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Simple Electrical Model and Initial Experiments for Intra-Body Communications

Y. M. Gao, S. H. Pun, M. Du, P. U. Mak and M. I. Vai

Abstract—**Intra-Body Communication(IBC) is a short range "wireless" communication technique appeared in recent years. This technique relies on the conductive property of human tissue to transmit the electric signal among human body. This is beneficial for devices networking and sensors among human body, and especially suitable for wearable sensors, telemedicine system and home health care system as in general the data rates of physiologic parameters are low.**

In this article, galvanic coupling type IBC application on human limb was investigated in both its mathematical model and related experiments. The experimental results showed that the proposed mathematical model was capable in describing the galvanic coupling type IBC under low frequency. Additionally, the calculated result and experimental result also indicated that the electric signal induced by the transmitters of IBC can penetrate deep into human muscle and thus, provide an evident that IBC is capable of acting as networking technique for implantable devices.

Keywords— Intra-Body Communication, Galvanic coupling type, Electrical model, Experiments

I. INTRODUCTION

IBC (Intra-Body Communication) is a short range "wireless" communication technique appeared in recent years. This technique relies on the conductive property of human tissue to transmit the electric signal among human body[1] [2] [3] [4]. This is beneficial for devices networking and sensors among human body which is becoming part of communication system, and additional arrangement, consideration of communication is reduced. The features and working principle of IBC are suitable for forming the communication network, data exchange for wearable sensors, telemedicine system and home health care system. Especially, the data rates of general physiologic parameters are usually low and currently, the achievable throughput of IBC is not high. Despite of the existing electromagnetic wave based technique [5] for biomedical sensors, IBC can realize an alternate communication link with less electromagnetic interference and less susceptible to external interference.

The research and development of the IBC has attracted much attention in recent years. Various methodologies [1] [4] [6], applications [3] [7] [5], modeling techniques [8] [9] [10] and in-vivo measurements [9] [11] [12] have been reported. In summary, there are two methodologies reported for realization of IBC; namely: Electrostatic/Capacitive coupling type and Waveguide/Galvanic coupling type techniques. Both of them share the same principle which relies on the conductivity of the human tissue; while in contrast, capacitive coupling depends on external environment as return path and galvanic coupling works with current flow propagation within the human tissue. Capacitive coupling is capable of attaining a higher data rate[4]; however, environment variation can jeopardize the stabilities and performance of the communication[13]. Galvanic coupling is much less easy to be influenced by the environmental variation but the achievable data rate, for the time being is low(around 4.8kbps) [4] [14]. Among reported applications prototypes, a wireless ECG Monitoring system has been reported by T. Handa et al. in 1997[5], which employed galvanic coupling type IBC as its communication technique. Furthermore, various models and in vivo measurements have been reported, these results provide insight about the working principle and lay the foundation of IBC.

In this article, the galvanic coupling type IBC application on human limb is investigated. In Section II, we first briefly review the mathematical model under quasi-static conditions. The related experiments are presented in Section III and Section IV. The experimental results show that the proposed mathematical model is capable in describing the Galvanic coupling type IBC under low frequency. Additionally, the authors believe that the Galvanic coupling type IBC would be a possible technique for networking with implantable devices as suggested by the mathematical model and the obtained experiment results. Both mathematical and experimental results indicated that the electric signal induced by the transmitters of IBC can penetrate deep into human muscle.

II. MATHEMATICAL MODEL

In reference to author's previous works[15] [16] [17], a mathematical model based on the electromagnetic theory is presented. In this model (as depicted in Figure 1), the

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quasi-static approximation has been adopted as the operating frequency of IBC are generally low (<100 kHz). Hence, the Maxwell Equations reduce into Laplace's Equation[18] [19]. Then, assuming the human limb as a length of homogeneous cylindrical shape muscle, with EQ. (1) defining the injected current to the lateral surface of the human limb acting as the transmitter of IBC. Additionally, to be consistent with experiments described in later Sections, the boundary conditions set for the problem are defined as EQ. (2).

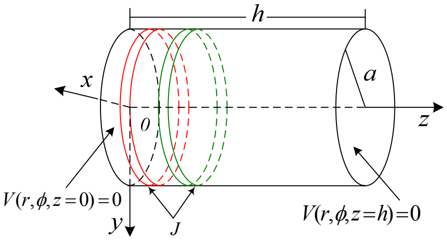

Figure 1 Simplified model with boundary conditions. A pair of ring electrodes is attached on the surface of the cylinder along the Z axis.

$$J(\phi,z)=\frac{I(\phi,z)}{s}=\begin{cases} J_i & z_1 \le z \le z_1+d \ ,0\le\phi\le 2\pi \\ 0 & \text{elsewhere} \\ -J_i & z_2 \le z \le z_2+d \ ,0\le\phi\le 2\pi \end{cases} \tag{1}$$

where, J_i represents the injected current density signal to the human limb and s is the area of the electrode.

The boundary conditions are

$$\begin{cases} V(r,\phi,z=0)=0 \\ V(r,\phi,z=h)=0 \\ \sigma \cdot \partial V(r=a,\phi,z)/\partial r = J(\phi,z) \end{cases} \tag{2}$$

After solving for the Laplace's Equation with boundary conditions and injected current ring electrodes, taking the advantage of symmetry, the voltage distribution induced by the injected current (transmitters) can be described by:

$$V(r,z)=\sigma\sum_{m=1}^{\infty}A_m I_0(\frac{m\pi}{h}r)\sin(\frac{m\pi}{h}z) \tag{3}$$

where,

$$A_m = 2\int_0^h J(z)\sin(m\pi z/h)\mathrm{d}z \Big/ [I_0(m\pi r/h)]'_{r=a} \tag{4}$$

and I_o, represents the modified Bessel function of the first kind of order 0, a is the radius of the cylinder, and h depicts the length of the cylinder.

III. EXPERIMENT I

In order to validate the presented, an experiment has been setup. A h=50 cm long PVC semi-cylinder non-conducting basin with radius of a=15cm is built and filled with tap water of conductivity about 100μS/cm. For the sake of convenient, the model scale in Experiment I is enlarged in comparison to human limb such that measurements would be easier to obtain without sacrificing the accuracy of the experiment. A pair of stainless steel half-ring electrodes with 1cm in width is attached to the lateral surface (z_1=5cm and z_2=7cm) of the basin as the transmitter of the IBC. It is noticed that, since ring type electrodes are employed the voltage induced by the transmitter would be symmetrical around the axis (z-axis) of the basin and thus, a semi-cylinder basin would be enough.

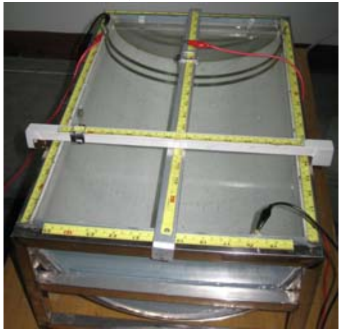

Figure 2 The photograph of Experiment I setup. The PVC semi-cylinder basin is filled with tap water. Stainless steel consists of the semicircular top, bottom and the ring electrodes.

TABLE 1
COMPARISON BETWEEN MEASURED POTENTIAL AND MODEL CALCULATED VALUE ALONG THE Z AXIS WHEN R=15CM AND 12CM WITHIN THE SETUP

Z (cm)	Surface			1cm deep		
	V_c (V)	V_m (V)	Deviation	V_c (V)	V_m (V)	Deviation
1	-0.093	-0.081	13.3%	-0.039	-0.035	11.5%
3	-0.363	-0.349	3.8%	-0.094	-0.100	5.9%
5	-1.684	-1.914	13.6%	0.014	0.013	10.9%
7	1.757	1.558	11.3%	0.445	0.381	14.5%
8	2.349	2.240	4.6%	0.637	0.548	14.0%
9	1.323	1.408	6.4%	0.732	0.627	14.4%
11	0.897	0.870	3.0%	0.740	0.653	11.8%
13	0.742	0.698	6.0%	0.684	0.611	10.7%
17	0.595	0.530	10.9%	0.582	0.521	10.5%
21	0.504	0.443	12.1%	0.500	0.445	10.9%
25	0.428	0.373	12.9%	0.427	0.375	12.3%
29	0.358	0.308	13.9%	0.358	0.311	13.1%
33	0.289	0.264	8.7%	0.289	0.246	14.7%
37	0.221	0.196	11.5%	0.221	0.188	14.9%
41	0.153	0.143	6.6%	0.153	0.130	14.7%
45	0.085	0.080	6.1%	0.085	0.074	12.4%

As shown in Figure 2, a 100 Hz injected current controlled by a voltage source of V_o is employed as the transmitter of the experiment. To satisfy the boundary conditions on the top and bottom of the cylinder, a pair of stainless steel semicircle is attached on the top and bottom of the basin with potential $V_o/2$. Therefore, the measured value V_m should be normalized by the equation EQ. (5)[20]

$$V(r,z)=V_m(r,z)-V_o/2 \tag{5}$$

where $V(r,z)$ is the measured voltage induced by the transmitter.

The experiments are repeated five times and Table 1 shows comparison between measured potential V_m with the same configuration along Z axis where r=15cm and 12 cm respectively. During the experiments the measured values are fluctuation slightly. It may be due to the polarization phenomenon of the tap water injected by the low frequency current signal and the deviation of the calculated and measured value is less than 15%.

Experiment I data and the numerical values from Section I mathematical model are measured and calculated for the same location of 12cm and 15cm depth respectively, as shown in Table 1 and Figure 3. In the figure, the blue circles and red crosses represent the measurement result in 12cm and 15cm depth respectively; while the red line and the blue line represent the calculated result of r=12cm and 15cm respectively. Figure 4 shows the comparison of the measurements against the calculated result through the cylinder with z=3cm and 9cm. In overall, experimental data match quite well with numerical calculations.

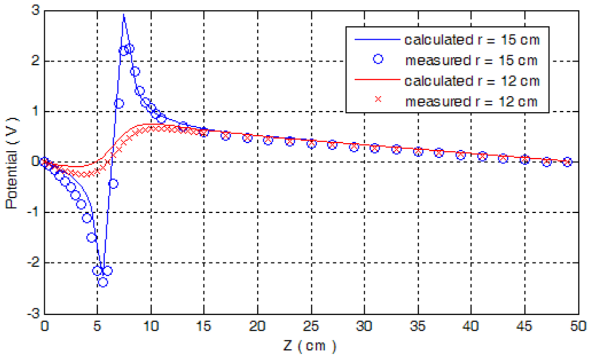

Figure 3 Comparison of the potential along Z axis for fixed value of r_1=15cm and r_2=12cm. The blue smooth line of r_1=15cm and the red smooth line of r_2=12cm are calculated by the analytical model. The circular symbols and cross symbols are the potential results measured via the experimental setup

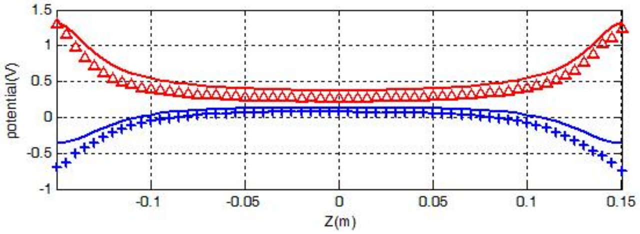

Figure 4 Comparison of the potential at the diameter of the setup for fixed value of z_1=3cm and z_2=9cm.

IV. EXPERIMENT II

In order to further validating the correctness of the mathematical model, a h=20cm long and *a*=3.6cm in radius cooked pork meat is selected for galvanic coupling type experiment. Cooked pork meat is chosen for Experiment II, because it is regular in shape, easy to obtain, and analogous to human tissue. In order to evaluate the result, we should obtain its conductivity first by using the following formula:

$$\sigma = hI / VS \tag{6}$$

where I is the input conduction current, h is the length, S is the cross section area of the cooked pork meat and V represents the voltage across the cooked pork meat. Then, the conductivities of the cooked meat at different frequencies are measured and given in Table 2. From the table, it is recognized that the conductivity of the cooked varies slightly under the measured frequency range and the value is just about three times higher than the conductivity of human muscle given by Garbriel, et al.[21].

TABLE 2
THE CONDUCTIVITY OF COOKED PORK MEAT FOR EXPERIMENT II

f(kHz)	0.1	1	10
σ(μS/cm)	0.99e4	1.17e4	1.16e4

During the experiment, the input current is set to 20mA(rms) injected into the stainless steel ring electrodes (*d*=0.5cm width) on the surface of the cooked pork meat. Similar to Experiment I, the measured value is normalized by using EQ. (5)[20]. Table 3 and Figure 5 show the comparison between the measured potential distribution and the calculation result. From the table and Figure 5, it is noticed that the deviation between the measurement results and the calculated results is less than 10%.

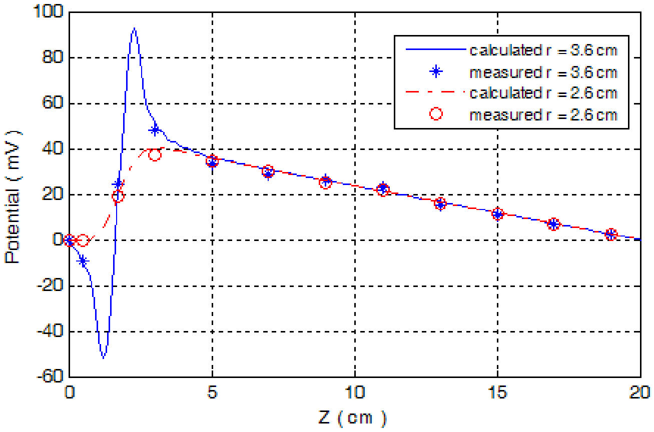

Figure 5 Comparison between measured potential and calculated value on the surface and 1cm deep of the cooked pork meat

TABLE 3
COMPARISON BETWEEN MEASURED POTENTIAL AND MODEL CALCULATED VALUE ON THE SURFACE AND 1CM DEEP IN COOKED PORK MEAT

Z (cm)	R=3.6cm			R=2.6cm		
	V_m (mV)	V_c (mV)	Deviation	V_m (mV)	V_c (mV)	Deviation
0.5	-10.01	-9.2	-8.09%	-0.51	-0.5	-1.96%
1.8	26.62	24.46	-8.10%	21.18	19.21	-9.31%
3	51.73	47.87	-7.46%	40.17	36.86	-8.24%
5	36.41	33.15	-8.94%	35.67	34.57	-3.07%
7	30.86	28.98	-6.09%	30.68	29.68	-3.26%
9	26.02	26.01	-0.05%	25.93	24.94	-3.82%
11	21.27	23.02	8.21%	21.21	21.71	2.35%
13	16.54	15.44	-6.66%	16.50	15.57	-5.62%
15	11.81	10.92	-7.57%	11.78	11.27	-4.36%
17	7.09	6.61	-6.74%	7.07	6.72	-4.96%
19	2.36	2.17	-8.13%	2.36	2.22	-5.81%

V. CONCLUSION

IBC is an emerging short range “wireless” communication technique appeared in recent years. This technique is suitable for various applications on human and especially for wearable sensors, telemedicine system and also home health care system. The technique is also able to use for communication with implantable devices.

In this paper, the simple electrical model for the IBC is presented and two experiments are conducted for validating this model. The first experiment employs a semi-cylinder basin filled with tap water and the second experiment employs a cooked pork meat for simulating the IBC problem on human limb. The measurement results show that the presented model can provide a good description about the voltage distribution both at the surface and inside the human limb induced by the transmitter of IBC. Furthermore, the mathematical model along with the experiment results also suggests that the signal induced by the transmitter of the IBC will penetrate deep into the center of the muscle under low frequencies. This observation shows the IBC is a possible solution for applications on the surface of the human. Furthermore, it is able to provide a convenient communication technique for implantable devices. In such a way, the complicated communication problem with implantable devices can be simplified.

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