Array of Slot-Sleeve Antennas for Hyperthermia Therapy

Soo-Man Park · Yeongseog Lim

Abstract

To increase the efficiency of an applicator during microwave hyperthermia therapy, first, the length from the antenna end to a slot is varied to get the optimal matching of the characteristic impedance at the frequency of 2.45 GHz. Using the electric and thermal constants of biological tissue, we compose a phantom to calculate temperature increment as well as the resonance characteristics and the *SAR* distributions.

The proposed 3-slot sleeve antenna inserted in an applicator plays an effective role in increasing the therapy size in the view of heating performance as electromagnetic energy tends to concentrate on not feed point direction but treatment area. The *SAR* is then used in combination with a finite difference heat transfer equation to determine the temperature distribution. Also, in order to shorten treatment time and increase therapy size, a square-array structure is suggested and analyzed.

Key words : *SAR*, Temperature, Cancer, Hyperthermia, Antenna.

Ⅰ. Introduction

Most of the researches on microwave and RF antennas for medical applications have focused on producing hyperthermia for medical treatments and monitoring various physiological parameters[1],[2].

Hyperthermia is the method that raises center temperature of human tissue artificially and treats tumor. This technique involves the use of elevated temperatures to hasten the destruction of cancerous tissue. At the critical temperature, cells lose their ability to divide[3].

Microwave interstitial techniques are used to produce localized deposition of electromagnetic energy in the hyperthermia cancer therapy. Electrical performance of the applicator is determined by both the degree of impedance matching and the specific absorption rate (*SAR*) distribution in the surrounding tissue[4]. Since up to tens of watts of energy is employed for raising tissue temperature to the hyperthermia level, the good impedance matching is necessary.

In fact, determination of an antenna's input impedance should be the first step in designing the applicator. Theoretical modeling of the characteristics of an applicator embedded in a homogeneous conductive medium was first undertaken by King[5].

To improve the performance of interstitial antennas for hyperthermia therapy, parameters such as *SAR* distributions, the uniformity of the heating pattern, the depth of penetration, and the impedance matching property must be optimized.

First, we analyze the general applicators and modify the antenna length, which has improvement in the impedance characteristics. We then obtain the return loss and the *SAR* with the tissue-equivalent phantom as a function of time and input power at 2.45 GHz which is one of the industrial, scientific, and medical(ISM) frequencies. Also we simulate the array structures which have two, three and four antennas.

The overall organization of this paper is as follows. Section 2 describes the review of the *SAR*, and bio-heat equation. In Section 3, design and analysis of the applicator with a three-slot sleeve antenna are described

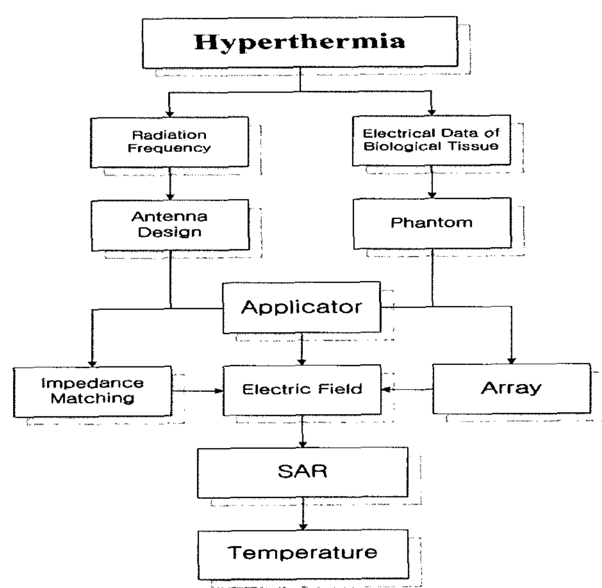

Fig. 1. Schematic diagram of our study on hyperthermia.

Manuscript received May 20, 2005 ; revised August 2, 2005. (ID No. 20050520-020J)

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for the calculations of the *SAR* and the temperature increment and distribution. In Section. 4, the array of the newly proposed antenna is described. Finally, some concluding remarks are made in Section 5.

II. Theory

Three parameters of critical importance in research of hyperthermia are temperature, time, and focusing of heat. It is dependent on the type of applicator used. Desirable temperature and time relationships depend on physical and physiological characteristics of the cancerous tissue. It is important that heating be rapid and that the temperature distribution over the region of the cancerous tissue be as uniform as possible.

The *SAR* is defined as the power absorbed into the unit mass of tissue. After the excitation of electric power, the maximum electric fields are continually stored at all the location inside of human body inside. The more practical *SAR* equation is defined as

$$SAR = \frac{\sigma}{2\rho} \mid E_i \mid^2 \quad (1)$$

where E_i is the peak value of electric field component. The constants σ and ρ denote the conductivity and mass density of the tissue. It is convenient to represent the *SAR* data as an analytical expression. The *SAR* data is used with a finite difference approximation to predict temperature increment during microwave power radiation.

A general form of the bioheat equation for the approximate modeling of the heating process in tissue is the Pennes' bio-heat transfer equation[6].

The temperature of tissue can be approximated as

$$\rho \cdot C_p \frac{\partial T}{\partial t} = K \nabla^2 T + \rho \cdot SAR - b \cdot (T - T_b) + W_m \quad (2)$$

where ρ is the density of tissue [kg/m^3], C_p is the specific heat [J/kg·℃], T is the temperature of tissue [℃], b is a coefficient of blood flow [W/m^3·℃], T_b is the temperature of blood [℃], $\nabla^2 T$ is the Laplacian of the temperature T, K is the thermal conductivity [W/m·℃], the *SAR* is the input EM heating source into bioheat equation [W/kg], and W_m is the power generated by metabolism [W/kg^3].

Temperature rise by EM wave can be obtained by difference of $T(t)$ and $T(0)$.

III. Design of Applicator

To decide the peak voltage of a sine wave, we calculate the electric field density by adding the vertical component of Poynting vector of each of 6 sides at a distant point about 5 cells in absorption boundary surface. The simulation is interrupted when the total energy in the studied domain is reduced by 40 dB, with reference to its maximum value. The characteristic impedance of the antenna is evaluated as the ratio between the Fourier transforms of the voltage and the current at the feeds.

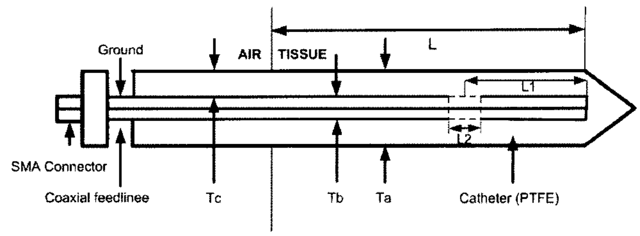

Fig. 2. Basic schematic of the general applicator with one slot antenna(longitudinal section).

The generalized representation of the structural detail associated with the microwave applicator with slot antenna is depicted in Fig. 2. This is a structure having a slotted flexible coaxial cable. A slot is cut on the outer conductor of a thin coaxial cable and the tip of the cable is the short-circuiting. Here, L is the insertion depth, L_1 is the length from antenna tip to center of slot, L_2 is the width of the slot, T_a is the external diameter of the applicator, T_b is the diameter of the inserted antenna, and T_c is the thickness of the catheter. The antenna is inserted into a catheter(ε_r=2.6) made of poly tetra fluoro ethylene(*PTFE*) for hygiene.

We compare two parameters of the antenna, the length of L_1 is varied so as to observe its effect of the resonance characteristics in the phantom. Fig. 3 and Fig. 4 show that increasing of L_1 leads to lowering of the

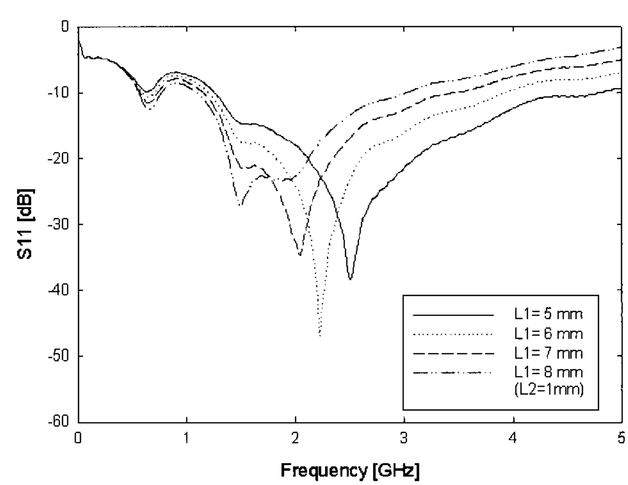

Fig. 3. S_{11} as a function of L_1 versus L_2 with tissue.

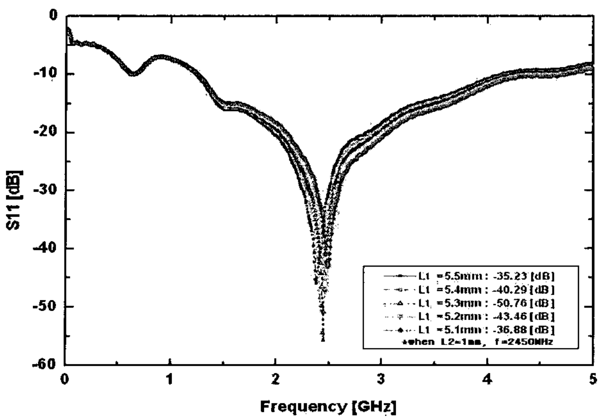

Fig. 4. Optimization of S_{11}.

resonance frequency. The optimized S_{11} is located between L_1=5 and 6 mm in case of L_2=1 mm, and L_1 =4 and 5 mm in case of L_2=2 mm, respectively.

Among the above results, to find the optimum resonance frequency as a function of L_1 at 2.45 GHz, the L_2 is set to 1 mm. The best results are shown in Fig. 5 and Table 1.

Next, We compare the *SAR* distributions for validation of our calculation. Parameters of the human phantom and the antenna are the same as depicted in Table 1.

The phantom of liver has almost the same electrical constants as those of human in the considered fre-

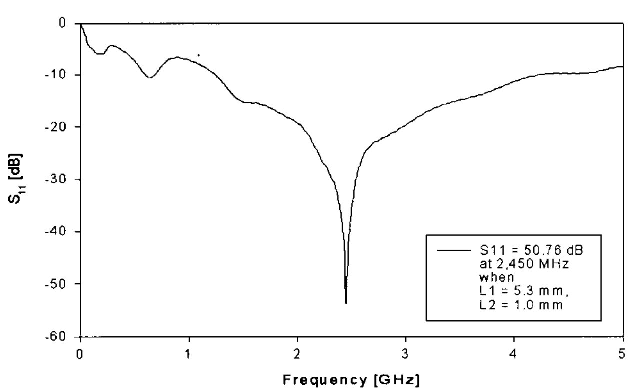

Fig. 5. S_{11} of applicator with 1-slot antenna within tissue.

Table 1. Parameter and result of one slot antenna.

Parameter of antenna	Result
ε_{rp}(relative permittivity of liver)	43.03
σ (conductivity of liver)	1.69 S/m
L(insertion depth)	70.0 mm
L_1(length from slot to tip)	5.3 mm
L_2(slot width)	1.0 mm
S_{11} at 2.45 GHz	50.7 dB

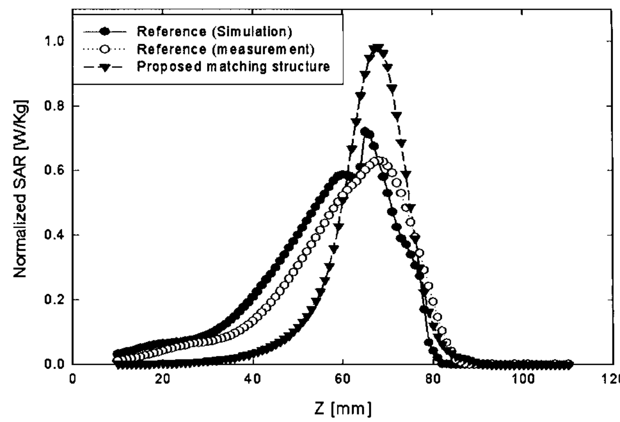

Fig. 6. *SAR* comparison between the general applicator and the proposed matching applicator at 2.45 GHz.

quency, 2.45 GHz. The applicator with one slot antenna is assumed to be inserted in a liver tissue of dimension $60\times60\times80$ mm^3.

In simulating the complete antenna, the electric field components is determined at the frequency of interest by a discrete Fourier transform of the time domain field behaviors.

The electric field at the center of each cell are then evaluated by averaging the 4 field components located at the cell sides, and the *SAR* distribution is evaluated as (1).

Fig. 6 is the result for the *SAR* comparison. The validity of the simulation is checked by comparing the *SAR* distributions.

As seen in Fig. 6, our results of calculation are

Table 2. Characteristics of the phantom and applicator dimensions for the comparison of temperature calculation simulation.

Tissue type	Liver
Relative permittivity ε_r	43.03
Conductivity σ	1.69 S/m
Volume	$60\times60\times60$ mm^3
Mass density	1,060 kg/m^3
Specific heat	3,600 J/kg·℃
Thermal conductivity	0.50 W/m·℃
Applicator type	3-slot sleeve
Frequency	2.45 GHz
Insertion depth	50.0 mm
L_1	1.0 mm
L_2	1.0 mm
L_3	5.0 mm
L_4	0.1 mm

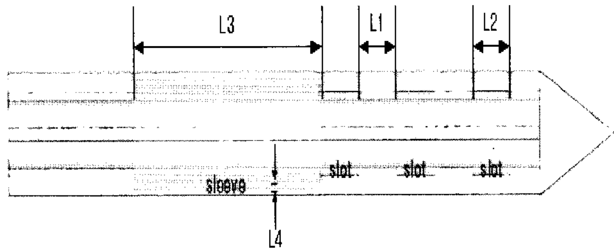

Fig. 7. Schematic of 3-slot sleeve antenna.

almost the same with the approximate ones of the reference[7] and the newly designed applicator has much higher *SAR* distribution than the structure of reference.

The microwave applicator, depicted in Fig. 7, is a three-slot and sleeve antenna mounted on an UT-34 flexible coaxial cable. The structure is realized by 3 slots cut on the outer conductor, the short-circuiting of antenna tip and a cylindrical coaxial sleeve to the outer one.

The sleeve prevents current from coupling to the outer conductor and flowing back along the cable, thus confining power deposition in the region around the antenna tip.

The performance of the applicator is evaluated numerically by embedding the one in the phantom, which had a dimension of $60 \times 60 \times 60$ mm^3, and is filled with a liver-equivalent material. The antenna tip is inserted to a depth of 50 mm below the top of the phantom.

Fig. 8 shows the time behavior of the temperature increments for four different antenna structures at a radial distance of 3 mm from the antenna axis at the level of the first slot. The temperature reaches steady state following an exponential behavior with a time constant of approximately 3∼5 min.

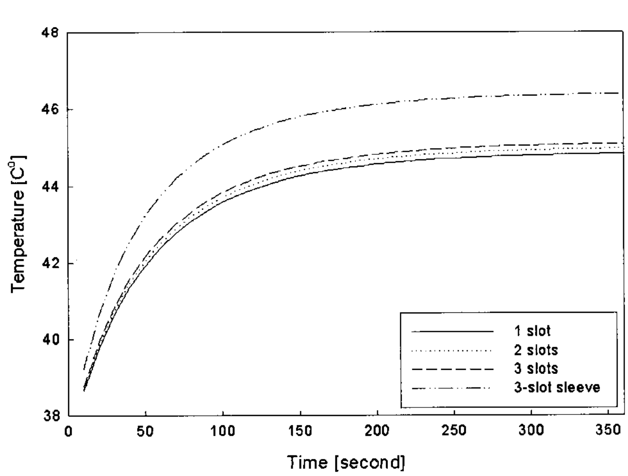

Fig. 8. Time course of maximum temperature increments about three different structures.

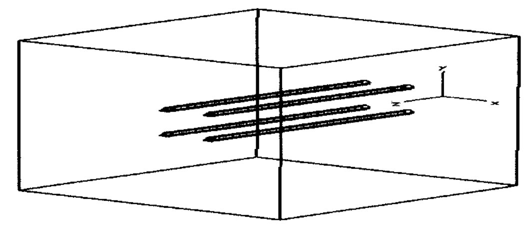

Fig. 9. Schematic of array with four-applicator with three-slot sleeve antenna.

Fig. 9 shows the *SAR* contour plot on the xy-plane passing through the first slot of the applicator with 3-slot sleeve antenna for 8 W of radiated power.

From the above results, we may say that, for a tumor radius exceeding 20 mm, new arrays made of more than three or four antennas are necessary.

Using the antenna constructed in Section Ⅲ, the extension to four element antenna array will now be demonstrated. The radiating structure is assumed to be inserted in a liver phantom as depicted in Table 2.

In order to provide some clinical indications about the optimal geometry and input power for achieving an efficient tumor heating, the array geometry has also been studied from the thermal point-of-view by variation of the input power.

Array made of four identical three-slot sleeve antennas placed at the vertices of a regular square of 10-mm sides, respectively, have been studied. Fig. 11 shows the *SAR* contour plot over the xy-plane section passing through the first antenna slot for a total radiated power of 1.0 W.

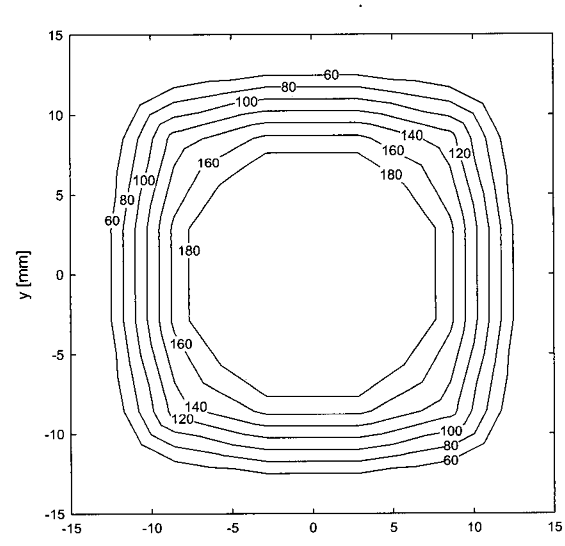

Fig. 10. SAR contour plot on the xy-plane passing through the 4-applicator for 1 W of radiated power with 10 mm applicator spacing.

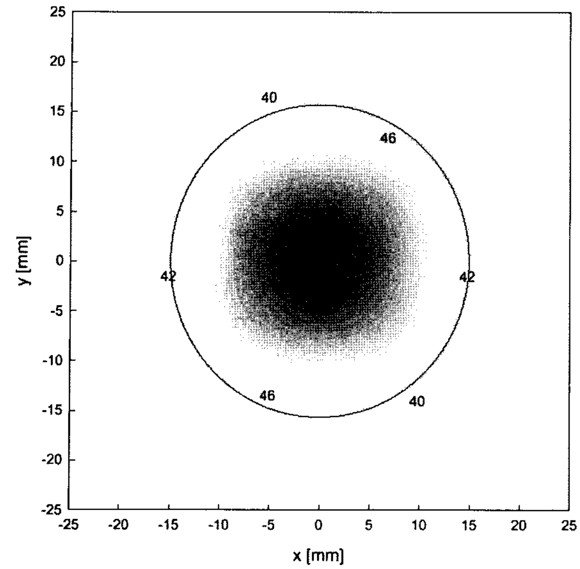

Fig. 11. Contour plot on the xy-plane passing through the first slot of the array applicator.

Table 3. Therapy size.

Number of Applicator	Time to Steady State	Contour Size of the xy-plane at 42 ℃(mm^2)
1	201 s	200
2	224 s	560
3	252 s	615
4	287 s	706

This figure shows that the power deposition is mainly concentrated in the region among the applicators.

In case of the proposed structure which has the three-slot and sleeve, the maximum temperature, the steady state of therapy time, the area of therapy are higher, faster, and wider than the 1-slot applicator as we expected in the time course of temperature increments for four different structures.

Our result of contour on the xy-plane passing through the first slot of the array applicator is shown in Table 3.

Ⅳ. Conclusion

By using the impedance matching technique, we present the resonance characteristics of applicator with coaxial slot configuration within phantom at 2.45 GHz.

The *SAR* distribution due to the EM waves emitted from a temperature controlled ring slot antenna used for the hyperthermia therapy is calculated in liver, which has the relatively well-localized heating performance in the phantom.

The result indicates an increase of heating effect by optimization of antenna dimensions. In case of the proposed structure which has a sleeve with slots, the maximum temperature, arrival time to steady state, and size of therapy are higher, faster, and wider than the applicator with one slot antenna.

But low power can't produce large lesion depth, even when the duration of the power radiation time is extended. From the simulations, we conclude the array structure is more effective than one applicator.

The results of this study demonstrate that predicting thermal distribution is an reliable and accurate method, which can dynamically monitor the therapy effect in the three-dimensional region. It provides a theoretical and technical basis for controlling the size of the thermal field during the microwave interstitial treatment of cancerous tissue and reaches the aim of eliminating the tumor. Further work is required for various designs of applicator and experimental evaluation.

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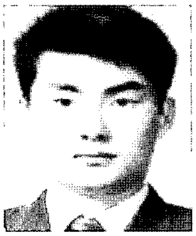

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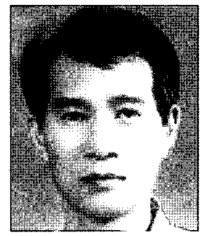

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