PAPER

Generation of Controllable Heating Patterns for Interstitial Microwave Hyperthermia by Coaxial-Dipole Antennas

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SUMMARY Hyperthermia is one of the modalities for cancer treatment, utilizing the difference of thermal sensitivity between tumor and normal tissue. Interstitial microwave hyperthermia is one of the heating schemes and it is applied to a localized tumor. In the treatments, heating pattern control around antennas are important, especially for the treatment in and around critical organs. This paper introduces a coaxial-dipole antenna, which is one of the thin microwave antennas and can generate a controllable heating pattern. Moreover, generations of an arbitrary shape heating patterns by an array applicator composed of four coaxial-dipole antennas are described.

key words: *hyperthermia, microwave heating, internal heating, controllable heating pattern, array applicator*

1. Introduction

In recent years, various types of medical applications of microwaves have widely been investigated and reported [1]. In particular, minimally invasive microwave thermal therapies using thin coaxial antennas are of great interest. They are interstitial microwave hyperthermia [2] and microwave coagulation therapy [3] for medical treatment of cancer, cardiac catheter ablation for ventricular arrhythmia treatment [4], thermal treatment of benign prostatic hypertrophy [5], etc. Up to now, the authors have been studying such thin coaxial antennas for interstitial microwave hyperthermia.

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

There are a few methods for heating the cancer cells inside the body. The interstitial microwave heating is one of the modalities for the treatment of a localized tumor. In such treatment, thin microwave antennas are directly inserted into the tumor and radiate microwave energy to the target [6]. Therefore, although there is small invasiveness, this is one of the reliable treatment schemes.

The authors have been studying a coaxial-slot antenna [7], which is one of the thin microwave antennas, for the interstitial microwave hyperthermia. As a result of these investigations, actual treatments could be realized in some cases by use of our developed antenna and the effectiveness of the treatments has been confirmed [8]. Figure 1 shows a photograph during the treatment.

In the interstitial microwave hyperthermia, it is possible to change the heating pattern in the perpendicular direction of the antenna axis by varying the number of elements

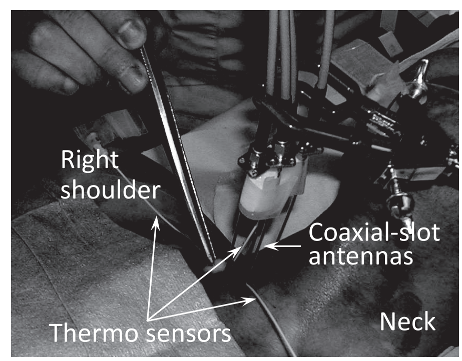

Fig. 1 Photograph during the interstitial microwave hyperthermia by coaxial-slot antennas.

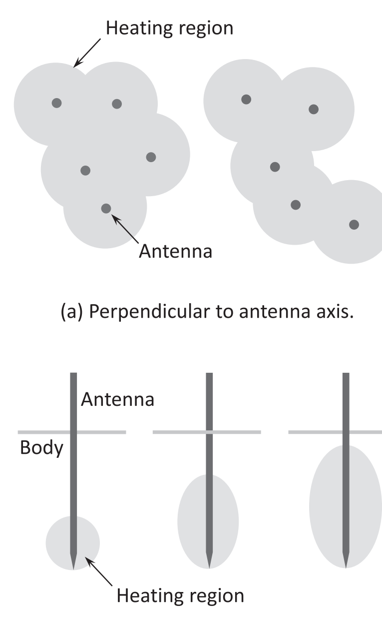

Fig. 2 Heating patterns generated by thin microwave antennas.

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and their insertion points (Fig. 2(a)). However, control of the heating pattern in the longitudinal direction of the antenna axis is realized by changing the structure of the antenna elements while keeping the thin structure (Fig. 2(b)).

In this paper, heating characteristics of the thin microwave antennas, which generate the controllable heating patterns in the longitudinal direction of the antenna axis, are described. Moreover, arbitrary shape heating patterns by an array applicator composed of the developed antennas are outlined.

2. Coaxial-Dipole Antenna

2.1 Antenna Configuration

In order to generate a controllable heating region in the longitudinal direction, a coaxial-dipole antenna is employed. This antenna was developed for generation of a localized heating region only around the antenna tip [9], [10]. In this paper, we will try to achieve the advanced heating pattern control by the coaxial-dipole antenna.

Figure 3 shows basic configuration of the coaxial-dipole antenna. Operating frequency of the antenna is 2.45 GHz, which is one of the industrial, scientific, and medical (ISM) frequencies in Japan. This antenna is composed of a thin semi-rigid coaxial cable. A ring slot is cut on the outer conductor of the thin coaxial cable and the tip of the cable is short-circuited. Here, L_{ts} is the length from the shorted point to the center of the slot and is set to 10 mm for impedance matching [9]. In addition, two conductive sleeves, whose lengths (L_{ld} and L_{ud}) affect a shape of heating region, are connected to both sides of the slot. Moreover, the antenna is inserted to a catheter for hygiene. In addition, although antenna insertion depth depends on position of a target tumor, it is set 70 mm, in this paper.

2.2 SAR Distributions

In order to estimate the heating pattern around the antennas, the specific absorption rate (SAR) around the antennas is calculated from the following equation:

$$\mathrm{SAR} = \frac{\sigma}{\rho} E^2 \qquad [\mathrm{W/kg}] \tag{1}$$

where σ is the conductivity of the tissue [S/m], ρ is the density of the tissue [kg/m^3], and E is the electric field (rms) [V/m]. The SAR takes a value proportional to the square of the electric field generated around the antennas and is equivalent to the heating source created by the electric field in the tissue. The SAR distribution is one of the most important characteristics of antennas for heating. In this study, the finite difference time domain (FDTD) [11] method is employed for calculations of electromagnetic field. Figure 4 and Table 1 show the FDTD calculation space and parameters for calculations, respectively.

Moreover, in order to confirm validity of the calculations, calculated results and measured SAR profiles by thermographic method [12] are compared. The thermographic method is one of the modalities for SAR measurements by use of a biological tissue-equivalent solid phantom and a thermographic camera. In the measurement, the solid phantom is heated short time to ignore heat conduction inside. In the measurement of SAR for this kind of antenna by the thermographic method, the heating time should be set around 10 to 20 second depending on antenna structure, radiation

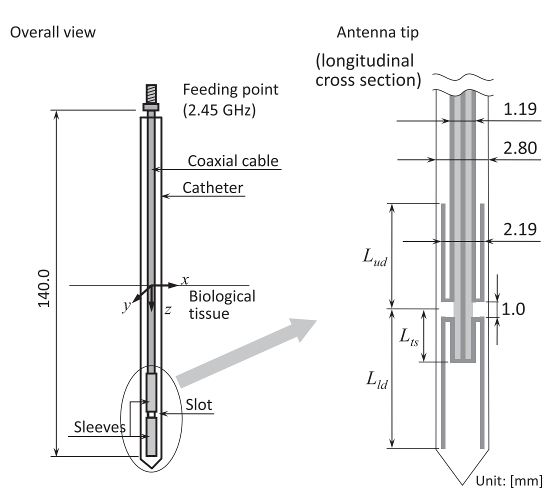

Fig. 3 Basic structure of coaxial-dipole antenna.

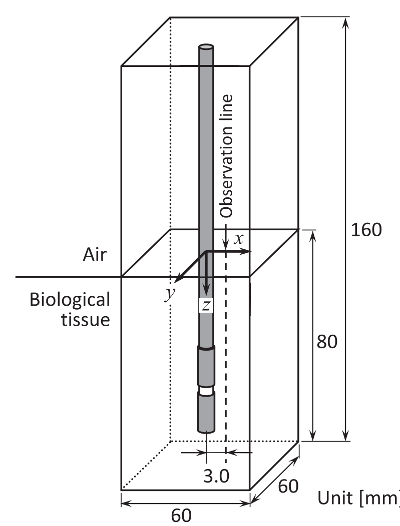

Fig. 4 FDTD calculation model.

Table 1 Parameters for FDTD calculations and material parameters.

Parameters for FDTD calculations		
Cell size [mm] (minimum)	Δx, Δy	0.05
	Δz	1.00 (const.)
Cell size [mm] (maximum)	Δx, Δy	1.50
	Δz	1.00 (const.)
Absorbing boundary condition	Mur (1st order)	
Material parameters		
	ε_r	σ [S/m]
Biological tissue (phantom)	42.5	1.5
Catheter	2.6	0.0

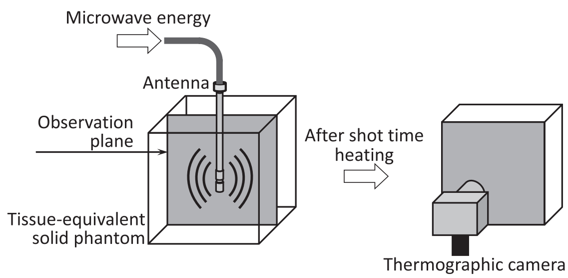

Fig. 5 SAR measurement system by thermographic method.

power etc. In this study, appropriate heating time was selected by preliminary measurements.

After that temperature distribution around the antenna is measured by the thermographic camera. The measurement system is shown in Fig. 5. In this case, the SAR is calculated from Eq. (2).

$$\mathrm{SAR} = c\frac{\Delta T}{\Delta t} \qquad \text{[W/kg]} \tag{2}$$

c: the specific heat of the phantom [J/kg·K], ΔT: the temperature rise of the phantom [K], and Δt: the radiation time [s]

Figure 6 shows the measured and calculated SAR distributions around the antenna. The SAR observation line is parallel to the antenna axis and is 3.0 mm away from the center of the antenna (shown in Fig. 4). Here, the length of the lower sleeve L_{ld} is changed from 10.0 mm to 30.0 mm when L_{ud} is set to 20.0 mm. From these results, the length of the high SAR region in the longitudinal direction is almost the same as the length of $L_{ld} + L_{ud}$ from the tip (gray region in Fig. 6). Moreover, in all cases, good agreements are observed between the calculations and the measurements except at the slot position. The SAR value at the slot is extremely higher than other positions. In such a case, heat transfer at the peak point cannot be ignored in the thermographic method and the measured SAR value is lower than the calculation.

From these results, it can be said that the coaxial-dipole antennas generate the controllable heating regions in the longitudinal direction. In addition, according to our preliminary investigations, the length of the sleeve (L_{ld} or L_{ud}) should be less than 30 mm for generating the controllable heating patterns.

Moreover, if an antenna with enough length of lower sleeve is prepared, size of the longitudinal heating region can be adjusted easily by cutting the lower sleeve. Here, minimum length of the lower sleeve L_{ld} is 10 mm, which is the same as L_{ts}.

3. Array Applicator

3.1 Array Structure

The controllable heating patterns in the longitudinal direction of the antenna axis could be generated by use of the

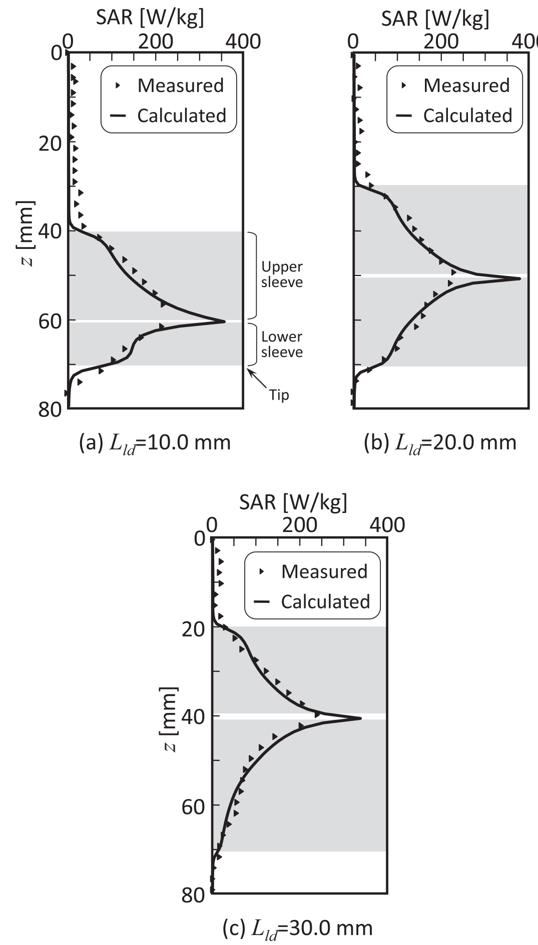

Fig. 6 Measured and calculated SAR distributions. All results are normalized by 1.0 W radiation power.

coaxial-dipole antennas. Here, generation of three dimensional arbitrary heating patterns is considered by array applicators. In this paper, heating patterns of the array applicators composed of four coaxial-dipole antennas are investigated. Figure 7 shows a calculation model of the array applicator. All the antenna elements are fed by same amplitude and in phase.

According to our previous study [8], 20 mm-array spacing (intervals of antenna elements) was suitable for actual treatment. Therefore, this paper complies with this array spacing. In addition, antenna insertion depths of all antenna elements are same as 70 mm, in this paper.

Here, two kinds of array applicators, which are composed of different antenna elements, as follows are considered.

a. All antenna elements have same parameters
   Element A, B, C, and D: L_{ld} = 20.0 mm, L_{ud} = 20.0 mm
b. Two sleeve parameters
   Element A and B: L_{ld} = 20.0 mm, L_{ud} = 20.0 mm
   Element C and D: L_{ld} = 10.0 mm, L_{ud} = 10.0 mm

Here, heating patterns of the array applicators are evaluated by temperature distributions. The temperature distri-

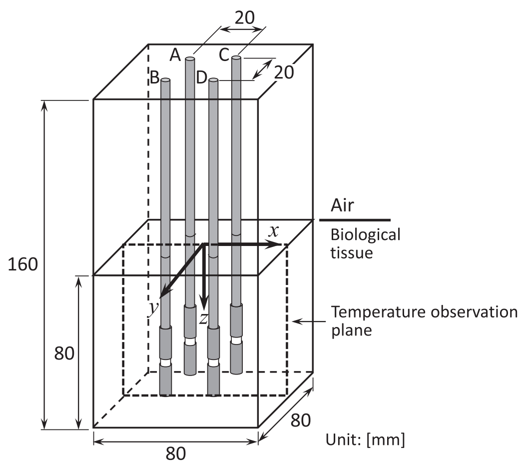

Fig. 7 Calculation model for the array applicator composed of four coaxial-dipole antennas.

Table 2 Electrical and thermal parameters for temperature calculations.

Electrical properties	
Relative permittivity (biological tissue) ε_r	47.00
Conductivity (biological tissue) σ [S/m]	2.21
Thermal properties	
Density (biological tissue) ρ [kg/m^3]	1,020
Density (blood) ρ_b [kg/m^3]	1,060
Specific heat (biological tissue) c [J/kg·K]	3,500
Specific heat (blood) c_b [J/kg·K]	3,960
Thermal conductivity κ [W/m·K]	0.60
Blood flow rate F [m^3/kg·s]	8.33×10^{-6}
Initial temperature [°C]	37.00
Blood temperature [°C]	37.00

butions inside biological tissue can be calculated by solving bioheat transfer equation [13] (Eq. (3)) numerically. Detail calculation scheme is the same as [14]. In addition, electrical and thermal parameters for the calculations are listed in Table 2 [15], [16].

$$\rho c \frac{\partial T}{\partial t} = \kappa \nabla^2 T - \rho \rho_b c_b F (T - T_b) + \rho \cdot \mathrm{SAR} \qquad (3)$$

where T is the temperature [°C], t is the time [s], ρ is the density of tissue [kg/m^3], c is the specific heat of tissue [J/kg·K], κ is the thermal conductivity of tissue [W/m·K], ρ_b is the density of the blood [kg/m^3], c_b is the specific heat of the blood [J/kg·K], T_b is the temperature of the blood [°C], and F is the blood flow rate [m^3/kg·s]

3.2 Calculated Results

Figure 8 shows calculated temperature distributions. Here, the temperature observation plane is defined in Fig. 7 and black solid line indicates the region more than 42°C, which is the lowest temperature for the treatment (effective heating region). Radiation power from the whole array is 20 W. Even in the array applicator, it is preferable that size of the effective heating region in z direction is same as the length of $L_{ld} + L_{ud}$ for heating pattern control.

As shown in Fig. 8(a), when all antenna elements have same parameters, size of the effective heating region in longitudinal direction (z direction at $x = \pm 10$ mm) is approximately 27 mm. Here, the length of $L_{ld} + L_{ud}$ is 40 mm, in this case. So, the size of effective heating region decreases 33%.

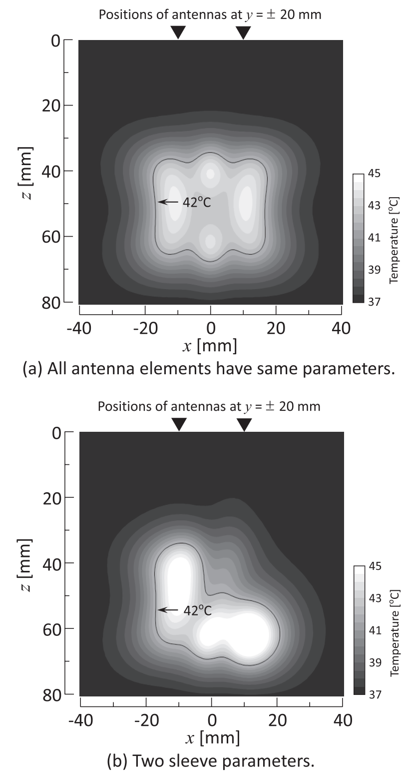

Fig. 8 Calculated temperature distributions by two types of array applicators.

On the other hand, as shown in Fig. 8(b), in the case of using two kinds of sleeve parameters, the sizes of longitudinal heating region are depend on the sleeve length. Therefore, length of the effective heating region in z direction close to the elements A and B (at $x = -10$ mm) is approximately 29 mm, even though the length of $L_{ld} + L_{ud}$ is 40 mm. It decline by 28%. In addition, the length in z direction around the elements C and D (at $x = +10$ mm) is 19 mm. It is almost same as $L_{ld} + L_{ud}$.

Relation between size of available heating region and the sleeve length is not depend the antenna structure but also the array spacing, radiation power etc. Therefore, this point should be investigated as a further study. Even so, from the results, it can be said that the heating pattern depends on the sleeve length also in the array applicator. It can be clearly understood from Fig. 9, which shows effective heating region by three-dimensional.

4. Conclusions

This paper has introduced the coaxial-dipole antenna for the interstitial microwave hyperthermia. First, it was cleared that the coaxial-dipole antenna could generate an arbitrary length heating region around the tip. Moreover, the array ap-

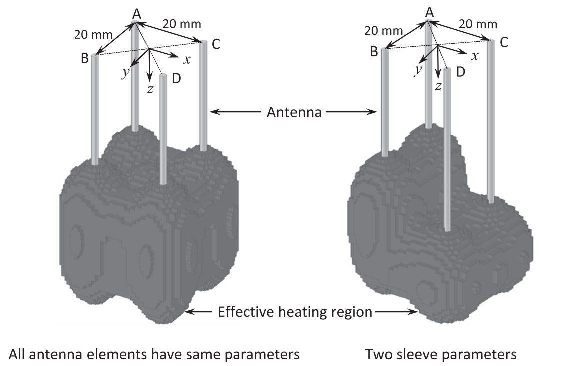

Fig. 9 Three-dimensional calculated temperature distributions.

plicator composed of four coaxial-dipole antennas has been explained. From some results of investigations, it may be said that the arbitrary heating pattern can be generated by use of the array applicator composed of the coaxial-dipole antennas. As a further study, we will fabricate the antenna for practical use. Moreover, some animal experiments are needed before clinical treatments.

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References

[1] F. Sterzer, "Microwave medical devices," IEEE Microwave Mag., vol.3, no.1, pp.65–70, 2002.
[2] M.H. Seegenschmiedt, P. Fessenden, and C.C. Vernon, eds., Thermoradiotherapy and thermochemotherapy, Springer-Verlag, Berlin, 1995.
[3] T. Seki, M. Wakabayashi, T. Nakagawa, T. Itoh, T. Shiro, K. Kunieda, M. Sato, S. Uchiyama, and K. Inoue, "Ultrasonically guided percutaneous microwave coagulation therapy for small carcinoma," Cancer, vol.74, no.3, pp.817–825, 1994.
[4] R.D. Nevels, G.D. Arndt, G.W. Raffoul, J.R. Carl, and A. Pacifico, "Microwave catheter design," IEEE Trans. Biomed. Eng., vol.45, no.7, pp.885–890, 1998.
[5] D. Despretz, J.C. Camart, C. Michel, J.J. Fabre, B. Prevost, J.P. Sozanski, and M. Chivé, "Microwave prostatic hyperthermia: interest of urethral and rectal applicators combination — Theoretical study and animal experimental results," IEEE Trans. Microw. Theory Tech., vol.44, no.10, pp.1762–1768, 1996.
[6] J.C. Lin and Y.-J. Wang, "Interstitial microwave antennas for thermal therapy," Int. J. Hyperthermia, vol.3, no.1, pp.37–47, 1987.
[7] K. Ito, K. Ueno, M. Hyodo, and H. Kasai, "Interstitial applicator com-posed of coaxial ring slots for microwave hyperthermia," Proc. Int. Symp. Antennas Propagation, pp.253–256, 1989.
[8] K. Saito, H. Yoshimura, K. Ito, Y. Aoyagi, and H. Horita, "Clinical trials of interstitial microwave hyperthermia by use of coaxial-slot antenna with two slots," IEEE Trans. Microw. Theory Tech., vol.52, no.8, pp.1987–1991, 2004.
[9] S. Kikuchi, K. Saito, M. Takahashi, and K. Ito, "Control of heating pattern for interstitial microwave hyperthermia by a coaxial-dipole antenna — Aiming at treatment of brain tumor," IEICE Trans. Commun. (Japanese Edition), vol.J89-B, no.8, pp.1486–1492, Aug. 2006.
[10] K. Saito, T. Kawamura, M. Takahashi, and K. Ito, "Generation of controllable heating patterns by two types of thin microwave antennas for interstitial microwave thermal therapy," Proc. Int. Symp. Antennas Propagation, 2008.
[11] K.S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equation in isotropic media," IEEE Trans. Antennas Propag., vol.14, no.3, pp.302–307, 1966.
[12] W. Guy and C.K. Chou, "Specific absorption rates of energy in man models exposed to cellular UHF mobile-antenna fields," IEEE Trans. Microw. Theory Tech., vol.MTT-34, no.6, pp.671–680, June 1986.
[13] H.H. Penns, "Analysis of tissue and arterial blood temperatures in the resting human forearm," J. Appl. Phys., vol.1, no.2, pp.93–122, 1948.
[14] K. Saito, A. Hiroe, S. Kikuchi, M. Takahashi, and K. Ito, "Estimation of heating performances of a coaxial-slot antenna with endoscope for treatment of bile duct carcinoma," IEEE Trans. Microw. Theory Tech., vol.54, no.8, pp.3443–3449, 2006.
[15] C.C. Johnson and A.W. Guy, "Nonionizing electromagnetic wave effects in biological materials and systems," Proc. IEEE, vol.60, no.6, pp.692–718, June 1972.
[16] P.M. Van Den Berg, A.T. De Hoop, A. Segal, and N. Praagman, "A computational model of the electromagnetic heating of biological tissue with application to hyperthermic cancer therapy," IEEE Trans. Biomed. Eng., vol.BME-30, no.12, pp.797–805, 1983.

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