In Vivo Validation of Quasi-Static Field Model in Intra-Body Communication

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ABSTRACT

Intra-Body communication (IBC) is a short-range body based communication using the human body as the transmission medium in biomedical application. Quasi-static electric field modeling of the galvanic coupling IBC channel is analyzed; Analytical solution of voltage distribution and signal attenuation in the forearm of human body from the model are investigated; Effects of human limb's properties in the model are studied. Finally, in vivo validation and calculation results are presented. Especially, the gain is greatly affected by the thickness of muscle both in calculation result and in vivo experiment.

Categories and Subject Descriptors

G.4 [Calculation]: Math function, calculation

General Terms

Experimentation, Theory, Verification

Keywords

Intra-Body communication; quasi-static; in vivo validation; thickness of muscle

1. INTRODUCTION

Sensor nodes placed on or implanted inside the body for the health monitoring and unable assisting spur the Body Area Network (BAN). The principle of BAN which uses the human body as a communication medium is named Intra-Body communication (IBC). IBC with the advantages in low power consumption, low electromagnetic radiation and high security became a novel data communication technique to transfer the data between sensor nodes and the unity of BAN.

The first IBC system, which capacitive couples a modulated pico-amp displacement current through the human body to receiver, proposed at MIT[1] in the Personal Area Network. The voltage signal couples through the human body by two electrodes. However, the received signal is affected by the orientation of the transmitter with respect to the receiver, the size of the ground electrode[1], the distance of ground electrode to the ground and the surrounding environment[2]. Another method is the galvanic coupling, in which the signal is modulated by the current flow through the body with four electrodes, and the steadily received signal will be less dependence on the environment. With the charming character in galvanic coupling, it undergoes the rapid development in the IBC mechanism analysis. Basic experiments are conducted to determine the transmission characteristics of the waveguide intra-body communication method[3]. Marc in[4] investigate the human body as a communication channel by injecting 2mA current and in [5] explores the galvanic coupling by means of finite-element (FE) model; Gao in[6] utilized the quasi-static electromagnetic model for IBC and obtained the analytical solution. However, research on the IBC does not often show enough grasp of the simulation in characteristic of different body properties and that in vivo measurement. In this paper, we utilize quasi-static electromagnetic model to better illuminate signal attenuation and the related performance of the signal affected by different body parameters.

As the in vivo measurement is investigated in the experiment, safety requirements need to be satisfied. Reference current are given in order to avoid hurt or burn hazards in the conductive objects[7]. Therefore, sophisticated current source system is needed to generate the safety current. Section 2 described the galvanic model and established electromagnetic model; the mathematical simulation based on the electric field transfer function and in vivo measurement is presented in section 3; finally section 4 concludes this paper.

2. QUASI-STATIC ELECTRIC FIELD MODEL

We should describe the principle and the basic system of IBC by galvanic coupling. As is shown in figure 1, the signal source as a current is applied to a pair of transmitting electrodes on the body. In the surface between conducting wire and the electrode, the source electronic current is transformed into the ionic current. The ionic current flows through the body medium. The primary current flow flows between the transmitter electrodes. The secondary flow of the ionic current propagates further into the body. And potential differences exist in every different point on the body. Another pair of electrode as part of receiver is placed differently from the transmitter to detect the tiny signal.

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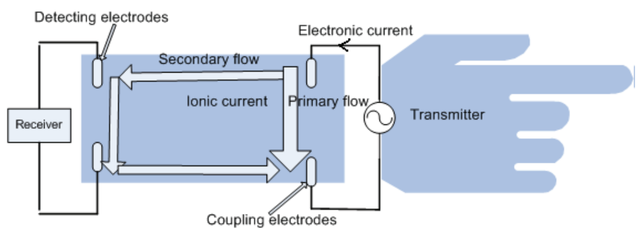

Figure 1. Principle of galvanic coupling IBC

The most important factors to analyze the signal transmission is to investigate the gain or attenuation at the receiver in the channel. In galvanic coupling IBC, the gain is defined as:

$$Gain = 20 \cdot \log_{10}\left(\frac{U_{receiver}}{U_{coupler}}\right) \quad (1)$$

where $U_{receiver}$ represents the voltage amplitude detected at the receiver electrodes. $U_{coupler}$ is the voltage amplitude coupled at the transmitter electrodes. Channel modeling is needed to access the dependence of gain factor on the transmission medium.

2.1 Mathematical Modeling of Forearm

Considering the geometry of the forearm, the arm can be assumed to be a concentric cylinder representing by the skin, fat, muscle and bone layers. Since the human body is a conductive medium, applied signal current is the conduction current and forms the electric field in the body. The transmission medium is characterized by the magnetic permeability μ, electrical permittivity ε and conductivity σ. One must consider both the conduction current and displacement current in the medium as the electric field or current changes with time. The relationship of conduction current and displacement current is:

$$\frac{J_{displacement}}{J_{conduction}} = \frac{\varepsilon}{\sigma}\omega \quad (2)$$

At the frequency of 100kHz, the electrical characteristic[8] of the four layers wet skin, fat, muscle and bone is showed in table 1.

Table 1.Parameters of Body Medium

	Wet skin	Fat	Muscle	Bone
Conductivity (S/m)	1×10^{-1}	2.4×10^{-2}	3.2×10^{-1}	5.8×10^{-3}
Relative Permittivity ε_r	0.3×10^{3}	4.5×10^{2}	7.8×10^{3}	1.2×10^{2}
$\varepsilon_r\varepsilon_0\omega/\sigma$	0.01	0.10	0.13	0.11

From table 1, at the frequency around 100kHz, the four layers medium satisfy:

$$\frac{J_{displacement}}{J_{conduction}} = \frac{\varepsilon}{\sigma}\omega << 1 \quad (3)$$

From formula (3), the displacement current is tiny and the effect can be neglected compared to conduction current, in other words, the capacitive effect can be neglected. Since the communication range on the body is limited to the radius of 1 meter, the propagation effects and inductive effects can be neglected[9]. The quasi-static condition is satisfied. The thickness of skin and fat is about several millimeters, while that of muscle is about twenty millimeter. Considering the simplicity, we neglect the effects of skin and fat layer. The arm is developed to be the muscle and bone effect medium. As is depicted in figure 2, the geometry of human arm is presented as a standard cylinder with radius b and height L. And the radius of bone is a.

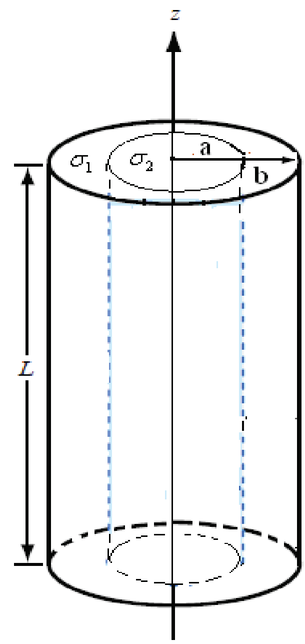

Figure 2. Simplified geometry of forearm.

The body medium in the arm can be characterized as the hollow bone layer with conductivity $\sigma_2 = 5.8\times10^{-3}S/m$ and muscle layer with conductivity $\sigma_1 = 3.2\times10^{-1}S/m$. The coupling current is directly placed on the surface of a medium with material equivalent to that of muscle.

2.2 Governing Function

According to the Maxwell's equation[10], the potential satisfied the Laplace's equation in cylindrical coordinate system:

$$\nabla^2 V = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 V}{\partial \phi^2} + \frac{\partial^2 V}{\partial z^2} = \frac{\nabla \cdot J_s}{\sigma} = 0 \quad (4)$$

where J_s is the current density of surface. To finding out the boundary condition, one must prescribe the *Dirichlet* and *Neumann* condition[11]. The continuity equation in the muscle-bone interface:

$$E_{1n} = \frac{\sigma_2}{\sigma_1}E_{2n} \approx 0 \quad (5)$$

where 1 and 2 refer to the muscle and bone, respectively, and n indicates the normal component of the electric field. Setting the transverse section at the wrist is $z = 0$, and $z = L$ at the joint. Combining the relationship of electric field and potential, the potential at the upper and lower surface, we have:

$$\frac{\partial V}{\partial r}(r = a, \phi, z) = 0 \quad (6)$$

$$V(r,\phi,0) = 0$$
$$V(r,\phi,L) = 0 \quad (7)$$

Considering the symmetry in the cylinder, the current source can be placed in band-type in the same radius.

$$\frac{\partial V}{\partial r}(r = b, \phi, z) = -\nabla V = \frac{J_n(\phi, z)}{\sigma_1} \quad (8)$$

$$J_n(\phi,z)=\begin{cases}1 & z_c \le z < z_c+d \quad and \quad -c/2b \le \phi < c/2b \\ -1 & z_c \le z < z_c+d \quad and \quad \pi - c/2b \le \phi < \pi + c/2b\end{cases} \tag{9}$$

where c and d is the arc length and width of the source injected area, respectively. We solve the Laplace equation (4) with *Dirichlet* boundary condition (7). The analytical result of the voltage distribution will be:

$$V(r,\phi,z)=\sum_{k=1}^{\infty}\sum_{n=0}^{\infty}\left(I_n\left(\frac{k\pi}{L}r\right)+D_{kn}K_n\left(\frac{k\pi}{L}r\right)\right)\left(P_{kn}\cos(n\phi)+Q_{kn}\sin(n\phi)\right)\sin\left(\frac{k\pi}{L}z\right) \tag{10}$$

where D_{kn}, P_{kn}, Q_{kn} are parameters to be determined. Using *Neumann* boundary condition (6), (8), we have:

$$D_{kn}=-\frac{I'_n\left(\frac{k\pi}{L}r\right)\Big|_{r=a}}{K'_n\left(\frac{k\pi}{L}r\right)\Big|_{r=a}} \tag{11}$$

And

$$P_{kn}=\begin{cases}\frac{2}{\sigma_1 L\pi\eta}\int_0^L\int_0^{2\pi}J(\phi,z)\cos(n\phi)\sin\left(\frac{k\pi}{L}z\right)d\phi dz & n=1,2... \\ \frac{1}{\sigma_1 L\pi\eta}\int_0^L\int_0^{2\pi}J(\phi,z)\cos(n\phi)\sin\left(\frac{k\pi}{L}z\right)d\phi dz & n=0\end{cases} \tag{12}$$

$$Q_{kn}=\begin{cases}\frac{2}{\sigma_1 L\pi\eta}\int_0^L\int_0^{2\pi}J(\phi,z)\sin(n\phi)\sin\left(\frac{k\pi}{L}z\right)d\phi dz & n=1,2... \\ 0 & n=0\end{cases} \tag{13}$$

$$\eta=I_n\left(\frac{k\pi}{L}b\right)'+D_{kn}K_n\left(\frac{k\pi}{L}b\right)' \tag{14}$$

where $I_n\left(\frac{k\pi}{L}r\right)$ and $K_n\left(\frac{k\pi}{L}r\right)$ are the modified Bessel function of the first kind, and second kind of order n, respectively. $I_n\left(\frac{k\pi}{L}b\right)'$ is the derivative of $I_n\left(\frac{k\pi}{L}r\right)$ with respective to r and evaluated at b. $K_n\left(\frac{k\pi}{L}b\right)'$ is the derivative of $K_n\left(\frac{k\pi}{L}r\right)$ with respective to r and evaluated at b. The analytical solution of the muscle and bone effect layered cylinder model is obtained in formula (10).

Note that other kinds of surface current density should be chosen, with only changing the description of the surface area in formula (9).

3. CALCULATION AND IN VIVO EXPERIMENT

We choose the 4cm by 4cm rectangular physiotherapy electrodes in the simulation and in vivo validation. The transmitter and receiver electrode pairs are placed in the symmetrical position around the forearm. The current injected into the body is set to 0.1mA, which is 200 times lower than the safety requirements. The length of the arm changes from 22cm to 28cm. The detecting and coupling electrodes are placed parallel in the same direction. We analyze the gain as the change of position of the receiver electrodes refer to that of transmitter.

The parameter L and radius b are investigated in calculation. As is showed in figure 3, higher gain is observed by increasing the radius of the arm in calculation. In other words, larger radius of arm indicates more thickness of muscle, then larger surface area of the radial section, lower resistance of the medium, then lower attenuation, which hints that muscle play a major role in conducting the current. However, the attenuation is almost unaffected with only the length of arm changed. The reason is with all parameters the same, the attenuation will be the same in the common part of two different length of forearm.

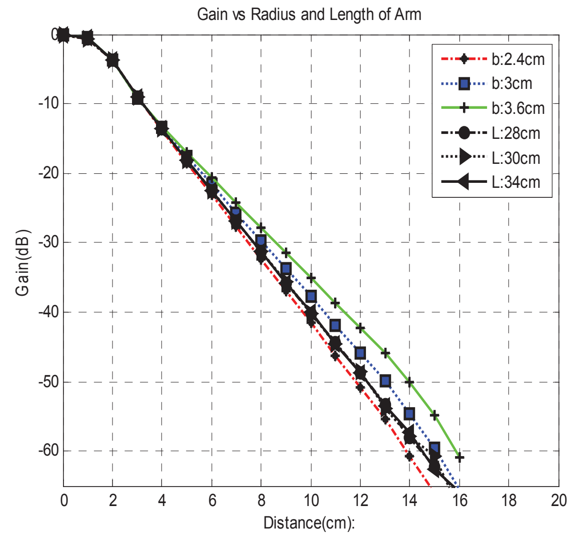

Figure 3. Gain of different parameters of arm versus different distance between transmitter and receiver (In changing the radius b, the length $L = 22cm$; In changing L, the radius $b = 2.6cm$)

To validate the correctness of the quasi-static electric field model, five volunteers are involved in the in vivo experiment. Body Mass Index (BMI) can not reflect the total parameter of the human body. We measure the length and the radius of the five subjects. The human limb's properties of the five subjects are displayed in table 2:

Table 2. Subjects' limb Properties

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
BMI	17.9	18.9	25.7	16.1	25.8
Length of arm	22cm	26cm	28cm	26cm	28cm
Radius of arm	2.4cm	3.0cm	3.2cm	2.8cm	3.2cm

The Calculation result and in vivo measurement result for the five subjects are expressed in figure 4.

Seen from the measurement result, the gain is about -23dB with the detector 4cm from the transmitter, and -35 dB, -42 dB with 8cm and 12cm, respectively. The maximum difference of gain is almost 10 dB among different subjects in measurement results. Subject 1 sustains the highest attenuation. That's because subject 1 exhibits the smallest radius of arm and lower BMI, then the forearm contains less muscle. Subject 2 and 4 appear almost the same gain along the distance. From table 2, we know that subject 2 and subject 4 obtain almost the same human limb's property. Compared to the other 3 subjects, subject 3 and subject 5 sustains the lower attenuation or highest gain. The reason is subject 3 and 5 reflects largest radius of arm and highest BMI.

Observed from the calculation result for the 5 subjects, the trend in calculation result coincides with that of measurement result, in other words, the higher BMI and larger radius of forearm, the higher the gain or lower attenuation. However, maximum error of 10dB exists in attenuation between the calculation result and measurement result. Minimum error of 1dB is at about 10cm from the transmitter. The calculation result shows a linear attenuation while that of measurement reflects a slower attenuation. One reason for the error is the ignorance of the effects of the skin and fat layer, the other is the structure of the arm may not be a standard cylinder.

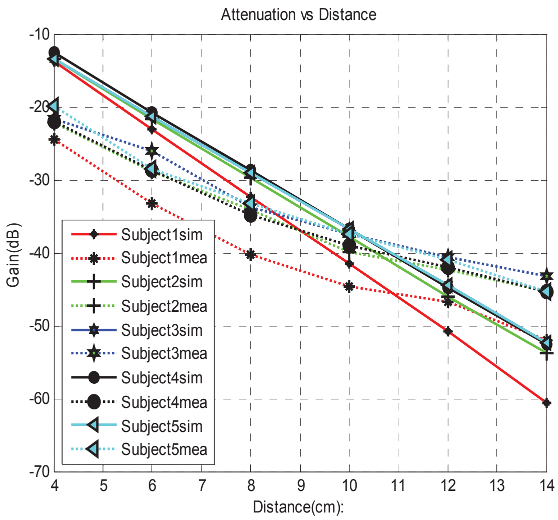

Figure 4. Calculation result and in vivo experiment result (Subject*sim stands for calculation result of subject*; Subject*mea stands for measurement result of subject*)

4. CONCLUSION

This paper studies the channel modeling in galvanic coupling IBC, calculates the analytical solution of quasi-static electric field model, conducts the in vivo validation of the model. Both the simulation result from model calculation and measurement result indicate higher gain would be obtained with larger thickness of muscle. The linear attenuation of the muscle-bone effect mismatches the measurement result. The simplified model induces the error in calculation. Future research would focus on the improvement of the model to obtained accordance with reality.

5. ACKNOWLEDGMENTS

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