Heating analysis of a realistic human model for non-invasive hyperthermia using multi-electrode applicator

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**Abstract:** We numerically analyze the heating characteristics of a realistic anatomical model of human body using multi-electrode method in the radio-wave hyperthermia of tumors. It is clarified that we can suppress heating around the electrode and achieve higher heating of tumor as compared to the conventional method.

**Keywords:** RF hyperthermia, multi-electrode, heating distribution, realistic body

**Classification:** Electromagnetic Compatibility (EMC)

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1 Introduction

In cancer hyperthermia, radio frequency (RF) wave capacitive-type heating (target temperature: 42.5 °C) is an effective treatment method [1]. In Japan, one of the proven treatment devices is the heating method using a pair of electrodes (electrode method) [2]. This non-invasive method offers wide heating range taking in account the risk of metastasis and has therapeutic effect on all tumors. However, the problem is to also heat normal cells in the region of local heating. Therefore, for the safety of treatment, the conventional method is used for heating shallow parts. On the other hand, a treatment method based on microwave coaxial antennas [3] that can heat the deeper local part has minimal invasiveness. Furthermore, in the resonance method [4] that is non-invasive and allows local heating, operating frequency (450 MHz) varies depending on size and shape of the human body. It is noted that the meaning of “local” in Refs. [2] and [4] is different from that of “local” in Ref. [3]. The former is a certain range and the latter is a pinpoint.

It is desirable to solve above-mentioned problems with the electrode method. We previously proposed a heating method with multi-electrode [5]. The numerical results of specific absorption rate (SAR) of a standard human model indicated the possibility of suppressing heat generation around electrodes and heating deeper parts by using large electrodes.

In this paper, we apply the multi-electrode method for analyzing the heating characteristics of a realistic anatomical model of the human body having tumor.

2 Human model and placement of electrode

First, Fig. 1(a) illustrates a standard human model [1] with multi-electrode applicator for explaining the multi-electrode method where left is zx plane (side), center is xy plane (top), right is xy plane (bottom). The body is made of three-layer cylinder (diameter $D_B = 300$ mm) of fat (height $H_F = 20$ mm) – muscle (height $H_M = 100$ mm) – fat (height $H_F = 20$ mm). Alternate current (frequency $f$, power $P_i$) is supplied between the large electrode (hereinafter called as $E_{\text{single}}$; diameter $D_1$, thickness $l$) and the four electrodes (hereinafter called as $E_{\text{multi}}$; diameter $D_2$, thickness $l$). There is no the phase difference in all electrodes. Furthermore, bolus (dielectric; diameter $D_B$, height $H_B$, relative permittivity $\varepsilon_r$, conductivity $\sigma$, temperature of circulating fluid $T_B$) between the electrode and the fat is placed for reducing burn injury.

Fig. 1(b) illustrates a realistic human model (adult male; Gustav at CST voxel Family, number of tissues: 51) with multi-electrode applicator where $E_{\text{single}}$ is placed in the abdomen (pit of the stomach) and $E_{\text{multi}}$ is placed in the dorsal region. Also, left is zx plane (side) and right is yz plane (side). The bolus is closely attached to human body and hence the thickness is changed according to the shape. This is the setting of the electrodes assumed the treatment of a spinal tumor. The tumor is placed at $(x, y, z) = (0, 0, -80)$ and its shape is a prolate spheroid, which is a size of 3 cm in major axis and 2 cm in minor axis. We treat both the same because the relative permittivity and conductivity of the tumor are close to those of muscle.

The finite-integration method (MW-Studio; CST) is used for numerical analysis. The SAR of heat source can be expressed by
\[ SAR = \frac{|J|^2}{2\rho \sigma} \quad \text{(W/kg)} \]  

where \( J \), \( \rho \), and \( \sigma \) are the current density, tissue density, and tissue conductivity, respectively. By using Eq. (1), rise temperature \( T \) can be determined from the following bio-heat equation:

\[ \rho \cdot C_p \frac{\partial T}{\partial t} = \kappa \cdot \nabla^2 T + \rho \cdot SAR - b(T - T_b) \]  

where \( C_p \), \( t \), \( \kappa \), \( b \), and \( T_b \) are the specific heat of tissue, heating time, thermal conductivity, blood flow constant, and blood flow temperature, respectively. The electrical and thermal constants are taken from Ref. [6]. Wiring from the feeding point up to electrodes is the same as Fig. 1, and we ignore its effect in numerical analysis [7].

Fig. 2 shows the temperature distribution (\( zx \) plane of \( y = 0 \)) of the standard human model where (a) and (b) represent the proposed and conventional methods, respectively. Also, \( f = 8 \text{ MHz} \), \( P_i = 1500 \text{ W} \), \( t = 60 \text{ min} \), air temperature \( T_a = 20 \degree \text{C} \), \( T_b = 37 \degree \text{C} \), \( D_1 = 150 \text{ mm} \), \( D_2 = 75 \text{ mm} \), \( l = 10 \text{ mm} \), \( D_B = 300 \text{ mm} \), \( H_B = 60 \text{ mm} \), \( e_r = 83 \), \( \sigma = 0.255 \text{ S/m} \), and \( T_B = 20 \degree \text{C} \). The area of large electrode and the total area of four electrodes are kept same in order to compare with the conventional method. In the proposed method shown in (a), the maximum temperature of muscle on \( E_{\text{single}} \) and \( E_{\text{multi}} \) sides is 49.4 \degree \text{C} at \( P(x, y, z) = (0, 0, 100) \) and 46.8 \degree \text{C} at \( Q = (0, 0, -100) \). The fat is cooled up to the depth of about 1 cm by the bolus, and the temperature is highest at the boundary of fat and muscle. In the conventional method shown in (b), the temperature of \( P \) and \( Q \) is equal at 45.2 \degree \text{C}.
In the proposed method, the temperature at $E_{\text{multi}}$ side is declined by about 5.6% than that at $E_{\text{single}}$ side. Current density increases at the smaller electrode and hence the heating temperature is high. However, most of the energy is absorbed in bolus. Furthermore, since the electrodes of both methods have the same area, current density of the large electrode is maintained at the same level. Because of these reasons, the proposed method is able to suppress heating around $E_{\text{multi}}$ while maintaining heating of the deeper parts.

Figs. 3(a), (b), and (c) show the temperature distribution ($xz$ plane of $y = 0$) of the realistic human model where $f = 8$ MHz, $P_i = 1500$ W, $t = 60$ min, $E_{\text{multi}}$ is placed in (a) dorsal region and (b) abdominal region respectively, while (c) is the conventional method. Other numerical conditions are the same as the standard human model. In the proposed method (a), the maximum temperature of fat at $E_{\text{single}}$ side is 45.6 °C at $P(x, y, z) = (15, 0, 102)$, and it is 38.7 °C at $Q = (-53, 0, -86)$ in the dorsal region. Temperature under electrode is high because abdominal part (shallow part) has much fat. In (b), the maximum temperature in the abdominal part on $E_{\text{multi}}$ side is 39.9 °C at $Q = (81, 0, 91)$, and it is 44.4 °C at $Q = (-50, 0, -100)$ in the dorsal part on $E_{\text{single}}$ side. Heating in the abdominal part (shallow part) is suppressed, and heating by $E_{\text{single}}$ has resulted in heating up to deeper part of bones. In the conventional method (c), the maximum temperature of fat in the abdominal region is 43.2 °C at $P(x, y, z) = (51, 0, 98)$, and it is 41.3 °C at $Q = (-50, 0, -98)$ in the spine of the dorsal part. Although heating happens from both sides, temperature is low.

Figs. 3(d), (e), and (f) show the temperature distribution ($yz$ plane of $x = 0$) of the realistic human model corresponding to Fig. 3(a), (b), and (c). In the proposed method (d), the maximum temperature of fat on $E_{\text{single}}$ side is 50.6 °C at $P(x, y, z) = (0, -40, 105)$, and it is 39.4 °C at $Q = (0, -34, -59)$ of spine (surface) on $E_{\text{multi}}$ side. In (e), the maximum temperature of fat on $E_{\text{multi}}$ side is 42.3 °C at $P(x, y, z) = (0, -57, 108)$, and it is 42.0 °C at $Q = (0, -18, -97)$ of spine (surface) on $E_{\text{single}}$ side.

Furthermore, in the conventional method (f), the maximum temperature of fat in the abdominal region is 47.3 °C at $P(0, -41, 105)$, and it is 41.3 °C at
$Q(0, -35, -61)$ in the dorsal region (surface). As can be seen from the above results, the multi-electrode placed on the abdomen is relatively selective heating of the tumor near the spine without excessive heating around the abdominal electrode.

Fig. 3. Temperature distribution of realistic human model; $f = 8$ MHz, $P_i = 1500$ W, $t = 60$ min.
in comparison with the conventional method. The average temperature in the tumor is about 41 °C, while it is about 39 °C in the conventional method. The shortage of the target temperature will be resolved if supplied power increases.

5 Conclusion

By using a realistic anatomical human model, we numerically analyzed the temperature distributions of the body part having a spinal tumor with RF hyperthermia’s multi-electrode method proposed previously. As a result, we verified decline in heating around electrodes, and deeper heating of large electrode although the effects of multi-electrode are small. The wide area slightly higher than the body temperature occurs around the tumor. However, it is known that there are few the side effects.

The next challenge is analyzing the appropriate placement of electrodes according to the types of tumor.

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