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Analysis of Current Density and Specific Absorption Rate in Biological Tissue Surrounding an Air-core Type of Transcutaneous Transformer for an Artificial Heart

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Abstract— **This paper reports on the specific absorption rate (SAR) and the current density analysis of biological tissue surrounding an air-core type of transcutaneous transformer for an artificial heart. The electromagnetic field in the biological tissue surrounding the transformer was analyzed by the transmission-line modeling method, and the SAR and current density as a function of frequency (200k-1MHz) for a transcutaneous transmission of 20W were calculated. The model's biological tissue has three layers including the skin, fat and muscle. As a result, the SAR in the vicinity of the transformer is sufficiently small and the normalized SAR value, which is divided by the ICNIRP's basic restriction, is 7×10^{-3} or less. On the contrary, the current density is slightly in excess of the ICNIRP's basic restrictions as the frequency falls and the output voltage rises. Normalized current density is from 0.2 to 1.2. In addition, the layer in which the current's density is maximized depends on the frequency, the muscle in the low frequency (<700kHz) and the skin in the high frequency (>700kHz). The result shows that precision analysis taking into account the biological properties is very important for developing the transcutaneous transformer for TAH.**

I. Introduction

Transcutaneous energy transmission (TET) is a method of supplying energy to a totally implantable artificial heart (TAH) from outside the body without injuring the skin [1]. This method is superior to others because it reduces the possibility of infectious diseases and keeps the skin uninjured, and also it provides the patient postoperatively with a better quality of life. In this method, a pair of coils, called transcutaneous coils, is used for energy transmission. Various types of transcutaneous coils have been studied, including the air-core type [2-6] and the externally-coupled type [7-9]. The authors have been developing both types of transformer and have obtained high-energy transmission efficiencies of greater than 94% between the internal coils and external coils.

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To make this method practical, we must investigate the electromagnetic influence of TET on biological tissue. Electromagnetic influences include the thermal effect and stimulant action. Although we have already investigated the thermal effect caused by electromagnetic induction due to the externally-coupled transcutaneous transformer [9], an investigation of the thermal effect and stimulant action caused by an air-core type transcutaneous transformer has not been performed.

This paper reports on the thermal effect and stimulant action caused by electromagnetic induction due to an air-core type transcutaneous transformer. The specific absorption rate; SAR, which is defined as the power of an electromagnetic wave absorbed into biological tissue per unit mass, is used as an index of the thermal effect. And, current density, which is defined as the current magnitude per unit area, is used as an index of the stimulant action. In this paper, both the SAR and current density are analyzed by the transmission-line modeling (TLM) method [10] and are compared with the basic restrictions defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [11].

II. Method

A. Construction of the transcutaneous energy transmission system

Fig. 1 shows a block diagram of the TET system. The changed AC power is transmitted inside the body using electromagnetic induction between two air-core coils placed inside and outside the body (transcutaneous transformer). The internal coil (secondary coil) is embedded under the skin. A maximum rating power of 20W in the TET system is required to power the TAH. Fig. 2 shows the transcutaneous transformer examined in this paper. The external coil has an outside diameter of 90 mm (35 turns), an inside diameter of 20 mm and a thickness of 1 mm. The internal coil has an outside diameter of 60 mm (20 turns), an inside diameter of 20 mm and a thickness of 1 mm. The coils are made of copper litz-wire, in consideration of the skin effects. An AC-to-AC energy transmission efficiency of 94.5% (maximum) is obtained between the frequencies of 500-800 kHz at a power output of 20W [6].

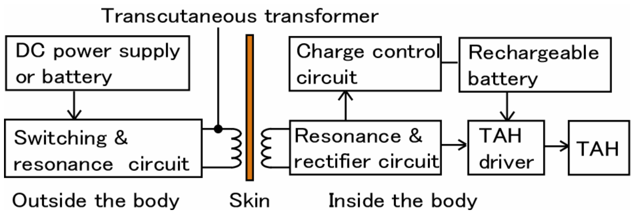

Fig. 1. Block diagram of the energy transmission system for a total artificial heart (TAH).

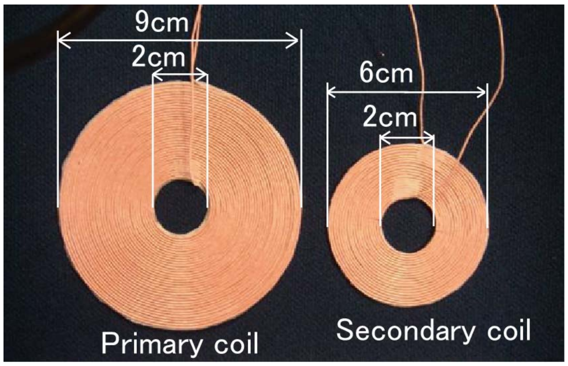

Fig. 2. The air-core type of transcutaneous transformer used in the experiment.

TABLE I
BASIC RESTRICTIONS FOR TIME VARYING ELECTRICAL AND MAGNETIC FIELDS DEFINED BY ICNIRP.

	Frequency range (Hz)	SAR (Localized SAR, head and trunk) (W/kg)	Current density for head and trunk (mA/m^2)
Occupational exposure	100k-10M	10	f/100, f(Hz)
General public exposure	100k-10M	2	f/500, f(Hz)

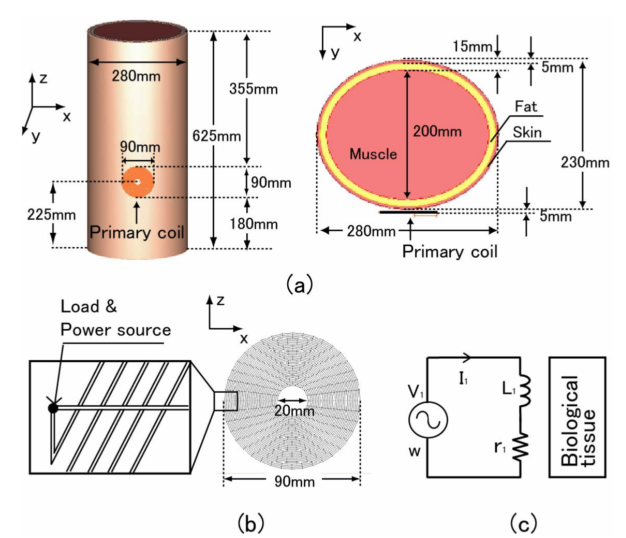

Fig. 3. (a) Analyzed model, (b) magnified figure of the external coil, and (c) equivalent circuit of the analyzed model.

B. Estimation of SAR

SAR is expressed by Equation (1):

$$SAR = \frac{\sigma E^2}{\rho} \tag{1}$$

where E is the electric field's root mean square (V/m), σ is the biological tissue's electrical conductivity (S/m) and ρ is the biological tissue's density (kg/m^3). Table I shows the basic restrictions on the SAR, as defined by the ICNIRP.

C. Estimation of current density

The current density J is expressed by Equation (2) [12]:

$$J = \pi R f \sigma \mu H \tag{2}$$

where H is the magnetic field's root mean square (A/m), σ is the biological tissue's electrical conductivity (S/m), f is the frequency (Hz), μ is the magnetic permeability (H/m) and R is the radius of the loop for current induction (m).

D. The TLM method

TLM is based on an analogy between the electromagnetic field and the grid of transmission lines. A mathematical derivation of a TLM method can be directly obtained from a full wave time-domain solution to Maxwell's equations. In this paper, "Micro-Strips Ver.7" (Flomerics, Japan branch), the electromagnetic simulator, employing the TLM method, is used to analyze the SAR and magnetic field H. Substituting magnetic field H in Equation (2) yields the current density.

E. Model for numerical analysis

A model for numerical analysis is shown in Fig. 3(a). The body's trunk is modeled to an elliptical cylinder. The biomedical tissue has three layers: skin (a thickness of 5 mm), fat (a thickness of 10 mm) and muscle (the rest). Fig. 4 shows the electrical properties of the biological tissue used in this model; (a) is the conductivity and (b) is the relative permittivity. This paper uses the conductivity and relative permittivity values as defined by the IFAC Institute for Applied Physics, "Nello Carrara" [13]. Here, an average value of 1000 kg/m^3 is used to represent the density of biological tissue consisting of skin, fat and muscle [14].

The air-core type of transcutaneous transformer (outside diameter: 90 mm, inside diameter: 20 mm) is placed 5 mm away from the trunk. The supply source and the resistance are placed at the coil's terminal, as shown in Fig. 3(b).

The analysis model's equivalent circuit is shown in Fig. 3(c). The magnitude of V_1 remains constant at 1000 V, and the magnitude of r_1 is adjusted, as is the current value I_1 for real. The model for numerical analysis by TLM had grids of 1mm in the coil's vicinity, and from 3 to 23 mm in other regions.

SAR and current density are analyzed as a function of the frequencies 200 kHz and 1000 kHz (200 kHz each) and output voltages of 12 V and 24 V, with a constant output power of 20 W.

III. Result and Discussion

A. SAR

The SAR distribution with the frequency of 600 kHz is shown in Fig. 5. Fig. 5(a) is the SAR distribution of a y-z plane through the analysis model's central axis, and (b) is the SAR distribution of an x-y plane; z=225 mm. These results show that the SAR is large near the external coil, and its maximum value appears in the skin layer which has a distance from the external coil of 5 mm.

The analytical results of the maximum SAR as a function of each frequency are shown in Fig. 6. The long dashed line indicates an output voltage of 24 V, the short dashed line indicates an output voltage of 12 V, and the mark indicates the analytical point. In addition, the voltage across the external coil with an output voltage of 24 V is shown in Fig. 6 by the full line. These results show that the SAR gets larger as the frequency and output voltage rise. The maximum value is 14 mW/kg, and falls well below the ICNIRP's basic restrictions for the general public exposure (2 W/kg). The normalized SAR, which is divided by its basic restrictions, is 7×10^{-3} or lower (<1, safety value).

Comparing the results of the SAR with the voltage across the external coil, their slopes correspond very well. It is thought that the SAR depends on the voltage across the external coil.

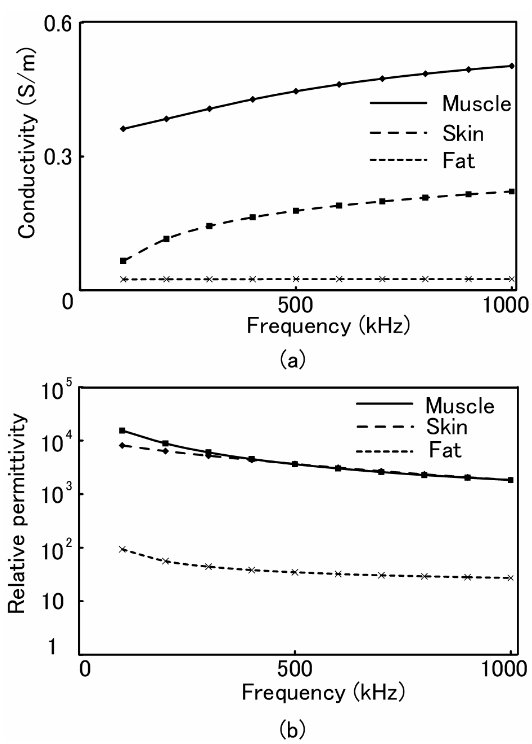

Fig. 4. (a) The conductivity and (b) relative permittivity values defined by IFAC

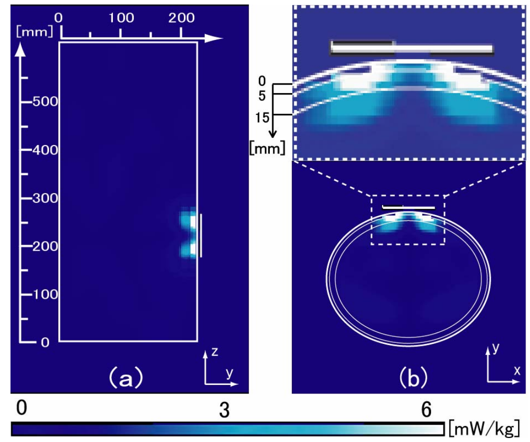

Fig. 5. Distribution of the SAR (600kHz)

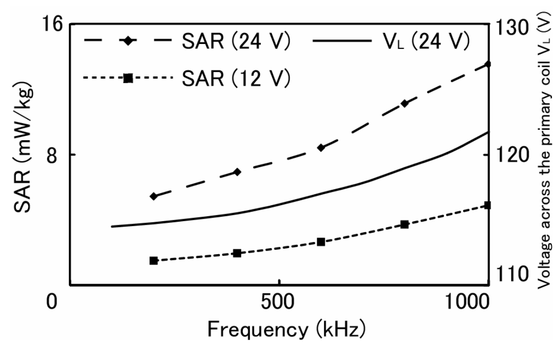

Fig. 6. Maximum SAR as a function of the frequency

B. Current density

The analytical results of the maximum current density as a function of each frequency are shown in Fig. 7. The short, dashed line indicates an output voltage of 12 V, the long dashed line with the mark indicates an output voltage of 24 V, and the full line shows the basic restrictions. As for the results under 700 kHz, the current density is maximized in the muscle layer at a distance of 20 mm from the body's surface. With regard to the results over 700 kHz, the current density is maximized in the skin layer at a distance of 5 mm from the body's surface. Also, the current density gets larger as the frequency and output voltage rise.

The normalized current density, which is divided by the ICNIRP's basic restrictions for the occupational exposure, is investigated here and is shown with the external coil's current in Fig. 8. The heavy, short, dashed line and the heavy, long, dashed line show the external coil's current when the output voltage is 12 V and 24 V, respectively. The normalized current density is safe when the value is under 1, on the condition of the output voltage of 12 V, or over 250 kHz at the output voltage of 24 V.

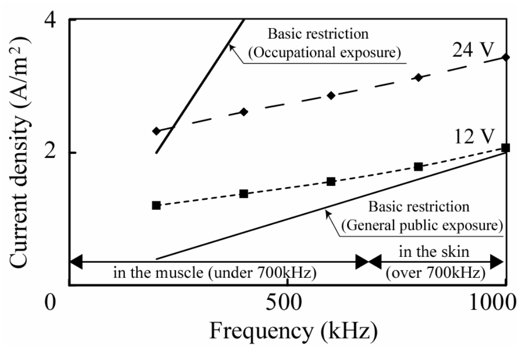

Fig. 7. Maximum current density as a function of the frequency.

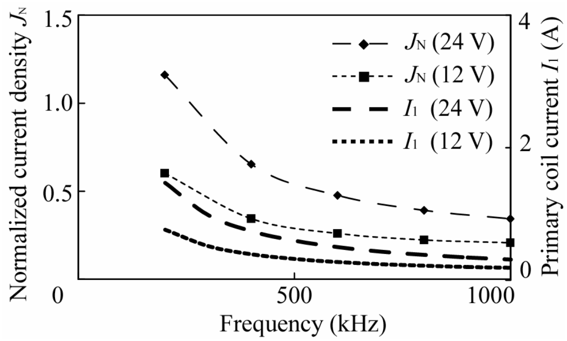

Fig. 8. Normalized current density as a function of the frequency.

Comparing the results of normalized current density with the external coil's current, their slopes correspond very well. This indicates the deep relationship between the external coil's current and normalized current density. This suggests that a decrease in the external coil's current causes the reduction of the normalized current density.

IV. Conclusions

In this paper, SAR and current density in biological tissue surrounding an air-core type of transcutaneous transformer were analyzed. First, the electromagnetic field in the biological tissue surrounding the transformer was analyzed by TLM, and the current density and SAR as a function of frequency were calculated. We found that the SAR in the vicinity of the transformer was sufficiently small for a transcutaneous transmission of 20 W, but the current density was slightly in excess of the ICNIRP's basic restrictions. High frequency and low output voltage caused reduction of the normalized current density. In addition, the layer in which the current's density was maximized depended on the frequency, the muscle layer being in the low frequency and the skin layer in the high frequency.

The result shows that precision analysis, taking into account the biological properties, is very important for developing the transcutaneous transformer for TAH. Therefore the results in this paper will be very valuable data, not only for the artificial heart system, but also for other implanted devices with the TET system.

In the future, experiments using the bioelectric phantom or animal experiments will be performed and evaluated with coils that account for the transmission characteristics and safety.

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References

[1] T. Masuzawa, E. Tastumi, Y. Taenaka, M. Nakamura, S. Endo, H. Takano, K. Koshiji, Y. Fukui, and K. Tsukahara, " Progress of an Electrohydraulic Total Artificial Heart System with a Separate Energy Converter," ASAIO Journal, vol. 45, pp. 471-477, 1999

[2] J. C. Schuder, H. E. Stephenson, Jr. and J.F.Townsend, "Energy transfer into a closed chest by means of stationary coupling coils and a portable high-power oscillator," Trans. Amer. Soc. Artif. Int. Organs, vol. 7, pp. 327–331, 1961

[3] K. Kosihji, K. Masuda, E. Shu, T. Utsunomiya, S. Takatani, H. Takano, and T. Akutsu, "Development of transcutaneous energy transmission system for totally implantable artificial heart," Jpn. J. Artif. Organs, vol. 18, no. 2, pp. 533-536, 1989

[4] Y. Abe, I. Fujimasa, K. Imachi, M. Nakajima, K. Mabuchi, T. Chinzei, K. Maeda, Y. Orime, M. Asano, H. Hata, S. Hosaka, A. Kouno, T. Ono, and K. Atsumi, "Development of transcutaneous energy transmission system for totally implantable artificial heart: Effect of coreless coils," Jpn. J. Artif. Organs, vol. 16, no. 1, pp. 212–215, 1987

[5] T. Mussivand, A. Hum, M. Diguer, K. S. Holmes, G. Vecchio, R. G. Masters, P. J. Hendry, and W. J. Keon, "A transcutaneous energy and information transfer system for implanted medical devices," ASAIO Journal, vol. 41, pp. M253-M258, 1995

[6] M. Nukaya, A. Sakane, K. Shiba, and T. Tsuji, "Transcutaneous energy transmission system for an artificial heart –Improvement of the transmitting efficiency in various load resistance-," The 55th Chugoku-section Joint convention record of Institutes of Electrical and Information Engineers, Japan, 2004, pp. 189-190

[7] K. Shiba, E. Shu, K. Koshiji, K. Tsukahara, K. Tsuchimoto, T. Ohu-mi, T. Nakamura, S. Endo, T. Masuzawa, E. Tatsumi, Y. Taenaka, and H. Takano, " Efficiency improvement and in vivo estimation of externally-coupled transcutaneous energy transmission system for a totally implantable artificial heart," Proceedings of the 19th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Oct.30-Nov.2, 1997, pp. 2503-2505

[8] K. Shiba, E. Shu, K. Koshiji, K. Tsukahara, T. Nakamura, T. Masuzawa, E. Tatsumi, Y. Taenaka, and H. Takano, " A transcutaneous energy transmission system with rechargeable internal back-up battery for a totally implantable total artificial heart," ASAIO Journal, vol. 45, no. 5, pp. 466-470, Sep-Oct. 1999

[9] K. Shiba, K. Koshiji, E. Tatsumi, Y. Taenaka, and H. Takano, " Analysis of specific absorption rate in biological tissue surrounding transcutaneous transformer for an artificial heart," J Artif Organs, vol. 5, no. 2, pp. 91-96, 2002

[10] C. Christopoulos, *The transmission-line modeling method*. New York, IEEE Press, 1995

[11] ICNIRP, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300GHz)," Health Phys. Vol. 74, no. 4, pp. 494-522, 1998

[12] J. P. Reilly, "Peripheral nerve stimulation by induced electric currents: exposure to time-varying magnetic fields," Med. Bio. Eng. Computing, vol. 27, pp. 101-110, 1989

[13] IFAC. Calculation of the Dielectric Properties of Body Tissues in the frequency range10Hz-100GHz. Available:http://niremf.ifac.cnr.it/tissprop/htmlclie/htmlclie.htm

[14] Japan Society of Medical Electronics and Biological Engineering, *Handbook of clinical engineering*. Tokyo, Corona Publishers, 1994