Improvement of Tissue-Equivalent Phantom with Capillary Blood Flow for Measurement of Temperature Rises due to Microwave Radiation

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1. Introduction

In recent years, interaction between the electromagnetic (EM) wave radiated from electronics devices and human body should be evaluated quantitatively. In general, the specific absorption rate (SAR) is one of the indexes for evaluation on the EM energy absorption of the human body. In order to measure the SAR, the experimental measurement by use of a biological tissue-equivalent phantom, whose electrical properties are equivalent to human is widely used [1]. However, in the case of evaluation of thermal effect on biological tissue, not only the SAR evaluation but also consideration of temperature rise in the body is necessary. The temperature rise inside the body can be calculated numerically under several assumptions. However, it is difficult to estimate the temperature rise inside the body by measurement and a few studies were performed [2], [3]. Consequently, the authors developed tissue-equivalent phantom with cooling effect by capillary blood flow [4]. In this phantom, cooling effect by capillary blood flow is modeled as the circulating saline water into interspaces of a number of the tissue-equivalent semi-hard phantoms processed small. However, this phantom has the problem with low reproducibility of flowing uniformity of the saline water. In this study, new type of phantom is developed to improve the reproducibility. Moreover, comparison of the cooling effect between the conventional and the proposed models by resultant temperature rise around the coaxial-slot antenna, which is used for thermal treatment of cancer, inside the phantom was measured.

2. Development of phantom

2.1 Phantom Structure

Figure 1 shows the structure of developed phantom model. In order to simulate the cooling effect by capillary blood flow, a number of small tissue-equivalent semi-hard phantoms are filled to an acrylic shell and 0.35 % saline water is sprinkled uniformly. The value of the conductivity of the 0.35 % saline water is 2.16 S/m, which is almost the same value as the human blood at 2.45 GHz. The blood flow rate can be controlled by varying the amount of sprinkled saline water.

![Figure 1: Structure of phantom model.](image)
2.2 Phantom Characteristics

Figures 2(a) and (b) show the shapes of small sized phantom of the conventional and the proposed models, respectively. The phantom of the conventional model was processed in short cored (diameter: approx. 2 mm, length: several tens of millimeter) as shown in Fig. 2(a). However, this type has the problem with low reproducibility of flowing uniformity of the saline water. Consequently, in order to improve this problem, the phantom was processed in small sphere (diameter: 10 mm) as shown in Fig. 2(b). Additionally, both phantoms were composed of water, polyethylene powder, agar and so on. Moreover, glycerin was added only to the proposed model to improve water holding property. Table 1 shows the physical properties of the phantoms and the muscle tissue (target values). From table 1, both electrical properties of the conventional and the proposed models are almost equivalent to the human muscle. Table 2 shows filling rate and the amount of the saline water. Here, filling rate means proportion of coded and spherical phantoms in space volume. In this phantom, circulating saline water is proper for cooling effect by capillary blood flow, though the flow rate of saline water was not equal to blood flow rate because the structure of the phantom is different from that of human. The flow rate of saline water at flow ratio ×1 was adjusted to obtain nearly equated temperature rise given by solving bioheat transfer equation [5] of blood flow rate as $8.3 \times 10^{-6}$ m$^3$/kg·s at heating experiments in either model. In addition, temperature rise in the case of flow ratio ×2 was measured for comparison.

![Figure 2: Shape of phantom.](image)

(a) Conventional model.                                (b) Proposed model.

Table 1: Physical properties of the phantoms and the muscle tissue (target values).

<table>
<thead>
<tr>
<th></th>
<th>Conventional model (Coded phantom)</th>
<th>Proposed model (Spherical phantom)</th>
<th>Muscle (target) [6], [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity $\varepsilon_r$</td>
<td>48.6</td>
<td>48.1</td>
<td>47.0</td>
</tr>
<tr>
<td>Conductivity $\sigma$ [S/m]</td>
<td>2.17</td>
<td>2.00</td>
<td>2.21</td>
</tr>
<tr>
<td>Density $\rho$ [kg/m$^3$]</td>
<td>1,000</td>
<td>1,145</td>
<td>1,020</td>
</tr>
</tbody>
</table>

$\varepsilon_r$, $\sigma$ are the values at 2.45 GHz.

Table 2: Filling rate and amount of the saline water.

<table>
<thead>
<tr>
<th></th>
<th>Conventional model (Coded phantom)</th>
<th>Proposed model (Spherical phantom)</th>
<th>Muscle (Calculation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling rate [%]</td>
<td>73.0</td>
<td>58.0</td>
<td>-</td>
</tr>
<tr>
<td>Flow rate $F$</td>
<td>Saline water flow</td>
<td>Blood flow [6]</td>
<td></td>
</tr>
<tr>
<td>[×10$^{-6}$ m$^3$/kg·s]</td>
<td>Flow ratio ×1</td>
<td>1.90</td>
<td>2.21</td>
</tr>
<tr>
<td></td>
<td>Flow ratio ×2</td>
<td>4.02</td>
<td>4.66</td>
</tr>
</tbody>
</table>

3. Heating experiments by microwave radiation

3.1 Experimental setup

In order to compare the cooling effect of the proposed model with the conventional model, the temperature rise was measured by heating experiments using the coaxial-slot antenna. Figure 3 shows the structure of the coaxial-slot antenna for interstitial microwave heating [8]. This antenna (operating frequency: 2.45 GHz) is used for thermal treatment of cancer. Figure 4 shows the phantom model for measurement using the coaxial-slot antenna and temperature observation points. The coaxial-slot antenna is inserted to almost center of the above-mentioned phantom. In addition, fiber optic thermosensors were placed around the tip of the antenna, and temperature rises caused by microwave radiation was recorded. The heating time was 300 seconds, and the radiation power from the antenna was estimated to be approximately 7.0 W.
3.2 Comparison by amount of saline water

Figure 5(a) shows measured temperature transitions of the conventional and the proposed models around the antenna tip. Here, the measured temperature rises without the sprinkled saline water were also measured for comparison. From Fig. 5(a), thermal steady state is observed by circulating the saline water in both models, and good agreements are observed between the measured and calculated temperature transitions. In addition, with regard to temperature transitions after feeding off, decreasing temperature of proposed model was larger than conventional model due to the difference of filling rate. Figure 3(b) shows measured temperature transitions of changing flow rate. From Fig. 3(b), temperature rise in the steady state corresponding to the difference of flow rate was confirmed. It was found from the result that the proposed model has a similar availability to the conventional model.

3.3 Comparison by flow directions of saline water

The difference of the cooling effect by flow directions of saline water was measured. Figure 6 shows the flow directions of saline water to the inserted coaxial-slot antenna. One was the direction vertical to the antenna axis as shown in Fig. 6(a), and the other was the direction parallel as shown in Fig. 6(b). Here, flow rates of the parallel model, which were $1.95 \times 10^6 \text{ m}^3/\text{kg}\cdot\text{s}$ and $2.44 \times 10^6 \text{ m}^3/\text{kg}\cdot\text{s}$ at the conventional and the proposed models, were almost the same as given above the vertical model. Figures 7(a) and (b) show measured temperature transitions of two directions of the conventional and the proposed models, respectively. From Fig. 7, the difference of temperature transition of the proposed model by flow direction was less than that of the conventional model. In other words, the dependence of the cooling effect on flow direction of saline water of the proposed model was less than that of the conventional model.
4. Conclusion
In this study, new type of tissue-equivalent phantom with cooling effect by capillary blood flow was developed. Moreover, comparison of the cooling effect between the conventional and the proposed models by heating experiment using the coaxial-slot antenna was investigated. As a result of measurements, good agreement was observed between the measured and the calculated temperature rises, thus the proposed model has a similar availability to the conventional model. In addition, the dependence of the cooling effect on flow direction of saline water was small compared to the conventional model. As a further study, it is necessary to consider different antennas such as antenna for external heating for hyperthermia.

References