel model with human tissue's characteristics and the one without human tissue's characteristics in MATLAB2010a. Next, these results are compared with the data obtained from measurement on human right forearm. It can be found from comparison that the gain curve of the channel model with human tissue's characteristics is highly consistent with experimental data.* ***Conclusion:*** *The model with human tissue's characteristics can show characteristics of the intra-body communication channel more accurately. On one hand, the channel precision is improved; on the other hand, it provides reference for building the implantable intra-body communication channel model with the transmission signal from inside to outside.*

Streszczenie. *Bazując na charakterystyce ludzkiego ciała i warunkach zewnętrznych określono model kanałowy wykorzystujący równani a Maxwella. Model weryfikowano eksperymentalnie. (**Sprzężenie galwaniczne w modelu kanałowym mięśni człowieka**)*

Keywords: Tissue's Characteristics; Galvanic Coupling Type; Intra-Body Communication; Channel Model
Słowa kluczowe: model kanałowy ciała człowieka, sprzężenie międzykanałowe

Introduction

The intra-body communication [1,2] is an important communication way in the modern medical monitoring [3]. In establishing the communication system, human tissue is used as the communication medium so as to avoid complicated wiring and injury to human tissue; therefore, this technology will become a significant component of future medical monitoring system [4]. In the galvanic coupling intra-body communication, the transmitter produces the information carrier of the alternating current in human body through coupling, and the signal flows into human tissue in the form of differential current [5]. In order to explain signal's distribution in human tissue, human tissue (skeleton, muscle, fat or skin) is generally regarded as a volume conductor [6,7] and considered to be isotropic, and the channel model is built based on the volume conductor theory and Maxwell equation [8-10]. However, this leaves out the effect of human tissue's characteristics on the channel. A large number of experiments show that, human tissue is not completely isotropic; lateral electric characteristics of some tissues differs greatly from their tangential ones [11-14] because of different growth characteristics in the two directions, as illustrated in Fig. 1. In this paper, based on human tissue's characteristics, the galvanic coupling intra-body communication channel model with tissue' characteristics is built in the quasi-static mode [15] by means of the volume conductor theory and Maxwell's equation and two models are verified through experiments.

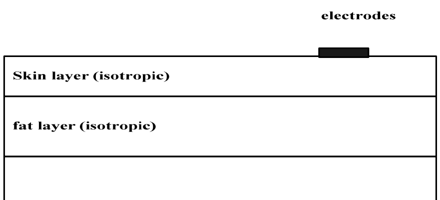

Fig.1 The heterogeneous and anisotropic volume conductor model is an integrated conductor model

Methods

It can be seen from the above research results that human forearm is firstly abstracted as a standard multilayer cylindrical structure in the galvanic coupling intra-body communication and two pairs of electrodes are used as the signal transmitter and the signal receiver respectively. In Figure 2,human forearm with the length of h is made equivalent to a multilayer concentric cylinder with skeleton, muscle, fat and skin according to anatomical characteristics. $(r_1,r_2,\ldots r_n)$ represents circumscribed radiuses of all tissues on the tangent plane,$(\varepsilon_{t1},\ \varepsilon_{t2},\ldots\ \varepsilon_{tn})$ and ,$(\varepsilon_{l1},\ \varepsilon_{l2},\ldots\ \varepsilon_{ln})$ represent the tangential and the lateral dielectric constants and the lateral one of all tissues respectively,$(\delta_{t1},\ \delta_{2},\ldots\ \delta_{tn})$ and ,$(\delta_{l1},\ \delta_{l2},\ldots\ \delta_{ln})$ indicate the tangential and the lateral conductivity of all tissue respectively.

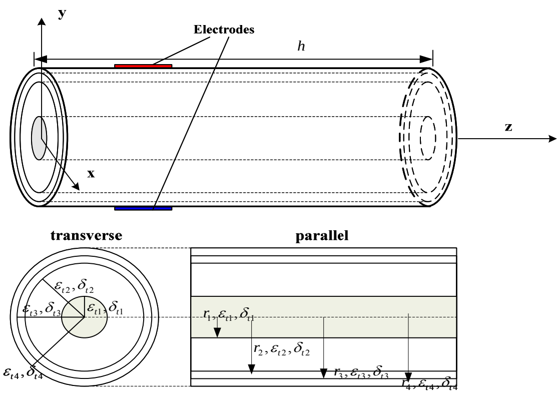

Fig.2 IBC model of human anisotropic forearm

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 frequency of the input electrode is less than 1MHz, propagation effect, inductive effect and irradiation effect from human skin to air, which are generated in the channel, may be ignored on the whole. With the increase of the frequency, the capacitance effect of human tissue becomes more and more obvious; therefore its impact on the overall system must be taken into account in modelling human tissue. The reduced equation [10] describing human tissue's potential distribution can be approximately derived in the cylindrical coordinate system by means of Maxwell's equation under the quasi-static approximation condition [9,15-17]:

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

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. The control equation of the galvanic coupling intra-body communication model is expressed through Laplace equation. Zero in the right of Equation (1) means that, human body as the transmission medium in the intra-body communication has no signal source and it is a passive body. However, for active bodies such as EEG or ECG, the control equation should be the Poisson equation. $\delta_{Eq(s)}(f)$ is presented as follows:

(2) $$\delta_{Eq(s)}(f)=\sqrt{\delta_{st}(f)\delta_{sl}(f)} \quad s=1,2,\cdots N$$

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

(3) $$\delta_{st}(f)=\delta_{it}(f)+j\omega\varepsilon_{rit}(f)\varepsilon_0,\ s=1,2,\cdots N,\ i=1,2,\cdots N$$

(4) $$\delta_{sl}(f)=\delta_{il}(f)+j\omega\varepsilon_{ril}(f)\varepsilon_0,\ s=1,2,\cdots N,\ i=1,2,\cdots N$$

where $\delta_{it}(f)$ and $\delta_{il}(f)$ indicate the tangential and the lateral conductivity of the tissue in the s-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. On the basis of quasi-static approximation electromagnetic boundary conditions and Laplace's equation concerning tissue's anisotropy in the cylindrical coordinate system, electric potential distribution (at the frequency of f) of all layers of tissues in human forearm can be expressed as follows:

(5) $$\begin{aligned}V_{Anisotropy}(f,r,\theta,z)=\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\Bigg[&E_{smn}(f)I_n\Big(\frac{m\pi r}{h}\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)\cos\Big(n\theta\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)+\\&F_{smn}(f)I_n\Big(\frac{m\pi r}{h}\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)\sin\Big(n\theta\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)+\\&G_{smn}(f)K_n\Big(\frac{m\pi r}{h}\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)\cos\Big(n\theta\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)+\\&H_{smn}(f)K_n\Big(\frac{m\pi r}{h}\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)\sin\Big(n\theta\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{st}(f)}}\Big)\Bigg]\sin\Big(\frac{m\pi z}{h}\sqrt{\frac{\delta_{Eq(s)}(f)}{\delta_{sl}(f)}}\Big)\end{aligned} \quad s=1,2,\cdots N$$

where $I_n(\bullet)$ is the n-order modified Bessel function of the first kind, $K_n(\bullet)$ is the n-order modified Bessel function of the second kind, $E_{smn}(f)$, $F_{smn}(f)$, $G_{smn}(f)$ and $H_{smn}(f)$ indicate constant coefficients of the electric potential equation concerning the tissue in the $s-th$ layer at the frequency of f.

When $\delta_{Eq(s)}(f)=\delta_{st}(f)=\delta_{sl}(f)$ is true, the tissue is isotropic at the frequency of f, so the electric potential equation concerning the isotropic tissue in the cylindrical coordinate system can be obtained as follows:

(6) $$\begin{aligned}V_{Isotropy}(f,r,\theta,z)=\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\Bigg[&E_{smn}(f)I_n\Big(\frac{m\pi r}{h}\Big)\cos(n\theta)+F_{smn}(f)I_n\Big(\frac{m\pi r}{h}\Big)\sin(n\theta)+\\&G_{smn}(f)K_n\Big(\frac{m\pi r}{h}\Big)\cos(n\theta)+H_{smn}(f)K_n\Big(\frac{m\pi r}{h}\Big)\sin(n\theta)\Bigg]\sin\Big(\frac{m\pi z}{h}\Big)\end{aligned} \quad s=1,2,\cdots N$$

The conclusion is identical with the conclusion drawn by X.M.CHEN et al.[10],in which the tissue is isotropic in the frequency domain.

Results

Because human forearm may be approximated as a standard cylinder, parameters concerning human tissue obtained by S. Gabriel [14] can be used. In the model, the alternating current input signal is $J_n(\theta,z)$,where:

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

and the carrier frequency of the current signal ranges from 1kHz to 1MHz; the relative distance between the transmitting electrode and the receiving one is set as 30cm.In combination with Equation (5) for the anisotropic channel model and Equation (6) for the isotropic channel model, the voltage gain inside human body can be calculated, as shown in Figure3.

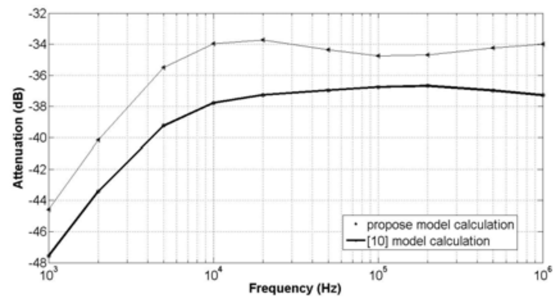

Fig 3. Result of model calculation

In order to verify the model, human right forearm is chosen as the research object of the experiment,1mA alternating current is inputted through 4×4cm Ag-Agcl physiotherapeutic electrode. At the transmitting terminal, the alternating current signal with the carrier wave of 1 kHz - 1MHz is inputted and its intensity is $J_n(\theta, z)$,the receiving terminal is connected with Agilent 4395A network which is used to analyze signal gain after the signal flows through human body, as illustrated in Figure 4.

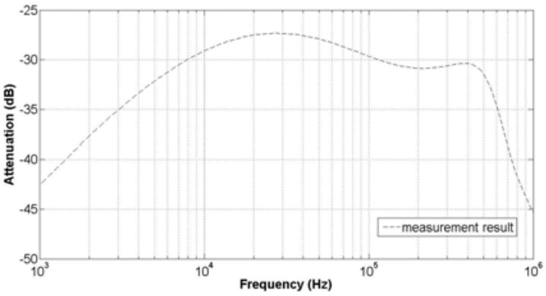

Fig.4 Experimental result

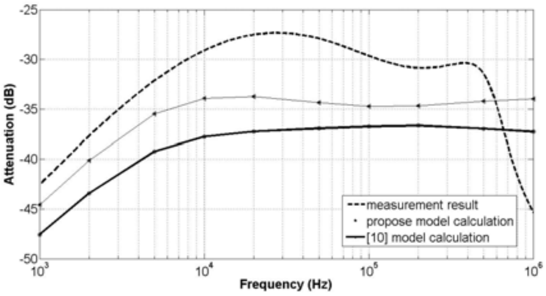

Fig.5 Corrected model calculation result and experimental result

Based on calculation result and experimental data, Figure 5 can be obtained after parameter correction. It can be concluded from Figure5 that, the model with tissue's characteristics is highly consistent with the experimental result, especially when the carrier frequency of the current signal is at 20KHz,the experimental result shows that signal gain tends to decrease obviously, and results of Equation (5) have the same trend curve but results of Equation (6) have not.

Conclusion

Through comparison between calculation results and experimental data, it is found that the channel model with human tissue's characteristics approximates to reality still more, and the maximum error between the calculation result and the experimental result is less. Especially, after the experimental data and the calculation result are properly corrected it can be seen that the experimental result is highly consistent with the calculation result when the carrier frequency is less than 20KHz.On one hand, building the model improves channel precision; on the other hand, it provides reference for building the implantable intra-body communication channel model with the transmission signal from inside to outside.

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