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SAR Analysis of the Improved Resonant Cavity Applicator with Electrical Shield and Water Bolus for Deep Tumors by a 3-D FEM

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***Abstract*— This paper discusses the improvements of the re-entrant resonant cavity applicator, such as an electromagnetic shield and a water bolus for concentrating heating energy on deep tumors in an abdominal region of the human body.**

From our previous study, it was found that the proposed heating system using the resonant cavity applicator, was effective for heating brain tumors and also for heating other small objects. However, when heating the abdomen with the developed applicator, undesirable areas such as the neck, arm, hip and breast were heated. Therefore, we have improved the resonant cavity applicator to overcome these problems. First, a cylindrical shield made of an aluminum alloy was installed inside the cavity. It was designed to protect non-tumorous areas from concentrated electromagnetic fields. Second, in order to concentrate heating energy on deep tumors inside the human body, a water bolus was installed around the body. Third, the length of the lower inner electrode was changed to control the heating area.

In this study, to evaluate the effectiveness of the proposed methods, specific absorption rate (SAR) distributions were calculated by FEM with the 3-D anatomical human body model reconstructed from MRI images.

From these results, it was confirmed that the improved heating system was effective to non-invasively heat abdominal deep tumors.

I. INTRODUCTION

Hyperthermia treatment is based on the clinical fact that a tumor is weaker than normal tissue around the temperature of 43°C and can be killed by heating for increments of approximately one hour. A variety of heating methods have already been proposed to heat deep tumors.

Some examples are radio frequency (RF) capacitive heating applicators and microwave heating applicators. Some of these applicators have been in practical use. However, all of these heating methods have advantages and disadvantages. A successful heating method has not yet been realized [1][2].

Therefore we proposed a non-invasive heating method as shown in Fig.1. In this system, a large size resonant cavity with inner electrodes was used for heating deep tumors in the abdominal region of the human body.

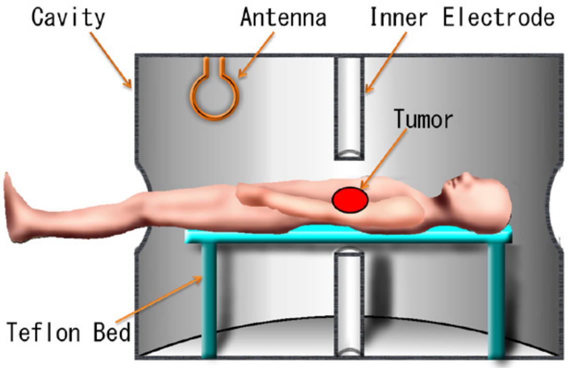

Figure 1. Illustration of heating system.

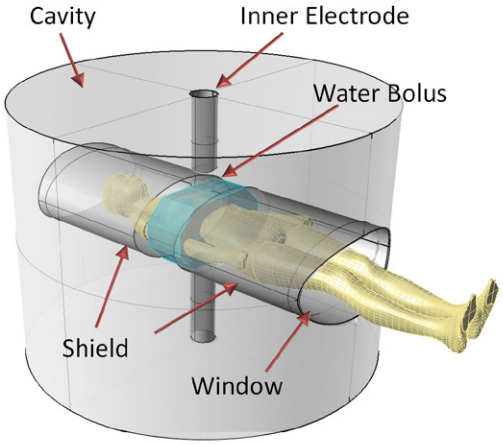

Figure 2. Illustration of new heating system.

The effectiveness of this heating method was proved with heating experiments using an agar phantom and computer simulations with a finite element method (FEM) using a 3-D human model [3]-[5].

However, the human body consists of many organs that have different electrical and thermal properties and also have various forms and sizes. Therefore, it was expected that the electromagnetic field would be concentrated in the convex part of the human body with the resonant cavity applicator.

In this paper, to overcome these problems, we propose a new heating method of using the resonant cavity applicator with a cylindrical shield made of an aluminum alloy and a water bolus. In this new heating system, the human body is covered with the cylindrical shield, except for the heated area. The surface of the human body is placed in the gap between two inner electrodes. It is then covered with the water bolus

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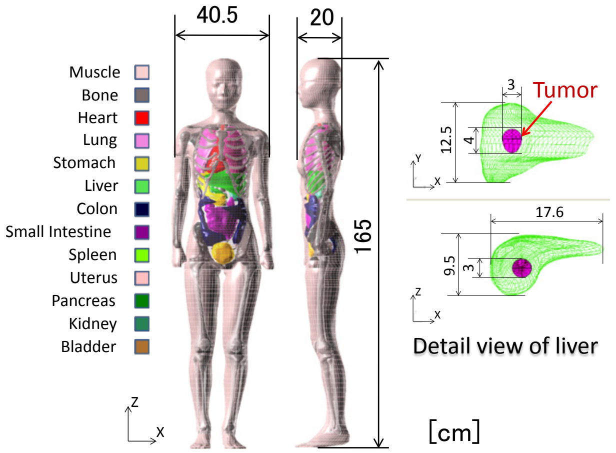


Figure 3. 3-D human anatomical FEM model.

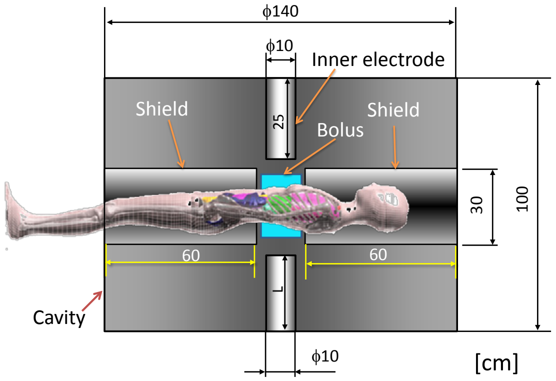


Figure 4. Cross-sectional view of improved applicator.

to concentrate the heating power on the deep-seated tumors. We calculated SAR distributions of a 3-D anatomical human body FEM model including the bone, muscle, fat, lung, liver, stomach and other internal organs.

II. METHODS

Figure 2 shows an illustration of a new heating system. In Fig. 2, a human body is placed in the center of the inner electrodes and is heated with the electromagnetic field patterns which are generated inside the cavity. No contact is made between the human body and the applicator. The elliptic cylindrical shield is connected to the cavity wall.

This shield was designed to protect non-tumorous areas in the human body from the electromagnetic heating energy. In order to concentrate heating energy on deep tumors, the water bolus is set on the human body surface without contact.

The SAR distribution inside a human body can be calculated by equations (1)-(5):

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

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

TABLE I. ELECTROMAGNETIC PROPERTIES AND ELEMENTS SIZES OF TISSUES AT 130MHZ

Tissue	**σ [S/m]**	**ε**	**ρ [kg/m³]**	**Average mesh size [cm]**
Air	0.0	1.00	1.165	5.0
Bladder	0.30	21.82	1000	2.0
Bone	0.18	26.21	1790	3.0
Colon	0.71	76.28	1000	2.0
Fat	0.036	5.91	900	2.0
Heart	0.77	83.89	1000	1.0
Kidney	0.86	89.14	1000	1.0
Liver	0.51	63.98	1000	0.5
Lung (air)	0.0	1.00	1.165	2.0
Muscle	0.72	63.36	1000	1.0
Small intestine	1.70	87.50	1000	2.0
Spleen	0.84	82.46	1000	2.0
Stomach	0.91	74.73	1000	2.0
Uterus	0.96	75.19	1000	2.0
Pancreas	0.80	66.67	1000	2.0
Bolus (Pure water)	0.0	75.00	1000	1.0
Tumor	0.6	65.00	900	0.2

$$k^2 = \omega^2 \varepsilon \mu \tag{3}$$

$$W_h = \frac{1}{2}\sigma |E|^2 \tag{4}$$

$$SAR = \frac{1}{\rho} W_h \tag{5}$$

Where E is the electric field vector, H the magnetic field vector, ω the radial frequency, ε the dielectric constant, μ the magnetic permeability, W_h the heating power generated inside a human body, σ the electrical conductivity, ρ the volume density of tissue. Equations (1) and (2) can be solved numerically by the FEM [3].

The anatomical FEM model is shown in Fig. 3. This female FEM model has 14 organs, for example the heart, liver, lungs, spleen etc. In this research, a tumor (3 × 4 × 3 cm) set in the liver is selected as a heated object. The dimensions of the model are 165 cm in height, and 40.5 cm in breadth at the shoulders. The average mesh sizes and the electrical parameter values at 130MHz for each organ are listed in Table I [6].

Figure 4 shows the cross-sectional view of the cavity. The cavity is 140 cm in diameter and 100 cm in height. To concentrate the heating energy in the center of the cavity, the inner electrodes are used. The upper inner electrode is 10 cm in diameter and 25 cm in height. The length "L" of the lower

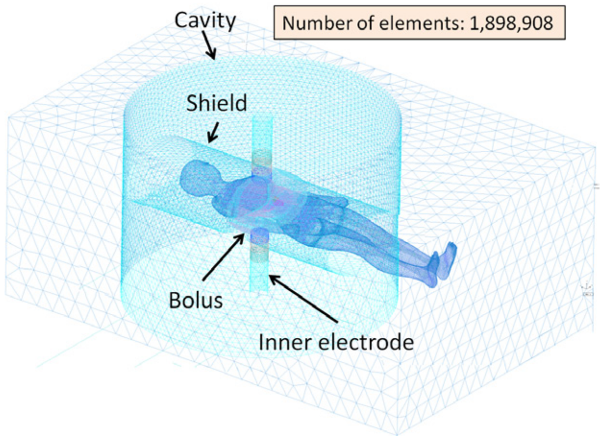


Figure 5. FEM model for calculating SAR distributions.

(Human body with the applicator)

inner electrode was changed from 15cm to 35cm. In order to compensate for the difference in length of a human body to the dimension of the applicator, ellipses (55 × 30 cm) are located at the head and leg regions. This allows the head and leg to rest outside of the cavity. Electromagnetic shields are 60 cm in length and are connected to the cavity wall. The water bolus, 45 cm in width, 25 cm in height and 16 cm in thickness, covers the surface of the human body. The water bolus is filled with pure water. In order to heat the liver tumor, which is the target of heating, the human body and bolus were put in a position shifted 5 cm from the center of the cavity.

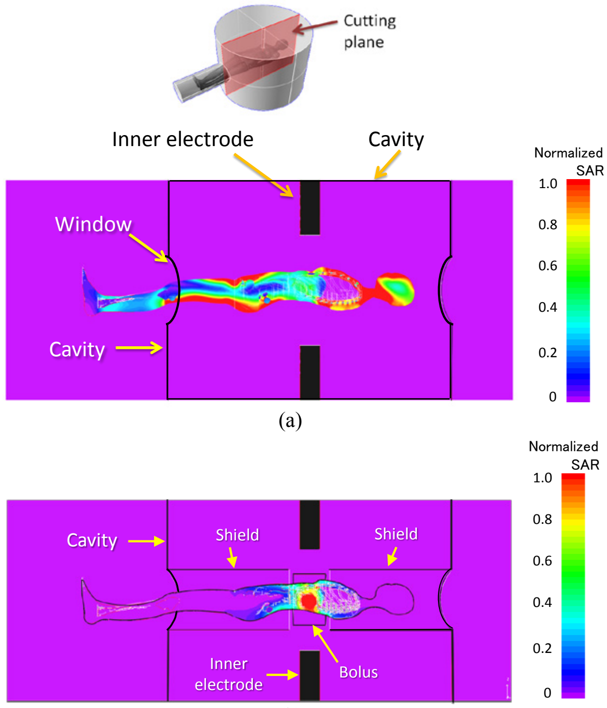
Figure 5 shows a finite element mesh for calculating the SAR distribution. This FEM model, created by the proposed method, and consisting of nonlinear elements, is included in the analysis area (250 × 100 cm). The total number of elements is 1,898,908. We carried out SAR analysis with the 3-D model using a personal computer constituted with the Intel Core i7-975 and 12GB memories. Here, JMAG-studio (JSOL Co. Ltd, Japan), which is a FEM application, was used in computer simulations.

III. RESULTS AND DISCUSSION

Figure 6 shows one of the results of the normalized SAR distributions calculated by the 3-D FEM with two applicators, before and after the improvements. In Figs. 6 (a) and (b), both inner electrodes were 25cm in height. Figure 6(a) shows the SAR distribution with the cavity applicator before the improvement. Here, the normalized SAR is given by,

$$SAR = \frac{(S - S_{\min})}{(S_{\max} - S_{\min})} \qquad (6)$$

Where $S_{\min}$ is the minimum SAR, $S_{\max}$ the maximum SAR in the human body. The resonant frequency was 123.0 MHz. The heating energy was concentrated on the hip and the head regions. However, in Fig. 6(b), the SAR distribution was concentrated on the selected regions with the proposed applicator. The resonant frequency was 131.5 MHz. The heating power is only concentrated on the gap between the inner electrodes.

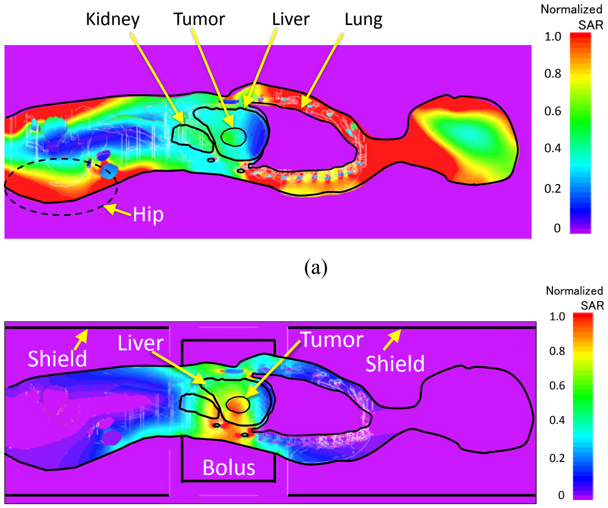


(a)

(b)

Figure 6. SAR distributions of side cutting plane. (when L=250mm)

(a) Cavity before the improvement. (Resonant Frequency: 123.0MHz.),
(b) Proposed cavity. (Resonant Frequency: 131.5MHz.)



(a)

(b)

Figure 7. Close up view of SAR distributions.

(a) Before the improvement, (b) After the improvement.

Figure 7 shows the close-up view of the SAR distribution near the liver tumor. In Fig. 7(a), it was shown that the electromagnetic heating energy concentrated on convex regions of the human body surface, such as the breast, head and hip. In Fig. 7(b), the electromagnetic heating energy does not concentrate on the region protected by the shields. The heating power is concentrated on the liver tumor that is placed deeply in the human body.

Figure 8 shows the normalized SAR profiles along X-axis when the length “L” is 25cm. Before the improvement, the normalized SAR of the tumor region was half of the abdominal surface region. After the improvement, the normalized SAR of more than 0.9 is concentrated only on the tumor. From these results, it was shown that the maximum heating energy was deeply concentrated on the liver tumor. However, the heating energy was also concentrated on the back region of the human body. To overcome this problem, the length of the lower inner electrode was changed.

Figure 9 shows the normalized SAR profiles when changing the length “L” of the lower inner electrode. The length of the upper electrode was 25cm constantly. All profiles show that the heating energy concentrated on the liver tumor the most. When the length of electrode becomes shorter, the heating energy of the back region decreases. When L is 15cm, the heating energy of the back region is reduced by approximately 15% of the result when L is 30cm in length. From this result, the heating energy of the back region can be eased with changing the length of the inner electrode by concentrating the heating energy on the deep tumor.

IV. CONCLUSION

This paper described the improvement of the resonant cavity applicator with the cylindrical shield made of aluminum alloy and the water bolus. In this new heating system, the human body is covered with the cylindrical shield except for the heated area. The human body, covered with the water bolus to smooth the surface of the human body for concentrating the heating power on deep tumors, is placed in the gap between two inner electrodes.

In order to show the validity of the proposed method, SAR distributions estimated with FEM were discussed. From these results, it is confirmed that the improvements of the heating system were effective for concentrating heating energy on the abdominal deep-seated tumors.

We are now trying to estimate temperature distributions during hyperthermia treatments using the proposed method with blood perfusion in consideration of temperature dependence.

ACKNOWLEDGMENT

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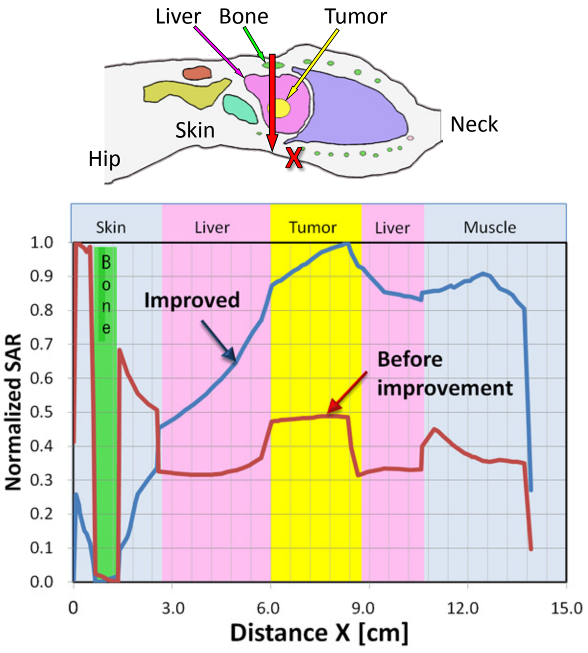

Figure 8. Normalized SAR profiles on the X-axis when L=25cm.

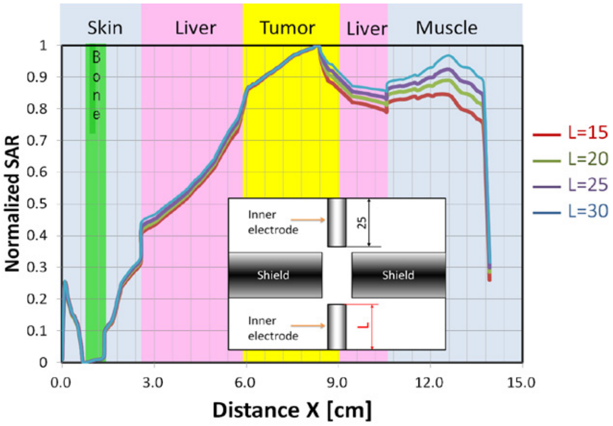

Figure 9. Normalized SAR profiles.

(When changing the length of inner electrode.)