Paper

Temperature calculations inside body during treatment by capacitive heating device

Kazuyuki Saito\textsuperscript{1a)} and Kazuki Kumagae\textsuperscript{2}

\textsuperscript{1} Center for Frontier Medical Engineering, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

\textsuperscript{2} Graduate School of Engineering, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

\textsuperscript{a)} kazuyuki.saito@faculty.chiba-u.jp

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Abstract: Hyperthermia is one of the modalities for cancer treatment, utilizing the difference of thermal sensitivity between tumor and normal tissue. In the treatment, tumor should be heated up to the therapeutic temperature between 42 and 45 °C. In Japan, large number of capacitive heating devices are employed for hyperthermic treatments. In addition, some effects, which do not need the heating more than 42 °C, such as mild hyperthermia have also been studied by use of the same heating device. Therefore, many papers, which describe effectiveness of these treatments, have been published. However, temperature distributions inside the patient body during the treatment have not been cleared. So, in this paper, numerical calculations of temperature distributions inside patient body during the capacitive heating have been described. As a result, surface of the patient body was easy to heat compared with deep region of the body. In addition, blood flow rate of a target had a large influence to its temperature.

Key Words: hyperthermia, capacitive heating, temperature distribution, blood flow rate

1. Introduction

Hyperthermia is one of the cancer treatment, utilizing the difference of thermal sensitivity between tumor and normal tissue and is one of the most effective medical applications of electromagnetic field. In this treatment, the tumor is heated up to the therapeutic temperature between 42 and 45 °C without overheating the surrounding normal tissues. The effect of other cancer treatments such as radiotherapy and chemotherapy can be enhanced by using them together with hyperthermia.

There are several heating schemes using electromagnetic energy for hyperthermia. The electromagnetic heating schemes can be classified into two such as external heating and internal heating [1]. Figure 1 illustrates these heating schemes. The internal heating can heat the target tumor directly. Therefore, it can be called localized heating. On the other hand, the external heating system using
high frequency (HF) current is widely employed especially in Japan and is called capacitive heating device [2]. Figure 2 illustrates the overview of the device. The device equips two electrodes and a generator [2]. The operating frequency is 8 MHz. The patient body is put between two electrodes and the HF current runs from one electrode to the other through the patient body. A region including the target tumors can be heated mainly by the Joule heating. In addition, the region has also been heated by the dielectric heating. However, the factor of the dielectric heating can be considered small because of low operating frequency. This heating scheme can also be called regional heating. Recently, thermal treatments are studied not only for cancer treatment (hyperthermia) but also various treatments which expect low temperature effect such as mild hyperthermia [3]. In this kind of studies, the capacitive heating device also plays an important role.

By the way, keeping of therapeutic temperature (more than 42 °C) is important for the reliable hyperthermic treatment. Therefore, the heating and the temperature measurement are both important techniques. The conventional capacitive heating device equips thin thermosensors of thermocouples. However, as far as we know, these thermosensors have been rarely used for the treatment because of their invasiveness. In addition, there are no similar studies regarding detail temperature distributions during the capacitive heating. In consideration of the current situation, temperature distributions inside a patient body have been calculated by use of high resolution human body model.

2. Analytical models and method

2.1 Device structure

The actual heating device is consisted from various parts such as generator, control unit, cooling unit, electrodes, etc. shown in Fig. 2. The most important part for the heating is the electrodes, which interpose the patient body between them. Therefore, in this study, only the circular electrodes with water boluses and feeding wires are employed for the analyses. Figure 3 illustrates an overview of the analytical model. In the actual heating device, there are some types of diameter of the electrode. In this paper, the diameters of the electrodes are set as 140, 210, and 250 mm for considering the actual device. In addition, overlay boluses (see inside the square in Fig. 3), which are expanded contact area of cooling water to the body surface, are also employed for reducing the unexpected hot spots. Table I lists parameters of the boluses and ambient temperature is set as 28 °C. Moreover, input power and heating time are assumed as 500 W and 1,800 s, respectively in all cases.
2.2 Patient (human body model)

High resolution whole body voxel model is employed as a patient. This model is developed by National Institute of Information and Communications Technology (NICT), Tokyo, Japan. The dimensions of the model such as height, weight etc. are average of male in twenties and location of all organs and bones have placed at anatomically correct positions. Details of the model are described in [4]. The model is consisted from tiny voxels whose sizes are 2 mm × 2 mm × 2 mm. Each voxel has physical properties according to its location. Table II lists a part of physical properties of the body. The parameters of all tissues (including Table II) are referred from [5].

2.3 Analytical model

In the calculation, first, the electric field inside the body was analyzed with computational electromagnetics techniques such as the finite-difference time-domain (FDTD) method [6] to calculate the specific absorption rate (SAR) by following equation:

\[
\text{SAR} = \frac{\sigma}{\rho} E^2 \quad \text{[W/kg]}
\]

where \(\sigma\) is the conductivity of the tissue [S/m], \(\rho\) is the density of the tissue [kg/m\(^3\)], and \(E\) is the electric field (rms) [V/m]. The SAR provides a measurement of the heat generated by the electric field in the biological tissue.

| Parameters                  | Values |
|-----------------------------|--------|
| Relative permittivity \(\epsilon_r\) | 83.0   |
| Conductivity \(\sigma\) [S/m] | 0.26   |
| Density \(\rho\) [kg/m\(^3\)] | 1,000  |
| Specific heat \(c\) [J/kg·K] | 4.178  |
| Thermal conductivity \(\kappa\) [W/m·K] | 0.59 |
| Temperature [°C] | 10.0   |

Table II. Physical properties of the body (partially listed). ( @ 8 MHz)

| Parameters                  | Muscle | Stomach | Liver | Fat | Skin | Bone | Tumor |
|-----------------------------|--------|---------|-------|-----|------|------|-------|
| Relative permittivity \(\epsilon_r\) | 193.7  | 304.7   | 262.2 | 15.2| 345.7| 42.6 | 193.7 |
| Conductivity \(\sigma\) [S/m] | 0.61   | 0.77    | 0.30  | 0.028| 0.26 | 0.041| 0.61  |
| Density \(\rho\) [kg/m\(^3\)] | 1,040  | 1,050   | 1,050 | 916 | 1,100| 1,990| 1,100 |
| Specific heat \(c\) [J/kg·K] | 3,500  | 3,600   | 3,600 | 2,300| 3,500| 1,300| 3,437 |
| Thermal conductivity \(\kappa\) [W/m·K] | 0.6    | 0.53    | 0.50  | 0.22 | 0.42 | 0.44 | 0.50  |
| Metabolic heat \(A_0\) [W/m\(^3\)] | 480    | 5,200   | 12,000| 300 | 1,620| 610  | 7,100 |
| Blood flow rate \(F \times 10^{-7}\) [m\(^3\)/kg·s] | 6.38   | 66.70   | 167.00| 5.07 | 19.7 | 4.07 | See Table IV
Second, the temperature distribution inside the patient body is calculated. Before performing the calculation with the temperature elevation distribution by electromagnetic energy absorption, the basal temperature \(T_0\) distribution due to metabolic heat production was evaluated. This temperature corresponds to the thermal equilibrium state without a heat stress. Finally, to achieve the temperature distribution in the body, bioheat transfer equation Eq. (2) [7] is analyzed numerically by including the obtained SAR and the basal temperature distribution, which was calculated in the preceding process. The bioheat transfer equation is given by

\[
\rho c \frac{\partial T}{\partial t} = \kappa \nabla^2 T - \rho \rho_b c_b F (T - T_b) + A_0 + \rho \cdot \text{SAR}
\]

where \(T\) is the temperature \(\left[\text{°C}\right]\), \(t\) is the time \(\left[\text{s}\right]\), \(\rho\) is the density \(\left[\text{kg/m}^3\right]\), \(c\) is the specific heat \(\left[\text{J/kg·K}\right]\), \(\kappa\) is the thermal conductivity \(\left[\text{W/m·K}\right]\), \(\rho_b\) is the density of the blood \(\left[\text{kg/m}^3\right]\), \(c_b\) is the specific heat of the blood \(\left[\text{J/kg·K}\right]\), \(T_b\) is the temperature of the blood \(\left[\text{°C}\right]\), \(F\) is the blood flow rate \(\left[\text{m}^3/\text{kg·s}\right]\), and \(A_0\) is the metabolic heat \(\left[\text{W/m}^3\right]\).

The FDTD scheme was used in a numerical calculation to solve Eq. (2). The finite-difference approximation is shown in [8]. A series of these calculations have made by our own code.

3. Calculated results
First, SAR and temperature distributions inside the patient body are explained. Figure 4 illustrates SAR and temperature distributions inside the patient body around two electrodes. The observation plane for each electrode model is a \(y - z\) plane at the body center.

In the SAR distributions, higher values are observed in skin region where \(z = 80\) mm and 250 mm. From Fig. 4, shapes of the all SAR distributions in the body are similar. However, the SAR values are different especially around the skin by electrodes sizes. In addition, the highest SAR (bright color in the figure) on the skin is observed in the smallest electrode model because of electric current concentration.

In the temperature distributions (Figs. 4(d) to (f)), there are some differences among them. It can be said that high temperature under the electrodes are induced by small electrodes. The temperatures at observation points indicated in Figs. 4(d) to (f) are listed in Table III. From Table III, the maximum temperature \(\left(57.4\ \text{°C}\right)\) is observed at observation point 3 of the smallest electrode (140 mm) model.

![Fig. 4. Calculated heating patterns under various electrode diameters.](image-url)
Table III. Temperatures of observation points.

| Diameter of electrodes | Temperatures at observation points [°C] |
|------------------------|-----------------------------------------|
|                        | No. 1 | No. 2 | No. 3 | No. 4 |
| 140 mm                 | 28.1  | 30.3  | 57.4  | 44.9  |
| 210 mm                 | 26.0  | 27.3  | 41.7  | 44.4  |
| 250 mm                 | 23.1  | 26.7  | 37.2  | 43.1  |

Table IV. Temperatures of tumor center.

| Blood flow rates of tumors $F \times 10^{-7}$[m$^3$/kg·s] | Temperature [°C] (tumor center) |
|----------------------------------------------------------|--------------------------------|
| A 5.07                                                   | 42.2                           |
| B 10.14                                                  | 40.8                           |
| C 25.35                                                  | 39.0                           |

Figure 5 shows temperature distributions inside the patient, who has a tumor (diameter: 60 mm) in his liver. The position of the tumor center is around $x = 75$ mm, $y = -320$ mm, and $z = 140$ mm. In addition, diameter of the electrodes is 210 mm. In this study, three blood flow rates of the tumor are considered. They are listed in Table IV. Basal rate A is referred from [9] and B, C are increased by two and five times for comparison. From Fig. 5, high temperature regions are observed at the region of under the electrodes and the tumor regions. It is obviously by comparison with Fig. 4(e).

In addition, Table IV summarizes temperatures of tumor center. The highest temperature value can be obtained inside the tumor whose blood flow rate is the lowest.

4. Discussion

From the calculated SAR distributions (Figs. 4(a) to (c)), high SAR values are observed at region of under the electrodes especially around the skin. This situation is the same as actual clinical treatment [10]. Although skin layer is thin, the conductivity of it is relatively high compared with the fat. This situation induces the high SAR in the skin layer. In addition, the E-field in the fat layer can be considered relatively high, because of low electric conductivity. Moreover, E-field concentrates at the border of skin and fat because of large difference of their electrical properties. Therefore, the
SAR elevation around the body surface can be observed. In the temperature distributions (Figs. 4(d) to (f)), high temperature around the skin and the fat layer can be observed. On the other hand, temperatures of deep region are not increased. Therefore, it may be said that the heating of deep region of the body is not easy by the capacitive heating device. This is a characteristics of the device that has been known previously.

However, from Fig. 5, temperature increase at the tumor region, whose blood flow rates are lower than the peripheral, can be observed. In addition, temperatures of the tumor strongly depend on their blood flow rate. Therefore, there is a possibility to heat the deep region of the body by use of capacitive heating device.

Although the heating of the deep region of the body may be possible, the undesirable hot spot of the skin and the fat layer is also problem. Therefore, structure of a bolus and an overlay bolus should continue be improved. In addition, temperature of the cooling water in the bolus must be investigated to reduce the excess thermal sense of the patient.

5. Conclusion
In this paper, calculated heating characteristics of the capacitive heating device have been introduced. As a result of some calculations, hot spots at the skin and the fat layer were observed. This result supports a problem of the clinical site. In addition, temperature increase could be found at the tumor region whose blood flow rate is lower than the peripheral.

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