A Study of RF Power Attenuation in Bio-tissues

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Abstract

Implantable biomedical micro devices (or micro-implants) are believed to be useful in many clinical applications. Using wireless radio frequency (RF) techniques to transmit power and signals to micro-implants is the main stream in this research area. Depending upon among of signals to be transmitted to a micro-implant, the frequencies used by the wireless RF techniques vary. An issue is that the power attenuation in bio-tissues will change, when the RF power transmission frequency is altered. In this work, a wireless RF power transmission/receiving system was developed to study power attenuation in bio-tissues. Common radio frequency range applied in neural prosthesis (500 kHz ~ 2 MHz) was used to transmit power in a fashion of electromagnetic wave (EM) in the study. Studies of power transmission in air and in pork were conducted. Our study results prove that for the coil based power coupling technique, the received power is proportional to the power transmission frequency. However, the power attenuation rate of low frequency EM waves is less than that of high frequency EM waves. In addition, the study results demonstrate that the power attenuation for high ε medium is slower comparing with low ε medium. More importantly, we have developed power attenuation models for various transmission frequencies using regression analysis technique. We believe these models can be further evolved to become more generic so that they can be used to facilitate positioning the micro-implants.

Keywords: Implantable micro device, Radio frequency, Wireless transmission, Power attenuation

Introduction

Neural prosthesis has great potential to restore function in the injured or diseased brain and spinal cord. Examples are auditory prostheses, visual prostheses, motor prostheses, bladder prostheses, diaphragm pacing, and cerebellar stimulation. Devices that are used in the above applications are known as “micro-implants.” These devices mostly are small in size and are to be implanted into human bodies. Thus, the development of neural prosthetic devices requires several state-of-the-art technologies such as very large scale integration (VLSI), biomaterial, micromachining, power supply, and data communication. Among these technologies, the power supply and the data communication have been the major issues.

In general, there are three approaches to supply the power: (1) conventional wire cord (focusing on the biocompatibility of the shielding materials), (2) battery technologies, and (3) radio frequency (RF) technologies. The major advantage of the wire cord approach is technically simple. Similar to regular devices, this approach applies power cords and data lines supply all necessary electrical energy and command signals to the microimplant. Unacceptable problems of cosmesis, maintenance, and infection hinder its development. Technologies of high energy density battery increase the life-span of implantable functional devices. Unlike the technologies of the wire cord and RF which supply both power and data transmission, solo function of supplying power limits the battery technologies in the neural prosthesis applications. The RF approach is believed to be the most promising technique for such applications. Its advantages include continuous availability of power to an implanted unit, and ability to control the implanted unit with the external device using the same RF link [1].

The issues of power supply and data communication of the neural prosthetic devices have gained major breakthrough with the RF technology. A wireless RF link system in general includes (1) an external unit and (2) an implanted unit (i.e. the microimplant). The external unit modulates signals and transmits power and the modulated signals to the implanted unit in a fashion of electromagnetic wave via a coil named transmission coil. The implanted unit couples the electromagnetic wave through a coil called receiving coil following a signal demodulating circuit and a frequency-to-dc rectifying circuit. Several literatures showed the RF technology is effective and can be practically used in the clinical applications as a transcutaneous power and data link [2-9].

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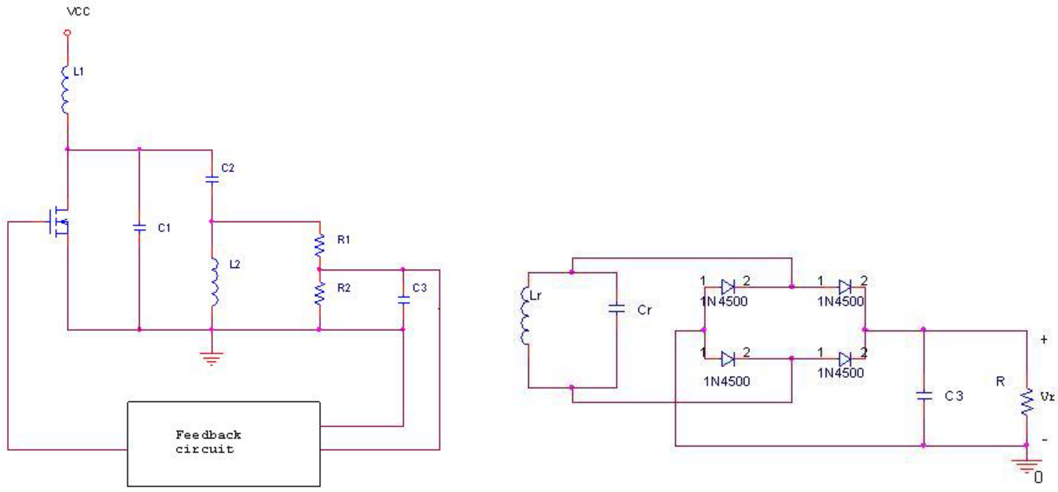

(a) (b)

Figure 1. (a) Class E power transmission circuit, and (b) receiving circuit

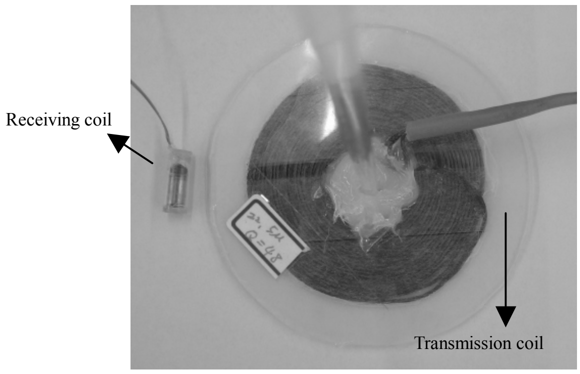

Figure 2. A transmission coil and a receiving coil

An issue is that RF transmission frequencies affect power attenuation. A micro-implant will not function properly if there is not enough power to supply it. Unfortunately, RF transmission frequencies used in applications vary when among of signal to be transmitted to micro-implants differs from one application to another. This study intends to develop models to assess how power attenuation is related to RF transmission frequencies. To do so, a wireless RF power transmitting/receiving system was developed. Common radio frequency range applied in neural prosthesis (500 kHz ~ 2 MHz) was used in the study. Studies of power transmission in air and in pork were conducted.

Methods

In order to conduct the studies of power transmission and then to derivate assessment models for estimating power received by a micro-implant which is positioned at a designated location within bio-tissues, an RF power transmission/receiving system must be developed first. Studies of power transmission in air were tested to verify the functionality of the developed system. To conduct the studies of power attenuation in bio-tissues, we used pork as the material in the experiments.

Development of the RF system

The RF power transmission/receiving circuitry development contains the circuitry implementation and transmission coil implementation. The RF power transmission system is very much based on a Class E power amplifier. The circuit of the power transmission system is shown in Figure 1(a). The Class E power amplifier can be operated at a sonant frequency range between 500 kHz and 2 MHz by altering the value of C_2 in Figure 1(a). Power receiving circuitry development contains receiving coil implementation and power regulation circuitry implementation. The receiving system is composed of receiving coil, tuning capacitor, bridge rectifier, parallel capacitor and resistor. Figure 1(b) shows the power receiving circuit. Voltage V_r is the DC voltage to be used by the receiver; and the receiving power equals to V_r^2 / R.

Figure 2 shows the transmission coil and the receiving coil. The transmission coil was made by 59 litz wires with each 0.11 mm (AWG37) in diameter. The litz wires are stranded together to become a bundle whose diameter is about 1.15 mm. Twenty three bundle turns were used to form the transmission coil, which has internal diameter 2cm and external diameter 7cm. The receiving coil was made by 65 litz wires with each 0.12 mm in diameter. These wires wind around a cylindrical ferrite rod. The ferrite rod is 0.4cm in diameter, 1.2cm in length, and the relative permeability (μ_f) is about 400. To prevent damage of the ferrite rod from tissue moisture while conducting studies, a packing material was used to wrap up the ferrite rod. As a result, the height of the receiving coil including a packing material is 2cm totally.

Power transmission in air

In this test, the output power to be transmitted was set to 2 Watts. The measurement distances between the transmitting

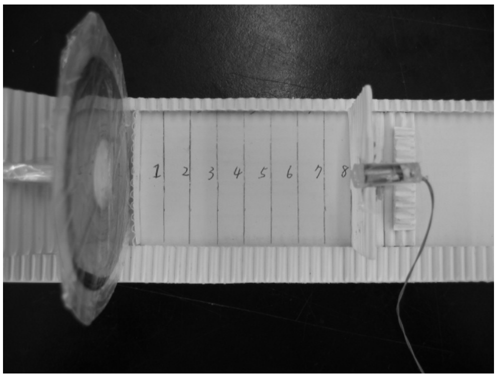

Figure 3. Measurement apparatus of power transmission in air

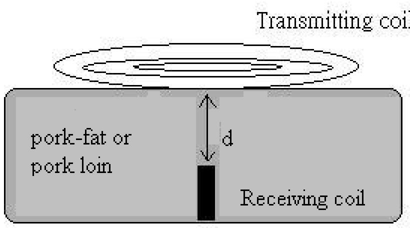

Figure 4. A schematic diagram showing pork loin and pork-fat studies

coil and the receiving coil ranges from 1 cm to 5cm. The measurement apparatus is shown in Figure 3. The output transmission power was oscillated at the frequencies of 1.70 MHz, 1.07 MHz, 773 kHz, and 658 kHz.

Power attenuation studies in pork

In the study of pork experiments, we used two tissues: pork-fat and pork loin. Three major parameters were considered in the study: (1) RF power transmission frequency, (2) thickness of the pork tissues, and (3) tissue section.

Pork fat and pork loin were sliced to 1cm in thickness, and then stacked them up from 1cm to 5cm. The section area of each pork fat and pork loin is about 10cm*10cm. Transmitted power is measured in pork-fat and in pork loin at distance ***d*** between the transmission coil and the receiving coil from 1cm to 5cm. The experimental setup is illustrated in Figure 4. The RF output power and the transmission frequencies used in the pork experiments are same as those tested in the air study.

Study Results

The data obtained from the experiments are presented in two ways: (1) comparisons of received power in various medium, and (2) comparisons of received power in various power transmission frequencies. First, for a given power transmission frequency, the experimental data are organized to compare the power attenuation in various media such as air, pork loin, and pork fat. The second presentation is to observe how the power attenuation differs when different transmission frequencies are applied on each of the medium.

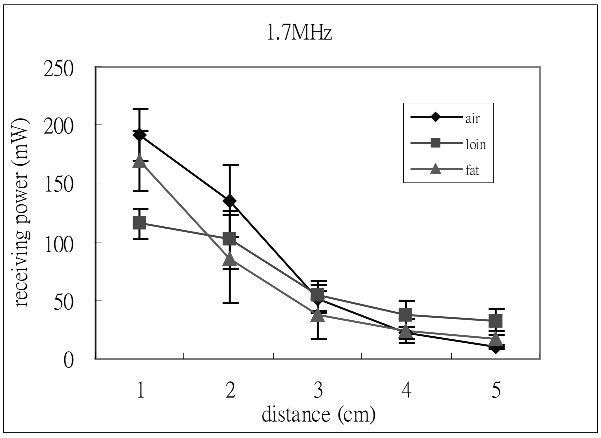

Figure 5. Comparisons of received power in air, in pork loin, and in pork fat at frequency 1.7MHz (n=15)

Comparisons of received power in various medium

Figures 5, 6, 7, 8 are summary of our experimental results for the power transmission frequencies 1.70 MHz, 1.07 MHz, 773 kHz, and 658 kHz, respectively. Each of them shows the comparisons of received power in air, in pork loin, and in pork fat. From these experimental results, an observation is that the received power decays exponentially when the transmission distance increases. For this reason, the mathematic model of power attenuation versus thickness of the transmission media can be formulated as $y = b_0 e^{-\alpha x}$, where *y* and *x* represents received power and transmission distance, respectively; and α is defined as the decay constant. In order to develop models for each given transmission frequency and medium, regression analyses were applied on the obtained data. The resultants are presented in the equations from (1) to (12).

$$y_{1.7MHz,\, air} = 512.793e^{-0.7844x} \quad (1)$$

$$y_{1.7MHz,\, fat} = 270.374e^{-0.5831x} \quad (2)$$

$$y_{1.7MHz,\, loin} = 175.481e^{-0.3573x} \quad (3)$$

$$y_{1.07MHz,\, air} = 459.685e^{-0.6861x} \quad (4)$$

$$y_{1.07MHz,\, fat} = 296.556e^{-0.7768x} \quad (5)$$

$$y_{1.07MHz,\, loin} = 164.333e^{-0.5546x} \quad (6)$$

$$y_{773kHz,\, air} = 441.12e^{-0.7601x} \quad (7)$$

$$y_{773kHz,\, fat} = 204.662e^{-0.7389x} \quad (8)$$

$$y_{773kHz,\, loin} = 157.552e^{-0.6021x} \quad (9)$$

$$y_{658kHz,\, air} = 233.17e^{-0.736x} \quad (10)$$

$$y_{658kHz,\, fat} = 100.415e^{-0.7751x} \quad (11)$$

$$y_{658kHz,\, loin} = 78.626e^{-0.6504x} \quad (12)$$

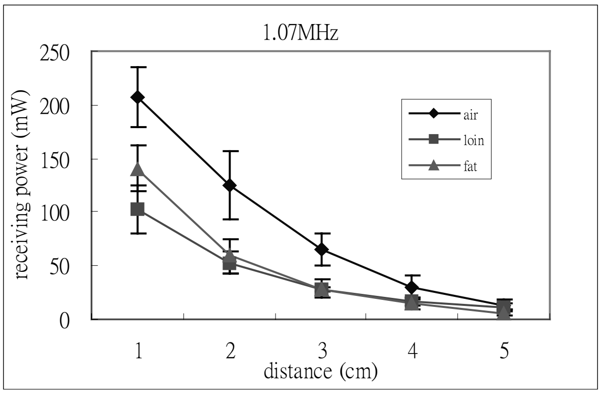

Figure 6. Comparisons of received power in air, in pork loin, and in pork fat at frequency 1.07 MHz (n=15)

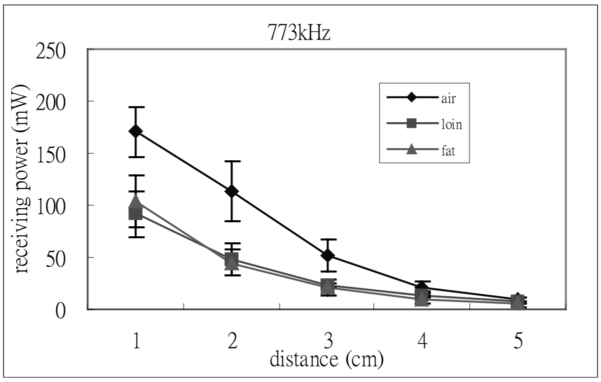

Figure 7. Comparisons of received power in air, in pork loin, and in pork fat at frequency 773 kHz (n=15)

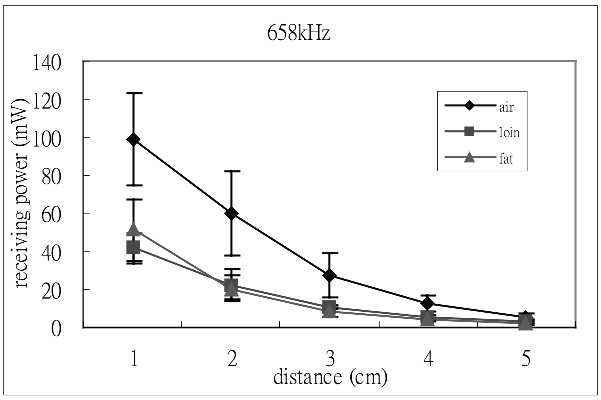

Figure 8. Comparisons of received power in air, in pork loin, and in pork fat at frequency 658 kHz (n = 15)

Comparisons of received power in various transmission frequencies

As stated in the introduction section, the main purpose of this study is to facilitate positioning a micro-implant into bio-tissues for a given RF transmission frequency. This is because RF transmission frequencies affect power attenuation. To assure a micro-implant receive sufficient power to perform its functions, it is important to understand the difference of received power for a given medium thickness when the applied power transmission frequency is changed. Figures 9, and 10 illustrate the relationship for the media of pork loin and pork fat, respectively.

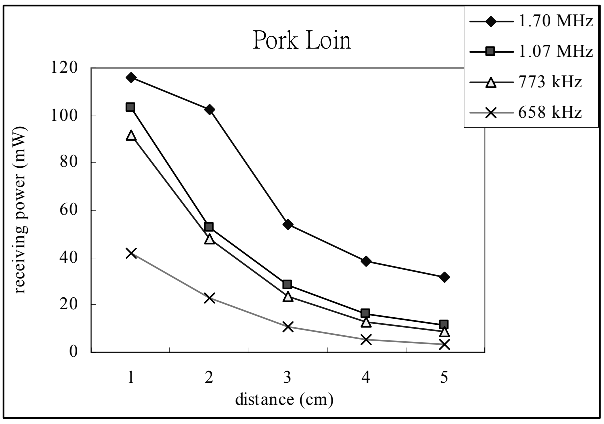

Figure 9. Comparisons of received power in frequencies 1.70 MHz, 1.07 MHz, 773 kHz, and 658 kHz in pork loin

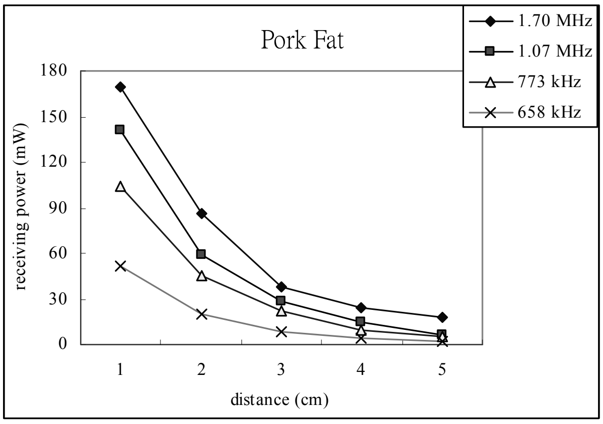

Figure 10. Comparisons of received power in frequencies 1.70 MHz, 1.07 MHz, 773 kHz, and 658 kHz in pork fat.

Discussions and Conclusions

As the study results shown above, the received power is proportional to the power transmission frequency. This can be explained by the following derivation. A transmission coil induces a magnetic flux density $\boldsymbol{B_0}$. Then the magnetic flux density received by the receiving coil is given by

$$B = B_0 \sin(\omega t) \tag{13}$$

The magnetic flux in the received coil is the integration of $\boldsymbol{B}$ within a cross section area, $\boldsymbol{S}$,

$$\Phi = \int_s Bds = B' \sin(\omega t) \tag{14}$$

Thus, the coupled (received) voltage can be re-written as follows:

$$V_r = -\frac{d\Phi}{dt} = -B'\omega \cos(\omega t)(volts) \tag{15}$$

It proves power received in the receiving coil is proportional to frequency (ω). Theoretically, the distance between the both coupling coils is not a concern based on the equation (15). However, when the thickness of the media increases, power received is no longer governed by the equation (15). This is because the power attenuation rate is transmission media dependent. To be more precise, the power attenuation rate has to do with dielectric constants (ε) of transmission media. In this study, we carried out the dielectric constant measurements for pork fat and pork lion. The dielectric constant of air and the measured dielectric constants of pork fat and pork lion are listed in the following:

- $\varepsilon_{r, air}$: 1
- $\varepsilon_{r, fat}$: 125.27
- $\varepsilon_{r, loin}$: 1106.09

As shown in Figures 5, 6, 7, and 8, for all frequencies used in the study the power attenuation of pork loin is the slowest, pork fat is the next, and air is the steepest. In terms of dielectric constants, the power transmitted in the lowest dielectric constant medium such as air is attenuated very fast when the thickness increases. This explains why the power received in pork loin is more than those in pork fat and in air when the transmission power travels the media deeper even though in the beginning the received power in pork loin is far less.

The experiment results in Figures 9 and 10 clearly provide a mean to estimate the received power difference between two applied transmission frequencies in the two bio-tissues. In addition, an observation is that the received power decays exponentially when the transmission distance increases. More importantly, we based on this observation developing mathematic models, the equations (1) – (12), with regression analysis. These models are derived from the data that were specifically resulted from the experimental setup and the parameters used in this study. Thus, they may not be able to be applied in most cases. However, it is the methodology that we believe it can be extended to derive more generic and useful models for clinical applications.

References

[1] Orhan Soykan, "Power sources for implantable medical devices" *Device Technology & Applications ELECTRONICS,* 2002.

[2] P. Talonen, J. Malmivuo, G. Baer, H. Markkula, V. Hakkinen, "Transcutaneous, dual channel phrenic nerve stimulator for diaphragm pacing " *Med. & Biol. Eng. & Comput.,* 21, 21-30, 1983.

[3] N. de N. Donaldson, "Voltage regulators for implants powered by coupled coils" *Med. & Biol. Eng. & Comput.,* 21, 756-761, 1983.

[4] P. R. Troyk, Martin A. K. Schwan, "Closed-loop class E transcutaneous power and data link for microimplants" *IEEE Trans. on Biomedical Engineering,* vol. 39, No. 6, June 1992.

[5] M. Nardin and K. Najafi, "A multichannel neuromuscular microstimulator with bi-directional telemetry" *the 8th international conference on solid-state sensors and actuators and eurosensors IX. Stockholm, Sweden,* June 25-29, 1995.

[6] T. Cameron, G. E. Loeb, R. A. Peck, J. H. Schulman, P. Strojnik and P. R. Troyk, "Micromodular implants to provide electrical stimulation of paralyzed muscles and limbs" *IEEE Trans. Biomedical Engineering,* 44: 781-790, 1997.

[7] B. Ziaie, M. D. Nardin, A. R. Coghlan and K. Najafi, "A signal-channel implantable microstimulator for functional neuromuscular stimulation" *IEEE Trans. On biomedical engineering,* Vol. 44, No. 10, October 1997.

[8] G. E. Loeb, R. A. Peck, W. H. Moore, and K. Hood, " BION system for distributed neural prosthetic interfaces " *journal of Medical Engineering and Physics,23: 9-11,* 2001.

[9] P. R. Troyk, I. E. Brown, W. H. Moore and G. E. Loeb, " Development of BION technology for functional electrical stimulation: bi-directional telemetry " *in 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Istanbul, Turkey,* October 25-28, 2001.