33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

A New Heating Method with Dielectric Bolus Using Resonant Cavity Applicator for Brain Tumors

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***Abstract*— In this paper, we discuss a new method of controlling heating location in the proposed resonant cavity applicator. A dielectric bolus was used to non-invasively treat brain tumors. We have already confirmed that our heating system using resonant cavity is useful to non-invasively heat brain tumors. In order to heat tumors occurring at various locations, it is necessary to control the heating area with our heating system.**

First, we presented the proposed heating method and a phantom model to calculate temperature distributions. The results of temperature distributions were discussed.

Second, a 3-D human head model constructed from 2-D MRI images was presented. The results of specific absorption rate distributions were discussed.

From these results, it was found that the proposed heating method was useful to non-invasively treat brain tumors.

I. Introduction

HYPERTHERMIA is one of the effective physical treatments of cancer. Local hyperthermia, a method of raising the temperature of a tumor up to 42 to 43°C, is useful to treat various kinds of cancer. In cases where tumors with small areas are heated, careful techniques are to avoid heating healthy tissues during hyperthermia treatments.

In the clinic, needle applicators are used for deep tumors [1], [2]. However, these applicators have some advantages and disadvantages. One of the advantages is that the direct and local heating of deep tumors is possible. Disadvantages are that needle applicators are invasive heating methods and have small heating areas. To overcome these problems, we proposed the resonant cavity applicator to non-invasively treat brain tumors [3]. In our previous study, from the results of computer simulations and animal experiments of heating a dog brain, it was found that the proposed resonant cavity applicator could heat deep regions of agar phantom and dog brain [4].

In the present paper, a dielectric bolus is used to control heating locations for non-invasive brain tumor hyperthermia treatments.

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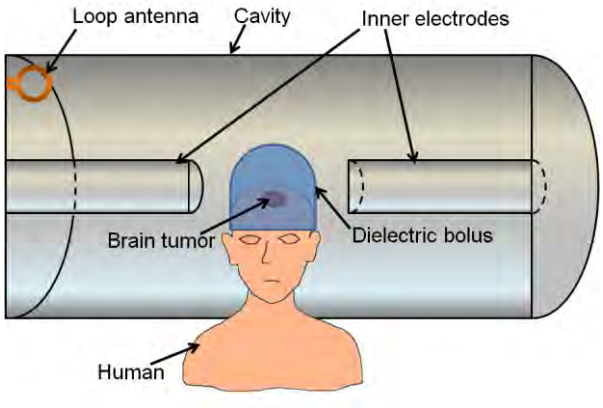


Fig. 1. Illustration of a new heating method.

First, we presented the proposed heating method and a phantom model to calculate temperature distributions using a finite element method (FEM). The results of temperature distributions were discussed. Second, a 3-D human head model constructed from 2-D MRI images was presented. The results of specific absorption rate (SAR) distributions using 3-D FEM were discussed.

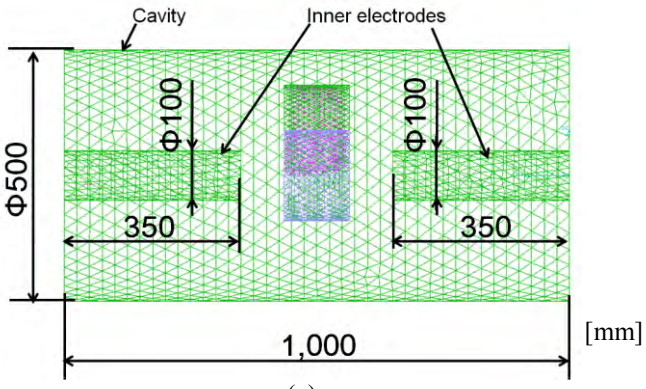
From these results, it was shown that the proposed heating method is useful to non-invasively treat brain tumors.

II. Methods

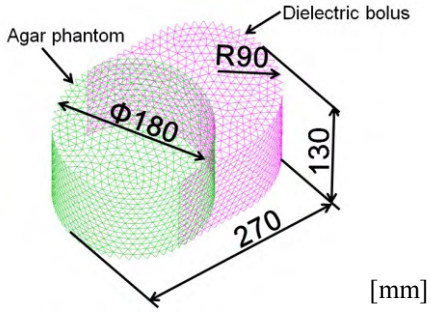
Figure 1 shows an illustration of a new method for controlling heating locations using a dielectric bolus. In Fig. 1, a human head is placed in the center of the inner electrodes. The brain tumor is heated by electromagnetic fields which correspond to resonant frequencies. These electromagnetic fields were stimulated inside the cavity without contact between the surface of the human body and the applicator.

In the proposed method, the dielectric bolus, which is filled with a dielectric such as water, is attached to a human head inside the cavity. The electrical properties of dielectrics inside the bolus are changed. Furthermore, heating locations and areas can be controlled in brain tumors.

The tissue temperature T and the SAR distributions in a human body, heated by the electromagnetic energy, can be calculated by equations (1)-(6):



(a)



(b)

Fig. 2. Calculation models;
(a) diagram of the cavity, (b) phantom model.

$$\nabla^2 E + k^2 E = 0 \tag{1}$$

$$\rho c \frac{\partial T}{\partial t} = div(\kappa \cdot gradT) + W_h - W_c + M \tag{2}$$

$$W_h = \frac{1}{2}\sigma |E|^2 \tag{3}$$

$$W_c = (F\rho)_{tissue} \times (\rho c)_{blood} \times (T - T_b) \tag{4}$$

$$M = M_0 (1.1)^{\Delta T} \tag{5}$$

$$SAR = \frac{1}{\rho} W_h \tag{6}$$

Where ρ is the volume density of tissue, c is the specific heat of tissue, κ is the thermal conductivity, σ is the electrical conductivity, $k^2=\omega^2\varepsilon\mu$, ω is the radial frequency, ε is the dielectric constant, μ is the magnetic permeability, F is the blood flow rate, T_b is the blood temperature, M_0 is the basal metabolic heat generation rate, respectively. Equations (1) and (2) can be solved numerically by the FEM. SAR distributions can be calculated by equation (6).

III. ANALYTICAL MODEL

Figure 2 shows a finite element mesh for calculating temperature and SAR distributions. Fig. 2 (a) shows the dimension of the cavity. The cavity is 500 mm in diameter and 1,000 mm in height. The inner electrodes inside the cavity are 100 mm in diameter and 350 mm in height. In order to discuss heating properties of the proposed method, the agar phantom used in a basic study is 180 mm in diameter and 130 mm in height. Fig. 2 (b) shows dimensions of agar phantom and dielectric bolus.

Figure 3 shows a 3-D anatomical human head model constructed from 2-D MRI and X-ray CT images.

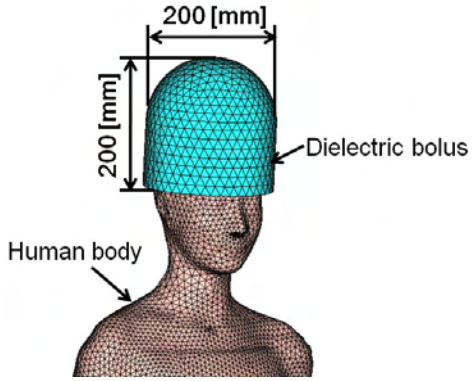


Fig. 3. Human head model for calculating SAR distributions.

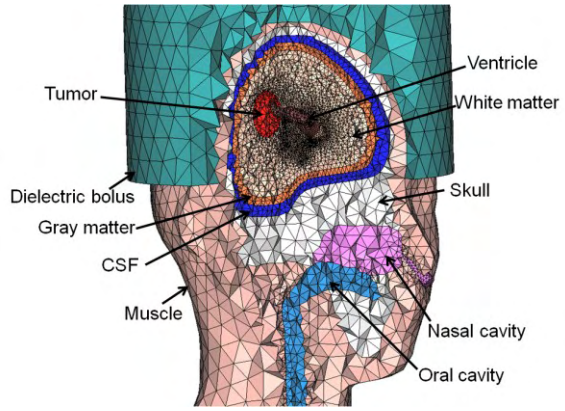
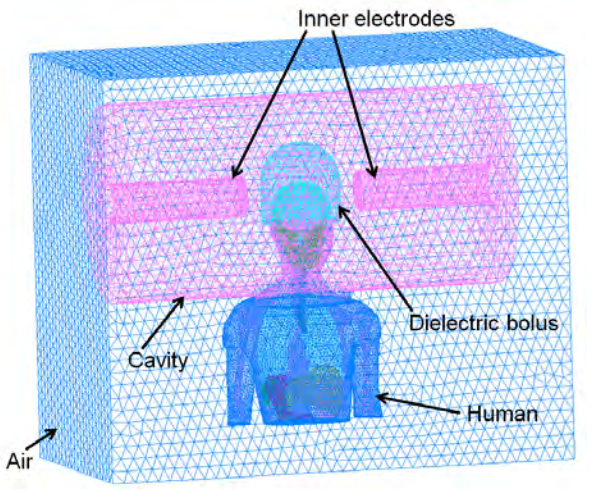


Fig. 4. Detail view of the 3-D FEM mesh human head model.



Total number of elements: 1,631,388

Fig. 5. FEM model.

TABLE I

PHYSICAL PARAMETER OF SIMPLE PHANTOM MODEL AT 150 MHZ

Tissue	σ[S/m]	ε_r	ρ[kg/m^3]	κ[W/m・℃]	c[J/kg・℃]
Agar phantom	0.61	75	1,000	0.6	4,200
Dielectric bolus	0.6	75	1,000	0.6	4,200
Air	0	1	1.165	0.025	1,010

TABLE II

ELECTROMAGNETIC PROPERTIES OF TISSUES AT 150 MHZ

Tissue	σ[S/m]	ε_r	ρ[kg/m^3]
Tumor(Muscle)	0.72719	62.179	1,040
Ventricle(CSF)	2.16060	81.169	1,010
Skull/Bone Marrow	0.024219	6.1064	1,810
Crebro Spenal Fluid(CSF)	2.16060	81.169	1,010
Gray Matter	0.60467	70.073	1,030
White Matter	0.35408	50.306	1,030
Eyeball(VitreousHumor)	1.5064	69.052	1,000
Nasal Cavity(Air)	0	1	1.165
Oral Cavity(Air)	0	1	1.165
Lung(Air)	0	1	1.165
Muscle	0.72719	62.179	1,040
Heart	0.78866	80.671	1,040
Cavity(Air)	0	1	1.165
Air	0	1	1.165
Dielectric Bolus(Pure Water)	0	74.0	1,000

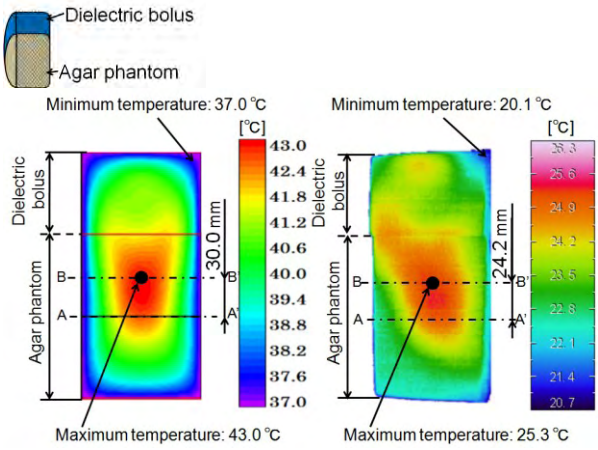
In Fig. 3, the dielectric bolus is attached to a human head. Here, by changing electrical properties of dielectrics in the bolus, the heating location and area can be controlled in the brain.

Figure 4 shows a detail view of 3-D FEM mesh of a human head model. This model consists of the skull, tumor, gray matter, white matter, certricle spinal fluid (CSF), ventricle, eyeball, etc. as shown in Fig. 4.

Figure 5 shows a FEM mesh for calculating SAR distributions. The total number of elements is 1,631,388. The physical parameters used in the calculations are listed in Table I and Table II [5]. In these computer simulations, it is necessary to consider the frequency dependencies of the relative permittivity ε_r and the electric conductivity σ shown in Table I and Table II. Here, JMAG-studio (JSOL Co. Ltd, Japan) was used in the computer simulations.

IV. RESULTS AND DISCUSSION

Figure 6 shows temperature properties of heating a cylindrical agar phantom. Fig. 6 (a) shows the temperature distribution calculated by FEM. Fig. 6 (b) shows a thermal image of the inside of the agar phantom. This image was taken by an infrared thermal camera immediately after it was heated and sliced in half. In Fig. 6 (a) and (b), lines A and A' shows the center of agar phantom. The maximum temperature appears each on line B and B', respectively. From Fig. 6,



(a) (b)

Fig. 6. Temperature distribution using a simple human head cylindrical phantom model;
(a) calcurated temeprature, (b) measured temperature.

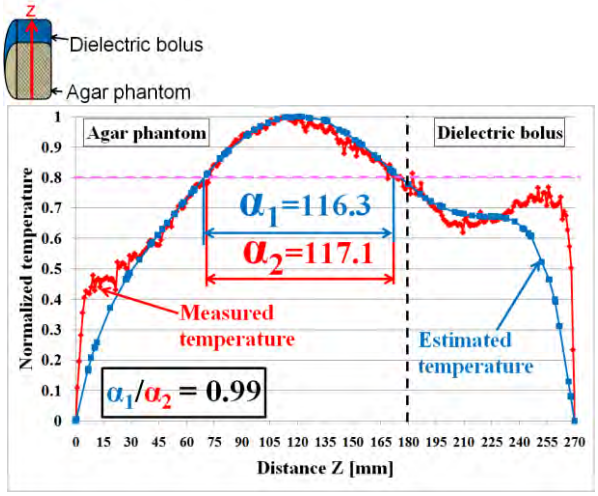
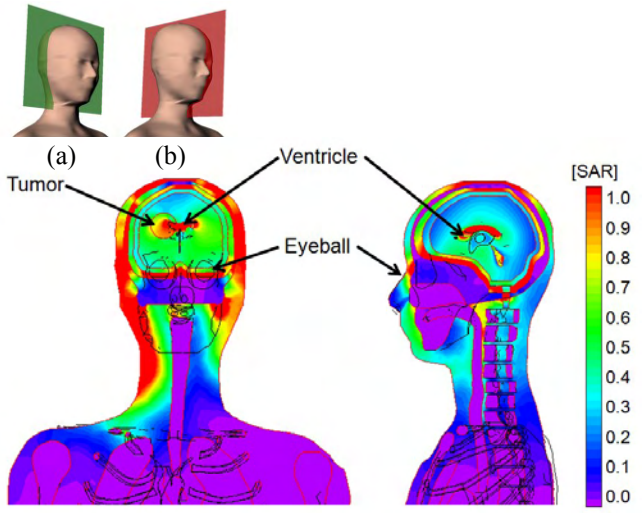


Fig. 7. Normalized temperaturedistributions along Z-axis.

it was found that the hot spot was generated at the center region of the agar phantom. The temperature increase at the center of the heated area was approximately 5°C to 6°C. Furthermore, the location of the hot spot occurred in the upper region rather than the center of the agar phantom. However, blood flow is an important factor. In living tissue, the temperature will be lower due to blood perfusion. The results shown in Fig. 6 do not account for this factor. To discuss the heating properties of this method in detail, the normalized temperature, T_N, is given by the following equation;

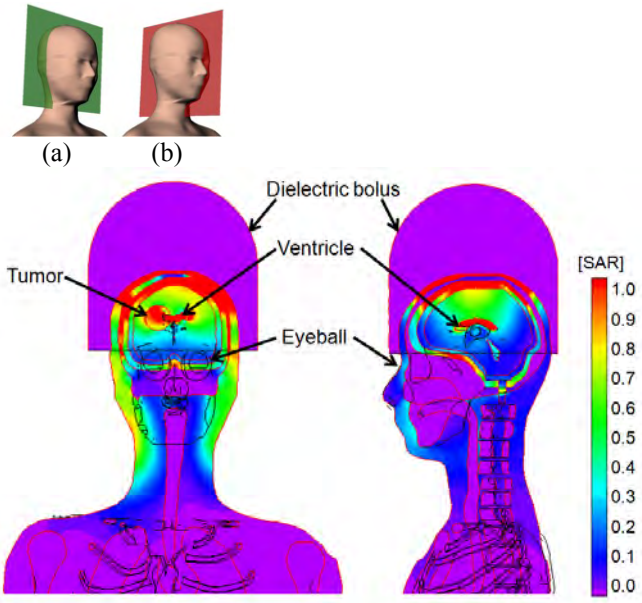
$$T_N = \frac{T - T_{\min}}{T_{\max} - T_{\min}} \tag{7}$$

Where T_{min} is the minimum temperature, T_{max} is the maximum temperature inside the phantom. The minimum temperature is 37°C and the maximum temperature is 43°C. The temperature rise 6.0°C, then 42°C is approximately 80% of the temperature rise. So, we used the normalized temperature value of 0.8.



(a) (b)

Fig. 8. SAR distributions without dielectric bolus (Resonant frequency: 166.6 MHz); (a) front of view, (b) side of view.



(a) (b)

Fig. 9. SAR distributions with dielectric bolus (Resonant frequency: 156.7 MHz); (a) front of view, (b) side of view.

Figure 7 shows the measured temperature and estimated temperature profiles along the z-axes. In Fig. 7, the measured temperature agrees with the estimated temperature with an error of 1.0% or less at the normalized temperature 0.8. Therefore, it was confirmed that FEM computer simulations are useful for estimating temperature distributions.

Figure 8 shows the normalized SAR distributions of the constructed 3-D anatomical human head model without the dielectric bolus. The resonant frequency was 166.6 MHz. From Fig. 8, the normalized SAR distribution near the tumor, which is located on a ventricle, is approximately 1.0. However, the heating energy is intense in the neck and eyeball.

Figure 9 shows the normalized SAR distributions of the 3-D human head model with the dielectric bolus. In this case, due to the large volume of the dielectric bolus and human head, the resonant frequency was 156.7 MHz. The frequency was approximately 10 MHz lower than the frequency used in the simulations without the bolus. From Fig. 9, the results of the SAR distributions show that the neck and eyeball were not significantly heated. However, in order to cool the hot spots on the surface of the human head, a system to circulate water through the inside of the bolus will be needed. From these results, it was found that the possibility of clinical heating without contact using our developed system was confirmed from the SAR simulations with the 3-D anatomical human head model.

V. Conclusion

This paper described the method to control heating location of the resonant cavity applicator using a dielectric bolus for non-invasive brain tumor hyperthermia treatments.

In order to show the validity of the proposed method, SAR distributions were estimated using the 3-D FEM.

According to our computer simulations, it was found that the possibility of clinical heating using our heating system was confirmed by estimating SAR distributions with the 3-D human head model.

We are now planning to calculate temperature distributions during hyperthermia treatments using the proposed method while considering blood perfusion and its temperature dependency.

Acknowledgement

This work was supported in part by Grants in Aid for Scientific Research (C) (20591484) from the Ministry, Education, Culture, Sports, Science, and Technology of Japan.

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