Fundamental Analysis of Electromagnetic Induction Effects on Human Biological Tissues: An Analysis of Four Human Models at 0.9 MHz Frequency

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Abstract Transcutaneous energy transmission systems (TETS), which use electromagnetic induction to wirelessly transfer energy, have been widely used as energy transmission systems for artificial hearts. TETS help to improve the patient’s quality of life and reduce the risk of infection caused by percutaneous connections. However, to provide protection against the established adverse health effects caused by electromagnetic induction, it is necessary to quantify the amount of energy absorbed by biological tissues. In this study, we sought to analyze the specific absorption rate (SAR) and the internal electric field $E$ of human biological tissues surrounding an air-core coil transcutaneous energy transmission transformer. We used four types of human biological tissue models with different genders, ages, weights, heights, and body sizes, at a frequency of 0.9 MHz. Each tissue model consisted of dry skin, wet skin, fat, muscle, and cortical bone tissue. A primary coil was placed on the surface of the dry skin tissue, while the secondary coil was embedded between the wet skin and fat tissues. The transmission power was 15 W, and the load resistance was 38.4 $\Omega$. The simulation data was obtained using the FEKO electromagnetic simulator. The results showed that the SAR and $E$ for adult models (male and female) were well below the limits specified by ICNIRP for both general public and occupational exposure. For children, the SAR and $E$ exceeded the ICNIRP general public exposure limits but remained below the limits prescribed by ICNIRP for occupational exposure. These results show that it is safe to transmit 15 W of energy in an adult.

Keywords: transcutaneous energy transmission, biological tissues, SAR, internal electric field.

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1. Introduction

The number of available donors for heart transplantations does not show any improvement [1–3]. The development of a total artificial heart and ventricular assist device therefore has been a continuously researched area [4, 5]. However, there are problems to be solved when these artificial heart systems or ventricular assist devices are put into practical use. An example is the problem of supplying energy to drive the system actuator. Energy is usually supplied by using a cable through a hole in the skin. However, infections caused by skin penetration often occur, and the patient’s quality of life (QOL) declines considerably. Transcutaneous energy transmission systems (TETS) are therefore being extensively researched and employed to solve these problems.

The use of TETS is the most reliable mean to transfer energy from the outside to the inside of the body without invasive processes. It uses inductive coupling between two coils to wirelessly transfer energy. A primary coil is placed outside the body and a secondary coil is placed subcutaneously inside the body [6–9]. This method was developed to decrease the risk of infections from the percutaneous driveline and simultaneously enhance the patient’s QOL.

However, due to electromagnetic induction produced by the coil, there is a possibility of adverse health effect in neighboring human biological tissues [10, 11]. Therefore, we sought to analyze the electromagnetic induction effect on human biological tissues, including the specific absorption rate (SAR)–a thermal effect–and the internal electric field ($E$)–a stimulant action.

In a previous study, we analyzed both SAR and $E$ in dry skin, wet skin, fat, muscle, and cortical bone of a male human model surrounding an air-core coil transcutaneous energy transmission system with frequencies between 0.3 and 1.5 MHz [12]. We found that SAR and $E$ were well below the limits prescribed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [13, 14], for general public and occupational exposure at frequencies ranging between 0.9 and 1.2 MHz. However, considering the efficiency of the inverter circuit, it is better to use lower frequencies, because the switching losses of the inverter circuit increase at higher frequencies (over 1 MHz). From the above findings, we confirmed that 0.9 MHz was the best transmission frequency for TETS, considering its efficiency and electromagnetic induction effects. In this study, we investigated whether our TETS is safe for human bodies of different physical properties by analyzing SAR and $E$ in four human anatomical models with different genders, ages, weights, heights, and body sizes, using a frequency of 0.9 MHz. The transmission power was 15 W and the load resistance was 38.4 $\Omega$.

2. Methods

2.1 Transcutaneous energy transmission systems

Figure 1 shows a block diagram of TETS and Fig. 2 shows their
equivalent circuit. In Fig. 1, an external power inverter is used to convert a direct current (DC) power source to alternating current (AC) power to drive the primary coil. The external power of this transcutaneous transformer is then transferred to the internal components by electromagnetic induction. A rectifier circuit at the output of the secondary coil is used to convert the AC power back to DC, and charge the internal battery through a charge control circuit.

In the equivalent circuit shown in Fig. 2, $V_1$, $V_2$, $L_1$, $L_2$, $C_1$, $C_2$, $r_1$, $r_2$, $M$, and $R_L$ are the input and output voltages, primary and secondary inductances, primary and secondary capacitances, transmitting and receiving coil resistances, mutual inductance, and load resistance, respectively. The power supply voltage is transmitted to the secondary side via the primary coil, and is then applied to the load $R_L$.

### 2.2 Electromagnetic induction effects

Electromagnetic induction effects include SAR and $E$. SAR is used as an indicator of thermal effects, to measure the amount of radiation absorbed into biological tissues subjected to electromagnetic induction. It can be mathematically defined by the following equation:

$$\text{SAR} = \frac{\sigma E^2}{\rho}$$  \hspace{1cm} (1)

where $\sigma$ is the electric conductivity of the biological tissue (S/m), $E$ is the root mean square amplitude of the electric field (V/m), and $\rho$ is the density of the biological tissue (kg/m$^3$). SAR is expressed in units of watts per kilogram (W/kg). $E$ is taken as an indicator of stimulant action and is generally expressed by the following equation:

$$E = \frac{J}{\sigma}$$  \hspace{1cm} (2)

where $J$ is the current density (A/m$^2$).

In this study, the basic SAR and $E$ limits for occupational and general public exposure established by ICNIRP were employed. Occupational exposure refers to adults exposed at their workplaces, generally under known conditions, as a result of performing their regular or assigned job activities. In contrast, the term general population refers to individuals of all ages and with various health statuses, which might increase the variability of the individual susceptibilities [13, 14].

Table 1 shows the limits prescribed by the ICNIRP. We determined the electromagnetic influence of TETS on human biological tissues including dry skin, wet skin, fat, muscle and cortical bone by comparing the SAR and $E$ obtained from the analysis with the limits prescribed by the ICNIRP.

### 2.3 Analysis model of an air-core coil

Figure 3 shows the dimensions of the primary and secondary coils used in this study. The method of moments (of the FEKO

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### Table 1 Basic occupational and general public exposure limits for time varying electric and magnetic fields.

| Exposure Characteristics | Frequency Range | Localized SAR (head and trunk) (W/kg) | Frequency Range | Internal Electric Field (all tissues of head and body) (V/m) |
|--------------------------|-----------------|----------------------------------------|-----------------|-------------------------------------------------------------|
| Occupational Exposure    | 100 kHz–10 MHz  | 10                                     | 3 kHz–10 MHz    | $2.7 \times 10^f$                                           |
| General Public Exposure  | 100 kHz–10 MHz  | 2                                      | 3 kHz–10 MHz    | $1.35 \times 10^f$                                          |

$f$: frequency [Hz]
The numbers of turns of the primary and secondary coils were 35 and 20, respectively. This coil model was divided into small mesh cells with a wire segment length and radius of 5 mm and 0.4 mm, respectively. The distances between the primary and secondary coils for Model 1, Model 2, Model 3, and Model 4 were 5.0 mm, 5.0 mm, 3.7 mm and 3.0 mm, respectively. The primary coil was placed on the skin tissue and the secondary coil was placed between the skin and fat tissue.

### 2.4 Four biological tissues models for analysis

**Figure 4** shows an image of the anatomical models of Duke, Ella, Billie, and Thelonious, from which the thicknesses of the tissues were obtained. We visualized and measured the thicknesses of skin, fat, muscle, and cortical bone tissues of each anatomical human model using the AMIRA 3D software to create simple models of human biological tissues for analysis (**Fig. 5**). A finite element method (FEM) was used to perform the numerical analysis of SAR and $E$ based on the tissue models.

Model 1 was obtained from Duke, a 34-year-old male model with a height of 177.0 cm and a weight of 72.4 kg. Model 2 was obtained from Ella, a female model 26 years of age, 163.0 cm in height and 58.7 kg in weight. Model 3 was obtained from Billie, an 11-year-old girl with a height of 147.0 cm and a weight of 35.4 kg. Finally, Model 4 was a six-year-old boy named Thelonious, 117.0 cm in height and 19.3 kg in weight. These models were obtained from the Virtual Family of the Foundation for Research on Information Technologies in Society (ITIS) [15]. The analysis models are shown in **Figs. 5 and 6**. The sizes and thicknesses of dry skin, wet skin, fat, muscle, and cortical bone tissues for Model 1, Model 2, Model 3, and Model 4 are shown in **Table 2**. **Table 3** shows the distances between fat and cortical bone tissue and between cortical bones for each model.

The dry skin, wet skin, fat, muscle, and cortical bone tissues were divided into a mesh of small cells with tetrahedral edge lengths of 1.5, 1.8, 3.0, 6.0, and 4.0 mm. The length, width and height of Model 1 were $120 \times 120 \times 37$ mm; the corresponding dimensions were $120 \times 120 \times 35.7$ mm for Model 2, $120 \times 120 \times 19.4$ mm for Model 3, and $120 \times 120 \times 18.9$ mm for Model 4.

![Fig. 3 Air-core coil model for numerical analysis.](image)

![Fig. 4 Images of the anatomical models of Duke, Ella, Billie and Thelonious.](image)

![Fig. 5 Biological tissue analysis model (Model 1).](image)
and the load resistance was 38.4 Ω. It is virtual family, we measured the thicknesses of skin, fat, muscle, and bone tissue of each model to observe the electromagnetic effects induced by the coil. Table 5 shows the maximum SAR obtained for Model 1, Model 2, Model 3 and Model 4 at evaluation areas 1, 2, 3, and 4. For both Model 1 and Model 2, the lowest SAR (approximately 0.52 mW/kg) were obtained in cortical bone, and the highest SAR (approximately 0.8 W/kg) in wet skin tissue. For Model 3, the lowest SAR was also obtained in cortical bone (approximately 1.24 mW/kg) and the highest SAR (approximately 1.42 W/kg) in wet tissue. For Model 4, the lowest and highest SAR were approximately 1.55 mW/kg in cortical bone and 3.5 W/kg in wet skin tissue, respectively.

We found that the SAR for Model 4 were higher than those for Model 1, Model 2, and Model 3. They exceeded the ICNIRP limits for general public exposure, but remained below the limit prescribed by ICNIRP for occupational exposure. The SAR results for Model 1, Model 2, and Model 3 were well below the internationally accepted limits.

### 3.2 Internal electric field, $E$

Table 6 shows the results obtained for the internal electric fields measured at evaluation areas 1, 2, 3, and 4 of Models 1, 2, 3 and 4. For Models 1 and 2, the lowest $E$ (approximately 6.4 V/m) were obtained in cortical bone tissue and the highest $E$ (approximately 86.2 V/m) in dry skin tissue. For Models 3 and 4, the lowest $E$ were also obtained in cortical bone tissue (approximately 96.0 V/m), while the highest $E$ of 97.5 V/m for Model 3 and 142.0 V/m for Model 4, respectively, were obtained in dry skin.

The above results show that $E$ for Model 1 and Model 2 were well below the ICNIRP limits for general public and occupational exposure, whereas $E$ for Model 3 and Model 4 exceeded the ICNIRP limit for general public exposure (but remained below the ICNIRP occupational exposure limit).

### 4. Discussion

In this paper, we analyzed the SAR and internal electric field $E$ for four types of human biological tissue models surrounding an air-core coil transcutaneous energy transmission transformer at a frequency of 0.9 MHz and transmitting power of 15 W. From the analysis results obtained for both SAR and $E$, we can conclude that the SAR and $E$ for adults (Model 1 and Model 2) were well below the limits specified by ICNIRP for both general public and occupational exposure. For 10- to 19-year-old adolescents (Model 3), SAR and $E$ remain below the ICNIRP limits for general public exposure. For children younger than 10 years of age (Model 4), the highest SAR and $E$ were found, both exceeding the ICNIRP limits for general public exposure, but remained below the limits for occupational exposure.

According to the results obtained, Model 4 shows the highest SAR. This is because Model 4 has the smallest distance be-

### Table 2 Tissue thickness for each model.

| type of tissues | Model 1 | Model 2 | Model 3 | Model 4 |
|----------------|---------|---------|---------|---------|
| dry skin [mm]  | 0.2     | 0.2     | 0.1     | 0.1     |
| wet skin [mm]  | 3.9     | 4.0     | 2.6     | 1.9     |
| fat [mm]       | 10.3    | 10.6    | 3.6     | 2.9     |
| muscle [mm]    | 22.6    | 20.9    | 13.1    | 14.0    |
| cortical bone [mm] | 16    | 14      | 8       | 7       |

Four evaluation areas were used, and are shown in Fig. 5. Evaluation area 1 was placed horizontally and included all of the dry skin and part of the wet skin. Evaluation area 2 was a vertical rectangle placed in the center of the tissue model. Evaluation area 3 was also rectangular and was placed vertically 22.5 mm from the edge of the coil. Finally, evaluation area 4 was an identical rectangle, but placed vertically at the edge of the coil. The magnetic and electric field distributions were obtained for these evaluation areas, and constitute the output data of the experiment. Table 4 shows the electrical properties of the dry skin, wet skin, fat, muscle, and cortical bone tissue that were obtained from the Nello Carrara Institute for Applied Physics (IFAC) [16]. The densities of the dry skin, wet skin, fat, muscle, and cortical bone tissue were 1050, 1050, 918, 1060 and 1900 kg/m³, respectively [17, 18].

We analyzed and compared the SAR and $E$ for each model at a frequency of 0.9 MHz when the transmitting power was 15 W and the load resistance was 38.4 Ω.

### 3. Results

#### 3.1 Specific absorption rate, SAR

Using the above-mentioned four different human models from the ITIS virtual family, we measured the thicknesses of skin, fat, muscle, and bone tissue of each model to observe the electromagnetic effects induced by the coil. Table 5 shows the maximum SAR obtained for Model 1, Model 2, Model 3 and Model 4 at evaluation areas 1, 2, 3, and 4. For both Model 1 and Model 2, the lowest SAR (approximately 0.52 mW/kg) were obtained in cortical bone, and the highest SAR (approximately 0.8 W/kg) in wet skin tissue. For Model 3, the lowest SAR was also obtained in cortical bone (approximately 1.24 mW/kg) and the highest SAR (approximately 1.42 W/kg) in wet tissue. For Model 4, the lowest and highest SAR were approximately 1.55 mW/kg in cortical bone and 3.5 W/kg in wet skin tissue, respectively.

We found that the SAR for Model 4 were higher than those for Model 1, Model 2, and Model 3. They exceeded the ICNIRP limits for general public exposure, but remained below the limit prescribed by ICNIRP for occupational exposure. The SAR results for Model 1, Model 2, and Model 3 were well below the internationally accepted limits.

### Table 4 Electrical properties of each tissue type.

| electrical properties | dry skin | wet skin | fat | muscle | bone |
|-----------------------|----------|----------|-----|--------|------|
| conductivity [S/m]    | 0.011    | 0.215    | 0.025 | 0.495  | 0.024 |
| relative permittivity | 1004.9   | 2027.4   | 28.069 | 2061.5 | 149.71 |

#### Table 3 Distances of fat tissue to cortical bone and between cortical bones for each model.

| model     | distance between fat and cortical bone [mm] | distance between cortical bone and cortical bone [mm] |
|-----------|---------------------------------------------|-----------------------------------------------------|
| Model 1   | 5.5                                         | 24                                                  |
| Model 2   | 6.2                                         | 21                                                  |
| Model 3   | 4.7                                         | 12                                                  |
| Model 4   | 6.1                                         | 10.5                                                |
between the primary and secondary coils (3 mm), which causes an increase in energy absorption by the skin. We consider that the depth of the secondary coil affects the values of SAR and $E$. In this analysis, the secondary coil was implanted between wet skin and fat, to reduce risk of invasive surgery. However, since the results of SAR and $E$ exceeded their respective limits, it is necessary to change the position of implantation of secondary coil for children, such as in the case of Thelonious, a six-year-old boy. In future research, we will attempt to analyze a model with the secondary coil implanted between fat and muscle. Table 2 shows that the depth between fat and muscle in Model 4 (4.9 mm from the surface of dry skin) is greater than that between wet skin and fat in Model 1 (4.1 mm from the surface of dry skin). On one hand, the disadvantage of deeper implant position is that the

| model | evaluation area | dry skin [mW/kg] | wet skin [mW/kg] | fat [mW/kg] | muscle [mW/kg] | cortical bone [mW/kg] | ICNIRP (Occupational) [mW/kg] | ICNIRP (General) [mW/kg] |
|-------|-----------------|-----------------|-----------------|------------|---------------|----------------------|-----------------------------|---------------------------|
| 1     | 1               | 79.3            | 732.3           | -          | -             | -                    |                            |                           |
|       | 2               | 66.0            | 695.2           | 40.4       | 41.1          | 0.62                 | 10000                       | 2000                      |
|       | 3               | 61.1            | 702.9           | 54.9       | 37.3          | 1.25                 |                            |                           |
|       | 4               | 18.2            | 89.5            | 8.2        | 74.7          | 2.60                 |                            |                           |
| 2     | 1               | 75.9            | 697.5           | -          | -             | -                    |                            |                           |
|       | 2               | 62.5            | 652.3           | 41.5       | 36.9          | 0.52                 | 10000                       | 2000                      |
|       | 3               | 61.1            | 672.9           | 51.2       | 37.1          | 0.93                 |                            |                           |
|       | 4               | 18.5            | 88.4            | 7.6        | 63.9          | 2.36                 |                            |                           |
| 3     | 1               | 101.6           | 1422.9          | -          | -             | -                    |                            |                           |
|       | 2               | 101.6           | 1338.2          | 67.4       | 81.8          | 1.24                 | 10000                       | 2000                      |
|       | 3               | 90.6            | 1382.2          | 94.2       | 74.8          | 2.54                 |                            |                           |
|       | 4               | 15.1            | 73.9            | 12.1       | 102.2         | 4.94                 |                            |                           |
| 4     | 1               | 215.2           | 3539.2          | -          | -             | -                    |                            |                           |
|       | 2               | 177.6           | 3080.6          | 111.1      | 93.4          | 1.55                 | 10000                       | 2000                      |
|       | 3               | 178.0           | 3224.1          | 190.1      | 90.2          | 2.18                 |                            |                           |
|       | 4               | 13.2            | 68.8            | 15.1       | 114.6         | 3.59                 |                            |                           |

Table 6 $E$ values obtained from the analysis of Model 1, Model 2, Model 3 and Model 4 (rms, $f = 0.9$ MHz).

| model | evaluation area | dry skin [V/m] | wet skin [V/m] | fat [V/m] | muscle [V/m] | cortical bone [V/m] | ICNIRP (Occupational) [V/m] | ICNIRP (General) [V/m] |
|-------|-----------------|----------------|----------------|-----------|--------------|---------------------|-----------------------------|-------------------------|
| 1     | 1               | 86.2           | 59.8           | -         | -            | -                   | 243                         | 121.5                   |
|       | 2               | 76.5           | 56.5           | 39.0      | 8.9          | 6.4                 | 243                         | 121.5                   |
|       | 3               | 75.6           | 57.4           | 43.3      | 8.9          | 8.6                 |                            |                         |
|       | 4               | 41.6           | 20.9           | 17.4      | 12.7         | 14.4                |                            |                         |
| 2     | 1               | 84.3           | 58.4           | -         | -            | -                   | 243                         | 121.5                   |
|       | 2               | 76.5           | 56.5           | 39.0      | 8.9          | 6.4                 | 243                         | 121.5                   |
|       | 3               | 75.6           | 57.4           | 43.3      | 8.9          | 8.6                 |                            |                         |
|       | 4               | 41.6           | 20.8           | 16.7      | 11.7         | 13.7                |                            |                         |
| 3     | 1               | 97.5           | 83.4           | -         | -            | -                   | 243                         | 121.5                   |
|       | 2               | 97.5           | 80.9           | 49.7      | 13.2         | 9.9                 | 243                         | 121.5                   |
|       | 3               | 92.1           | 82.2           | 58.8      | 12.7         | 14.2                |                            |                         |
|       | 4               | 37.6           | 19.0           | 21.1      | 14.8         | 19.8                |                            |                         |
| 4     | 1               | 142.0          | 131.5          | -         | -            | -                   | 243                         | 121.5                   |
|       | 2               | 129.0          | 122.7          | 63.8      | 14.1         | 9.6                 | 243                         | 121.5                   |
|       | 3               | 129.1          | 125.5          | 83.5      | 13.9         | 13.2                |                            |                         |
|       | 4               | 35.2           | 18.3           | 23.5      | 15.7         | 16.9                |                            |                         |
The transformer’s efficiency becomes slightly lower because of the longer transmission distance. On the other hand, the advantage is the decrease in the risk of tissue necrosis, which is mitigated because of increased blood flow in the skin tissue on the secondary coil.

The SAR values obtained are largely dependent on the conductivity of the tissue type. Wet skin tissue has higher conductivity (0.215 S/m at 0.9 MHz) than dry skin, and hence it shows the highest SAR. In addition, the largest eddy currents ($J$) in the wet skin and the large power losses also contribute to the highest values of SAR observed in wet skin tissue.

The electric field are also largely dependent on the position of the primary coil. Dry skin is the tissue closest to the primary coil, and therefore shows the highest $E$. As shown in Fig. 7, the maximum magnetic field distribution in dry skin is larger than the magnetic field distribution in wet skin. The maximum magnetic field strength in dry skin at evaluation areas 1, 2, 3, and 4 are marked by points A, B, C and D in this figure. The magnetic field strengths obtained in A, B, C, and D were 716.1, 697.1, 748.7, and 249.9 A/m, respectively. In the same figure, the maximum magnetic field strengths in wet skin for evaluation areas 1, 2, 3, and 4 are marked by points a, b, c, and d, with values of 700.5, 702.5, 701.4 and 231.4 A/m, respectively. Dry skin shows a larger magnetic field than wet skin, except in evaluation area 2, resulting in greater electric field.

To further examine whether $E$ depends on the permittivity, the relative permittivity $\varepsilon_r$ of dry and wet skin in Model 4 was set to 2061.5 (the relative permittivity of muscle tissue). The maximum electric field strength in dry skin at evaluation areas 1, 2, 3, and 4 are marked by points a, b, c, and d, with values of 700.5, 702.5, 701.4 and 231.4 A/m, respectively. Dry skin shows a larger electric field than wet skin, except in evaluation area 2, resulting in greater electric field.

According to the $E$ distribution results for Model 1 (Fig. 9), points I and J corresponded to 9.94 V/m and 20.3 V/m, respectively. There was a large difference in $E$ at the cortical bone between evaluation area 2 (point I) and evaluation area 4 (point J). However, the distances between the center point and these measurement points (I and J) are almost the same.

Then, we assumed that this difference was mainly caused by the arrangement and shape of the cortical bones, which were not symmetrical with respect to the center axis of the coils. To confirm these effects, we further analyzed Model 6, in which the shape of the cortical bones was changed from columnar to flat plate. Figure 10 shows the result for $E$ in Model 6. Points K and L, which are at the same positions as those of points I and J, corresponded to 14.8 V/m and 15.6 V/m, respectively. According to these results, $E$ at point K coincided approximately with $E$ at point L. We then conclude that the arrangement and shape of the cortical bones significantly affect $E$. We suspect that this causes the large differences in electrical properties between muscle and cortical bones. This result indicates that a model including cortical bones is important for the analysis of electromagnetic induction effects of TETS.

In future work, we will observe SAR and $E$ in human biolog-
5. Conclusion

The values of SAR and $E$ depend largely on the distances between the primary coil and the secondary coil. In this study, we demonstrated that the SAR and $E$ for a six-year-old child model exceeded the international regulation limits for general public exposure.

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