Original Paper

Improvement in Localized Heating Characteristics by Loading Dielectrics in a Heating Applicator Based on a Cylindrical Reentrant Cavity

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Abstract: A heating applicator has been designed which utilizes a reentrant resonant cavity to noninvasively heat a localized deep region inside of a human body. With this cylindrical heating applicator, the electric field distribution can be concentrated between the reentrant electrodes and act as a heat source, however, the effective localization of the electric field distribution must be more precisely defined and limited in order to selectively heat cancers which are localized in the head and neck regions. In the work described here, the electric field distribution was narrowed into a beam shape by loading dielectrics between the reentrant electrodes and a target, and by optimizing the shape and size of the loaded dielectrics. A basic experiment was performed with this prototype applicator and numerical analysis using three-dimensional finite element method analysis both indicated that by loading dielectrics, the electric field distribution in the radial direction can be narrowed by 10-20% when compared with previously developed applicators. In addition, it is possible to narrow the electric field distribution by loading dielectrics and to rotate a beam-shaped electric field distribution to accurately heat a small localized region.

Key Words: regional hyperthermia, reentrant cavity, dielectric-loaded cavity, non-invasive heating

Introduction

Various heat therapy devices with the ability to apply electromagnetic wave energy from outside of the human body to selectively and noninvasively target localized cancers have been proposed. Some of these noninvasive methods involve targeting of heat generation in an object by using dipole antennas with different amplitudes and phases,^{1,2)} or by using high-temperature thermal ablation with focused ultrasound (FUS)³⁻⁵⁾. Clinical experiments utilizing both methods have already been conducted and

promising results have been obtained. However, with the method utilizing an array antennas, localized heating of deeper internal body regions is difficult because a relatively large region will be heated due to the limitations in choices of the electromagnetic wavelength which can be used, which is in principle determined by the size of the antenna. Another drawback of this method is that a water bolus is required to prevent excess heating at the surface of the human body. On the other hand, it is difficult to apply the FUS method to internal organs and tissues surrounded by bones due to limitations caused by the characteristics of ultrasound.

In order to noninvasively heat a deep region within a human body, a heating applicator based on a cylindrical reentrant cavity (Fig. 1) has been designed. This type of design is widely used in microwave communications⁶⁾ as well as in linear accelerators⁷⁾. In this heating applicator, most of the electric field energy is stored and concentrated at the center of the gap between the reentrant electrodes. Thus, localized and deep regions in an object can be heated by placing the heating target in this reentrant gap region. After numerical and experimental analyses, it has already been reported that localized heating is possible with this method^{8,9)}. Moreover, in order to improve therapeutic effects of such a device and to enable a more efficient use on localized cancers, attempts were made to miniaturize the applicator^{10,11)} as well as to optimize the size of the applicator by using current experimental design methods¹²⁾. Consequently, it has been shown that the electric field distribution generated between a pair of reentrant electrodes can be localized within a localized target region with a diameter of 70-90 mm. However, when the target for treatment is a small cancer localized in the head and neck regions, a localized region with a diameter of 30-50 mm must be selectively heated; thus the heating characteristics achieved in the previous studies were still insufficient.

In this study, concepts from dielectric loaded antenna technology^{13,14)} have been utilized, and these concepts provide a method to improve radiofrequency antenna directivity, sharpening, and gain. Moreover, it is proposed that the loading of dielectrics between the reentrant electrodes and a target can further narrow the electric field distribution, contributing to localized heating in a very small region. By loading dielectrics in this region, it was possible to improve the localized heating characteristics as a secondary effect since the resonance frequency of the cavity was reduced. In this report, a numerical

Fig. 1. Overview of the heating system using reentrant resonant cavities. (a) Cross-section of the reentrant resonant cavity. (b) Electromagnetic distribution in the reentrant resonant cavity in the lowest order mode.

analysis of the narrowing effect and localized temperature characteristics which depend on the shape and size of the loaded dielectrics is described. Experimental data using the prototype heating applicator were obtained to evaluate the effectiveness of this proposed method.

Principle

Localized heating system based on a reentrant cavity

Figure 2 shows a schematic representation of the electromagnetic distribution in a commonly used radio frequency (RF) capacitive heating system, as well as the proposed heating system using a reentrant resonant cavity. In the RF capacitive heating system, the electric field distribution will be uniform between the electrodes along both the radius (r) and longitudinal (Z) axes ; this distribution is expressed by Laplace's equation. Hence, not only the cancer tissue but also healthy tissue located between the electrodes can become heated. In addition, the electric field tends to concentrate at the ends of the electrodes, so that any tissues in this area may be heated excessively ; therefore, a water bolus is required to cool the surface of the human body.

On the other hand, the electromagnetic distribution inside the reentrant resonant cavity is expressed by the Helmholtz equation (equation (1)). Furthermore, the electromagnetic distribution, which is

Fig. 2. Electric field distribution inside the phantom which is positioned between the heated electrodes. (a) Electric field distribution in a standard capacitive heating system. (b) Electric field distribution between reentrant electrodes.

shown in Fig. 1 (b), is generated inside the resonant cavity with its lowest resonance mode. In this mode, the electric field distribution is concentrated in the gap between the reentrant electrodes.

$$\begin{aligned}\nabla^2 \vec{E} + k^2 \vec{E} &= 0 \\ \nabla^2 \vec{H} + k^2 \vec{H} &= 0 \\ k^2 &= \omega^2 \epsilon \mu\end{aligned}\tag{1}$$

In equations (1), $\vec{E}$ represents the electric field vector; $\vec{H}$, the magnetic field vector; ω , the angular frequency (rad/s); ϵ , the complex dielectric constant (F/m); and μ , the permeability (H/m). Using this heating system, a standing wave will be generated and maximized between the reentrant electrodes; further, the electric field strength is the highest at the center of the electrode, and it decreases rapidly along the r-direction. In addition, the electric field along the Z-direction will be distributed between the reentrant electrodes in a sinusoidal form, and therefore the electric field at the center of the electrode will be higher than that around the electrode, unlike in the case of RF dielectric heating systems. Thus, by placing the target object between the reentrant electrodes for treatment, deep regions of a human body can be heated locally, noninvasively, and without contact. By using such a heating system, it was confirmed that not only agar phantoms (cubical, oblate spherical¹⁵⁾, and human-like in shape), but also a dog brain¹⁶⁾ could be heated locally.

If the electric field distribution between the reentrant electrodes can be further localized, it would be possible to achieve more effective localized heating than is possible by using current applicators. To achieve this, a method is proposed here which involves the loading of dielectrics between the reentrant electrodes and a target object, as shown in Fig. 3. This method takes advantage of the fact that the transverse magnetic wave (the TM wave) generated between the electrodes becomes narrow when the dielectrics are loaded. This technique is widely applied in radiofrequency antennae to form incident and outgoing electromagnetic waves. This principle is also used in hyperthermia applications for interstitial applicators¹⁷⁾ as well as in lens applicators which use microwaves^{18,19)} although the principles are not exactly the same, this design is known to be effective in improving heating characteristics.

Materials and methods

Results of narrowing the electric field effect by using the specific absorption rate (SAR) distribution

To confirm the narrowing effect of the electric field achieved by loading dielectrics between the reentrant electrodes, the electromagnetic distribution of the reentrant applicator model was analyzed. This is shown in Fig. 3, using a three-dimensional finite element method with 15,000 nodes and 1,000 elements. It was assumed that the applicator container is an ideal conductor, and that an element analysis region corresponding with this assumption was considered to be a perfect electric conductor (PEC) by applying appropriate boundary conditions. The target object was a cylindrical phantom with a radius of 160 mm and a height of 120 mm, with a relative permittivity of 63, and an electric conductivity of 0.47 S/m (assuming a cerebral hyperthermia treatment²⁰⁾).

The dielectrics loaded between the reentrant electrodes had a diameter (D) of 20-100 mm and height (H) of 20-100 mm, and were cylindrical in shape. The resonant conditions inside the reentrant cavity

Fig. 3. Conceptual diagram of a reentrant resonant cavity with loading dielectrics.
 (a) Cylindrical dielectrics. (b) Cone-shaped dielectrics.

were analyzed when each dielectric was loaded, and the electromagnetic distributions were obtained. The expected resonant frequency of this applicator is approximately 150 to 180 MHz. Pairs of dielectrics were loaded at each intermediate position between the reentrant electrodes and the target object. Although it was not possible to achieve a significant narrowing effect of the TM wave due to the limitations of the resonance mode and the distance between the reentrant electrodes, this effect was also evaluated by loading truncated cone-shaped dielectrics (Fig. 3). When distilled water was used as a dielectric (relative permittivity 78 and electric conductivity 5.0×10^{-4} S/m), the optimal total reflection angle ($\theta_m > 6.52^\circ$) of the TM wave could be calculated using equation (2) and Snell's law of optics.

$$\sin \theta_m = \frac{n_A}{n_W} = \sqrt{\frac{\frac{\epsilon_A \mu_A}{\epsilon_0 \mu_0}}{\frac{\epsilon_W \mu_W}{\epsilon_0 \epsilon_0}}} = \sqrt{\frac{\epsilon_A \mu_A}{\epsilon_W \mu_W}} \quad (2)$$

θ_m : optimal angle

n : index of refraction

ϵ : relative permittivity

μ : permeability (subscript A indicates air and subscript W indicates dielectrics)

ϵ_0 : dielectric constant in vacuum

μ_0 : permeability in vacuum

Therefore, the diameter at the bottom surface was selected such that the incident angle of the TM waves was 50-80° (angle against the vertical axis), while the diameter at the tip of the truncated cone-shaped dielectrics was 10-80 mm, and their height was 40-80 mm.

The narrowing effect of the electric field distribution was evaluated by the full width-half maximum (FWHM) of the normalized SAR distribution along the r- and Z-directions of the applicator inside the phantom.

Evaluation of localized heating characteristics from the temperature distribution

To experimentally confirm the narrowing effect of the electric field distribution by loading dielectrics, the prototype system shown in Fig. 4 was designed and used in a phantom experiment. This heating system consists of a reentrant cavity, matching circuit, power amplifier, and signal generator. To efficiently transmit the RF power to the reentrant cavity, the resonance frequency was measured using a network analyzer (E5061A ; Agilent Technologies, Santa Clara, CA, USA), and the matching circuit was adjusted before the RF wave was provided. The phantom (agar : 4%, NaCl : 0.24%, and NaN₃ : 0.1%) was fixed to a Teflon table, and distilled water inside the polyethylene containers served as loaded dielectrics. A spacer was then placed between each dielectric and the phantom, and each dielectric was positioned at the center of the phantom and the electrodes.

The electric field strength around the sides of the phantom was measured using an electric field intensity meter (EMR-20 ; Narda Safety Test Solutions, Pfullingen, Germany) ; further, the RF power supplied to the heating applicator was adjusted so that the SAR value of the phantom at the center would be approximately 20 W/kg. The temperature distribution over the cross-section of the phantom was measured immediately after heating by using thermography (InfraEye 1200 ; Fujitsu Ltd., Kawasaki, Japan) to evaluate heating characteristics.

In addition, an analysis of the temperature distribution was performed using the three-dimensional

Fig. 4. Experimental system to confirm the narrowing effect of loaded dielectrics.

finite element method with the same models evaluated in the above mentioned SAR distributions. In this case, the loaded dielectrics (distilled water) in polyethylene containers (relative permittivity : 2.3 and electric conductivity : 4.0×10^{-4} S/m) were surrounded by an agar phantom with a relative permittivity of 80 and an electric conductivity of 0.4 S/m in order to make this analysis correspond to experimental conditions. Table I lists the thermal parameters^{21–23)} of each region used in the temperature distribution analysis.

Table I. Thermal parameters used in the calculation of temperature distribution

	Density (kg/m ³)	Thermal conductivity (W/(m-K))	Specific heat (kJ/(kg-K))	Initial temperature (K)
Phantom	1000	0.55	4.2	300
Distilled water	1000	0.60	4.2	300
Polyethylene container	940	0.46	2.2	300

Results

Narrowing effect of electric field in the r-direction

Figures 5 and 6 show the normalized SAR distributions at the central plane of the phantom (r-Z surface) when the height (20, 60, and 80 mm) and diameter (20, 60, and 80 mm) of the cylindrical dielectrics are varied.

First, the narrowing effect of the electric field distribution was evaluated in the r-direction. From the results shown in Figs. 5 (a) and 6 (a), it can be seen that the smaller the radius of the dielectrics is, and the higher the height of dielectrics, the better the convergence effect of the electric field distribution is. The FWHM of the SAR distribution was 104 mm when the dielectrics were not loaded, while the FWHM was 88 mm when dielectrics with a height of 80 mm and a diameter of 60 mm were loaded (Fig. 6, chain line), which was the maximum narrowing effect observed in the r-direction. This represents an improvement of approximately 16% in narrowing the absorbing region when compared to the absence of dielectrics.

On the other hand, when truncated cone-shaped dielectrics were loaded, we observed approximately a 2-5% improvement in the narrowing effect when compared with the cylindrical dielectrics.

Narrowing effect of the electric field in the Z-direction

When considering the normalized SAR distribution in the Z-direction, the electric field strength on the surface of the phantom was approximately 1.5 times higher than that at the center of the phantom when the height of the dielectric was 80 mm (Fig. 6 (b)). These results indicated that the convergence of the electric field in the Z-direction is more difficult to obtain than in the r-direction due to the partial concentration of the electric field which occurs due to the loading of dielectrics. As will be discussed later, although it is possible to obtain a focusing effect by rotating the beam-shaped electric field distributions generated by the loading dielectrics, effective localized heating characteristics still cannot be

Fig. 5. Narrowing effect on the electric field when the diameter of the loaded dielectrics is varied (height (H)=60 mm). (a) Normalized SAR distribution in the r-direction. (b) Normalized SAR distribution in the Z-direction.

Fig. 6. Narrowing effect on the electric field when the height of the loaded dielectrics is varied (diameter (D)=60 mm). (a) Normalized SAR distribution in the r-direction. (b) Normalized SAR distribution in the Z-direction.

expected when the surrounding SAR distribution is higher than that the SAR in the central region. Therefore, when dielectrics with a radius of 60 mm and a height of 60 mm are loaded, the SAR distribution is optimal when it is in a beam shape (Figs. 5 and 6, dashed line) in order to achieve a focusing effect along the r- and Z- directions which is achieved by rotating such a beam-shaped electric field distribution.

Localized heating characteristics using a prototype applicator

Figure 7 shows the temperature distribution of the cross-section (r-Z surface) at the center of the agar phantom with and without loading dielectrics under conditions where the incident RF power is approximately 25 W, which corresponds to an SAR of 20 W/kg at the object center and with a heating period of 20 min. Figure 8 shows the temperature distribution along the r and Z axes. These figures indicate that the results of the numerical analysis and those obtained in the actual experiment were almost identical. From these experimental results, the heating region was evaluated using by the FWHM of the temperature distribution, and confirmed that the localized heating region can be improved by

Fig. 7. Temperature distribution of the cross-section of the phantom at the center. (a) Without loaded dielectrics. (b) With loaded dielectrics.

Fig. 8. Temperature profile of the phantom cross-section at the center with loaded dielectrics. (a) Temperature distribution in the r-direction. (b) Temperature distribution in the Z-direction.

approximately 16% by loading dielectrics in the r-direction ; the FWHM was 88 mm without dielectric insertion, while it was 74 mm with loading dielectrics. As described above, it is difficult to obtain the convergence effect in the Z-direction in such a manner that the temperature distribution has the shape of an oblate sphere. These results were approximately the same as those obtained from the numerical analysis based on the normalized SAR distribution.

Discussion

It was shown that loading dielectrics between the reentrant electrodes and the target object is a useful method which can narrow the electric field distribution and improve localized heating characteristics. In particular, by adjusting the size of the loaded dielectrics, the electric field distribution in the r-direction of the applicator was narrowed by 10-20%.

However, by loading dielectrics, the electric field distribution generated inside the target object became beam-shaped ; thus it was found that the convergence of the electric field in the Z-direction was more difficult to achieve than in the r-direction. This was explained qualitatively : the temperature distribution over the cross-section (r-Z surface) at the center of the phantom was oval in shape, as shown in Fig. 7 (b). It seems that even these characteristics would enable us to obtain a regional deep heating area with a diameter of approximately 70 mm if cooling with a water bolus is used. However, it is

necessary and highly desirable to achieve deep heating without contact.

If this beam-shaped electric field distribution is rotated, it is possible to focus the electric field distribution in the region around the rotating axis where the beam-shaped electric field distributions intersect. Figure 9 shows an example of a basic experiment to confirm the possibility of focusing the electric field distribution by rotating the applicator. The temperature distributions are caused by a beam-shaped electric field distribution, which is obtained by loading dielectrics, rotated relative to the phantom. In this experiment, a cubic agar phantom with sides having a length of 120 mm, was rotated from 0° to 90°, and the incident RF power was approximately 20 W, which corresponds to an SAR of 20 W/kg at the object center, and the irradiation period was 20 min. This result indicated that the heating region is focused cylindrically, although the narrowing effect degrades in the r-direction due to the averaging of the electric fields by rotation around the heated region. Therefore, narrowing the electric field distribution in the r-direction by loading dielectrics, and then focusing the electric field distribution in the Z-direction by rotating the applicator will greatly contribute to an improvement in localized heating characteristics. However, as described above, since the narrowing effect of the electric field in the r-direction and the concentration effect of the electric field in the Z-direction each affects the other, and an ideal diameter of the heating region formed by these methods reaches 2 times the width of

Fig. 9. Improved heating characteristics which are obtained by rotating the focusing electric field. (a) Temperature distribution after heating for 20 min from the 0° direction. (b) Temperature distribution after heating for 10 min from the 0° direction and 10 min from the 90° direction.

the beam-shaped electric field, parameters must be optimized by taking into consideration the rotation of the applicator.

On the other hand, although attempts were made to narrow the electric field by loading the truncated cone-shaped dielectrics, these had only a small effect. This is because the length of the loaded dielectrics was short when compared to the wavelength at the resonance frequency. Therefore, a significant narrowing effect of the electric field may be expected by using a dielectric with a higher permittivity based on the wavelength shortening effect.

By using the abovementioned methods and a heating applicator with an optimized size^{10–12)}, it is predicted that the localized heating region will be an area with a diameter of 50–60 mm, and any further improvement in the local characteristics may be difficult to achieve due to restrictions in the convergence of the electric fields in the Z-direction. In addition to the methods proposed in this study, it should also be possible to achieve more localized heating with noninvasive real-time temperature measurement²⁴⁾ and active temperature controls, since the heated region generated by the reentrant heating applicator produces concentrated spherical distributions with a maximum intensity at the center of the reentrant electrodes. Consequently, a heating region with a diameter of approximately 30–50 mm, which is required to heat localized cancers in the head and neck regions, can theoretically be achieved.

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