A Large Waveguide Applicator for Deep Regional Hyperthermia

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Abstract —**A large waveguide applicator is proposed for deep regional hyperthermia, where a part of a patient's body is exposed to the TE_{10}-mode waves in the rectangular waveguide through the holes made to fit the body cross section in the broad walls. The electric field and the specific absorption rate distribution produced by the applicator in a realistic model of a human body cross section calculated by a two-dimensional (2-D) numerical method are given.**

I. Introduction

Hyperthermia as a treatment for cancer has been a subject of intensive studies for the last several years, and a large amount of biological and clinical data demonstrating its effectiveness has been accumulated [1], [2]. However, further progress appears to depend strongly on the development of equipment for regional deep heating and for thermometry in a human body. Developing new equipment is difficult because the problems involved stem to a large part from the physical properties of biological materials and systems. Nevertheless, a number of techniques have been developed for the electromagnetic energy deposition for deep heating: annular phased array [3], ridged waveguide applicator [4], coaxial TEM applicator [5], phased multiple-dipole applicator [6], [7], and capacitive applicator [8], [9].

In this paper, a large waveguide applicator [10] is proposed for deep regional heating. In addition, a numerical example of specific absorption rate (SAR) distribution produced by the applicator in a realistic model of a human body cross section is given.

II. Large Waveguide Applicator

A proposed large waveguide applicator is depicted in Fig. 1, where a part of a patient's body is exposed to the TE_{10}-mode waves traveling in opposite directions. The waveguide is assumed to be filled with air in the present discussion, but may be filled with an appropriate dielectric material. The holes in the broad walls of the waveguide can be fitted to the patient's body. A frequency between 25 and 100 MHz is used for heating, depending on the size of the patient's body. The selection of frequency is made by considering the resultant electric field pattern in the body, which is the result of competition between the large attenuation and interference of the waves in the body. Since the applicator has an almost closed structure, any desired frequency consistent with waveguide propagation of TE_{10}-mode can be used for heating without an external shielding arrangement.

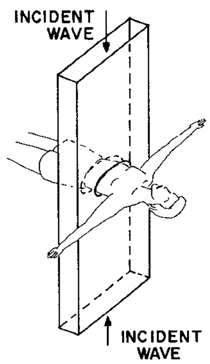

Fig. 1. A large waveguide applicator.

III. Two-Dimensional Analysis

In the following analysis, the large waveguide applicator is replaced with a model shown in Fig. 2: a waveguide with no holes in the broad walls with a lossy dielectric cylinder at its center. The field analysis then reduces to a two-dimensional (2-D) one, and the electric field is obtained by solving the following integral equation [11]:

$$E_z(x, y) = E_z^i(x, y) + j\omega\epsilon_0 \iint \{\epsilon_r - 1\} E_z(x', y') \cdot G(x, y|x', y')\, dx'\, dy' \quad (1)$$

where $E_z(x, y)$ and $E_z^i(x, y)$ are the total and the incident fields, respectively, and $\epsilon_r(x, y)$ is the complex relative dielectric constant which is a function of position. Since only the z-component of electric field is excited, the relevant Green's function can be given by [12]

$$G(x, y|x', y') = -\frac{j\omega\mu_0}{a} \sum_{p=1}^{\infty} \frac{1}{\Gamma_p} \sin\frac{p\pi}{a}\left(x + \frac{a}{2}\right) \cdot \sin\frac{p\pi}{a}\left(x' + \frac{a}{2}\right) \exp\{-\Gamma_p|y - y'|\} \quad (2)$$

where

$$\Gamma_p = \left[\left(\frac{p\pi}{a}\right)^2 - k_0^2\right]^{1/2}$$

$$k_0 = \omega\sqrt{\mu_0\epsilon_0}$$

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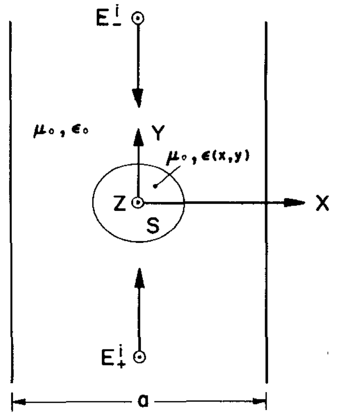


Fig. 2. A two-dimensional model of the large waveguide applicator and the coordinate system used in the analysis.

and a is the width of the waveguide. When the incident fields E^i_+ and E^i_- are symmetric with respect to the coordinate origin, referring to Fig. 2, the resultant field $E^i_z(x, y)$ can be written as

$$E^i_z(x, y) = 2A\cos\frac{\pi x}{a}\cos\beta_{10}y \tag{3}$$

where

$$\beta_{10} = \left[k_0^2 - \left(\frac{\pi}{a}\right)^2\right]^{1/2},$$

and A is the amplitude of the one side incident field.

Substituting (2) and (3) into (1) and using the numerical method developed by Borup and Gandhi [13], [14], we can solve (1) for $E_z(x, y)$. After dividing the dielectric cylinder into small cells measuring Δx and Δy using an $N \times M$ square grid, one can convert (1) into a numerical expression

$$E_z(n, m) = E^i_z(n, m) + \sum_{i=1}^{N}\sum_{j=1}^{M}\{\epsilon_{ij} - 1\}E_z(i, j) \cdot [K_1(n-i, m-j) + K_2(n+i, m-j)] \tag{4}$$

with

$$K_1(n-i, m-j) = \sum_{p=1}^{\infty}\frac{k_0^2}{p\pi\Gamma_p^2}\sin\frac{p\pi}{a}\frac{\Delta x}{2}\cos\frac{p\pi}{a}(n-i)\Delta x \cdot \begin{cases} 2\left[1 - \exp\left(-\Gamma_p\frac{\Delta y}{2}\right)\right], & m = j \\ 2\exp(-\Gamma_p|m-j|\Delta y)\sinh\Gamma_p\frac{\Delta y}{2}, & m \neq j \end{cases} \tag{5}$$

and

$$K_2(n+i, m-j) = \sum_{p=1}^{\infty}\frac{(-1)^p k_0^2}{p\pi\Gamma_p^2}\sin\frac{p\pi}{a}\frac{\Delta x}{2}\cos\frac{p\pi}{a}(n+i)\Delta x \cdot \begin{cases} 2\left[1 - \exp\left(-\Gamma_p\frac{\Delta y}{2}\right)\right], & m = j \\ 2\exp(-\Gamma_p|m-j|\Delta y)\sinh\Gamma_p\frac{\Delta y}{2}, & m \neq j \end{cases} \tag{6}$$

In the right-hand side of (4), the first term is a 2-D convolution of $\{\epsilon_r - 1\}E_z$ and K_1 and the second term consists of a cross correlation for x, and a convolution for y, of $\{\epsilon_r - 1\}E_z$ and K_2, and can be computed efficiently by use of the FFT algorithm, as pointed out in [13].

A system of equations (4) written down for all the cells forms a matrix equation of the form

$$\boldsymbol{E}_z = \boldsymbol{E}^i_z + \boldsymbol{KDE}_z \tag{7}$$

where $\boldsymbol{D}$ is a diagonal matrix representing $\{\epsilon_r - 1\}$ for all the cells and $\boldsymbol{K}$ is a matrix containing the elements $K = K_1 + K_2$. K_1 and K_2 are, in turn, defined by (5) and (6). Equation (7) is then solved by using the conjugate gradient method (CGM) as described in [14]–[16].

The specific absorption rate (SAR) is then computed by

$$\text{SAR} = \frac{1}{2}\frac{\sigma}{\rho}|E_z|^2 \tag{8}$$

where σ and ρ are the conductivity and the density of the dielectric material. The density ρ is assumed to be one in this paper.

IV. Numerical Results

The SAR distribution in a dielectric circular cylinder which has muscle-like properties and a diameter of 40 cm placed at the center of a 6-m-width waveguide was calculated. A SAR pattern for two-side TE_{10} illumination (A = 1 V/m) at 40.68 MHz is given in Fig. 3, where the vertical axis represents relative SAR values normalized by its maximum value (3.13×10^{-5} W/kg) in the cylinder. The pattern shows the interference effect near the center which is masked by large attenuation. The competition between the interference and the attenuation in a biological body can be controlled by the selection of frequency. Fig. 4 shows SAR distributions along the x-axis and the y-axis for illumination at 27.12, 40.68, 50, 100 MHz, suggesting that a frequency between 25 and 40 MHz would be practical for deep heating of a 40-cm diameter body. The dielectric properties of muscle at these frequencies used in the above computation were taken from [17], [18]. For comparison, similar calculations were made for the case of plane wave illumination from two opposite sides. Results showed that SAR distribution patterns were nearly the same for the plane wave and the TE_{10}-wave illumination cases.

Another numerical example was worked out by using the human body cross section shown in Fig. 5. In order to facilitate comparison with the previously published result for plane wave illumination in [13], the same drawing [13, fig. 5] is used here. The results are given in Figs. 6 and 7. The electric field distribution is smooth, as it should be for the 2-D case where the electric field is parallel to the boundaries, in spite of the inhomogeneity in the dielectric properties over the cross section. The corresponding SAR distribution is given in Fig. 7, which reflects the inhomogeneity in the tissue conductivity σ over the cross section.

The results shown in Figs. 6 and 7 indicate that it is possible to deposit a sufficient amount of electromagnetic energy for hyperthermia in high-conductivity regions deep

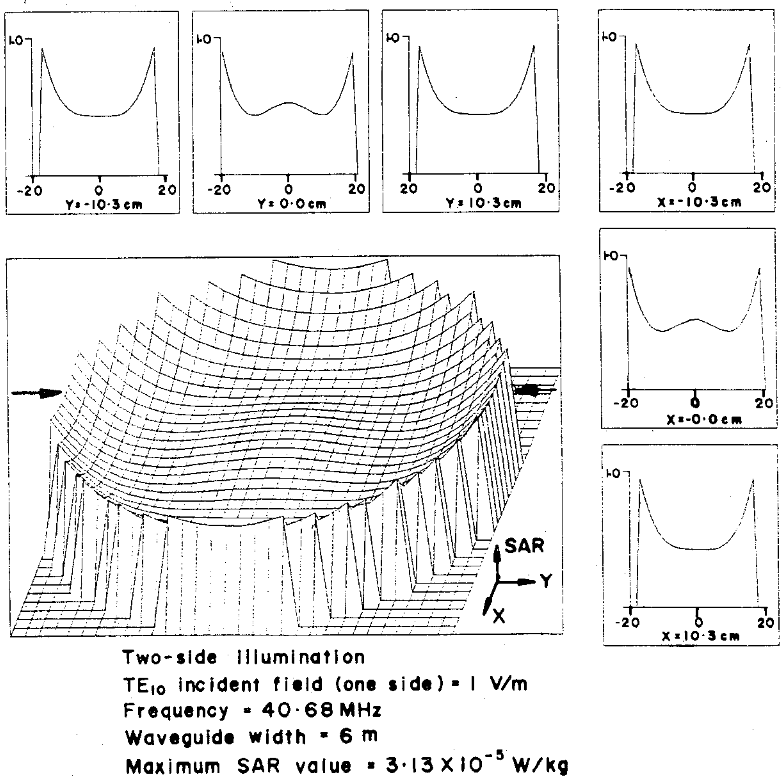


Fig. 3. SAR distribution in a circular cylinder having muscle-like dielectric properties and a 40-cm diameter at the center of a 6-m-wide waveguide. The cylinder is illuminated by TE_{10} incident waves from both sides.

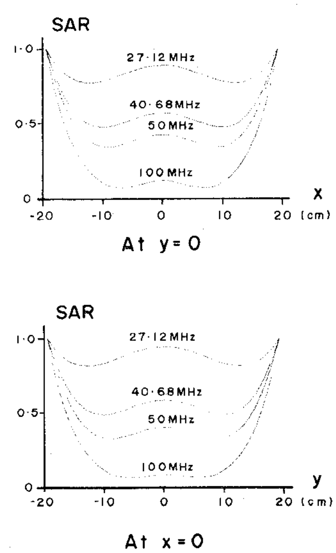
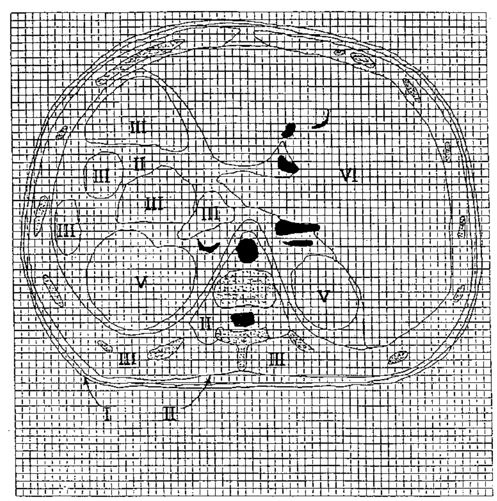


Fig. 4. SAR distributions in a circular cylinder having muscle-like dielectric properties and a diameter of 40 cm. The cylinder is placed at the center of a 6-m-wide waveguide and is illuminated by TE_{10} incident fields from both sides at various frequencies.



TISSUE	ϵ	σ
I. SKIN	97	0.693
II. FAT	15	0.05
III. MUSCLE	97	0.693
IV. BONE	7	0.034
V. KIDNEY	137	0.769
VI. LIVER	92	0.511
VII. BLOOD	100	1.358

BLOOD
BONE
64X64 cells
$\Delta x = \Delta y = 6.5$ mm
Width = 40.3 cm

Fig. 5. A seven-tissue model of a human body cross section. The drawing is taken from [13] (© 1984 IEEE).

in a body, without inducing excessive heating near the periphery by the large waveguide applicator operated at a frequency around 40 MHz.

V. Conclusions

This paper proposes a large waveguide applicator for deep regional heating. The numerically efficient method based on the FFT and the CGM is used to analyze a two-dimensional model of the proposed applicator. Results of the analysis show that the deposition of large amounts of energy in high-conductivity regions deep in a body is possible without an excessive peripheral energy deposition by the use of the applicator. Because the applicator has an almost closed structure, it can be operated at any frequency

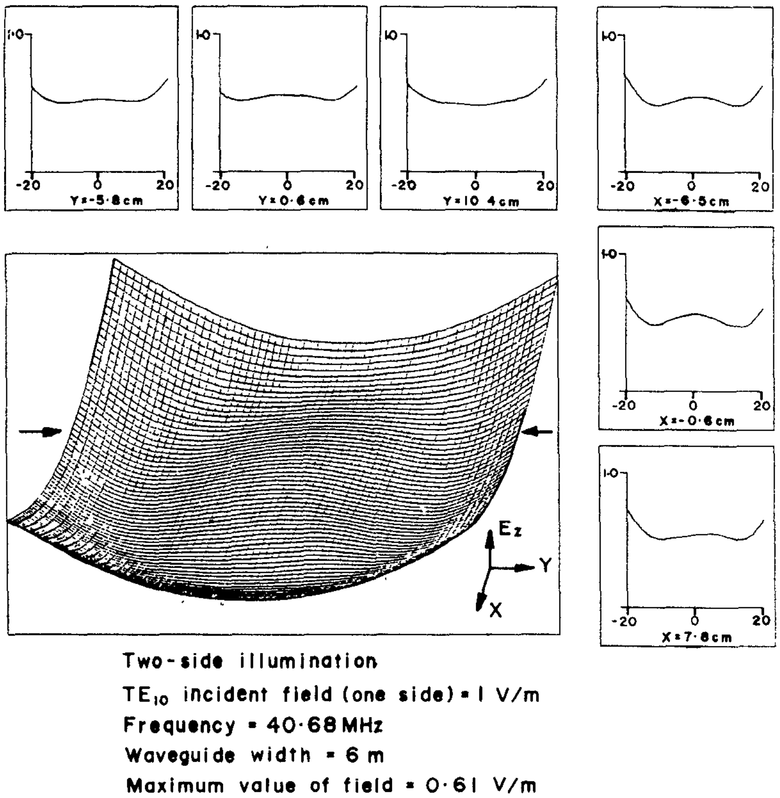


Fig. 6. Electric field distribution for the inhomogeneous model of a human body of Fig. 5. The model is placed in a 6-m-wide waveguide and is illuminated by TE_{10} fields incident from both sides.

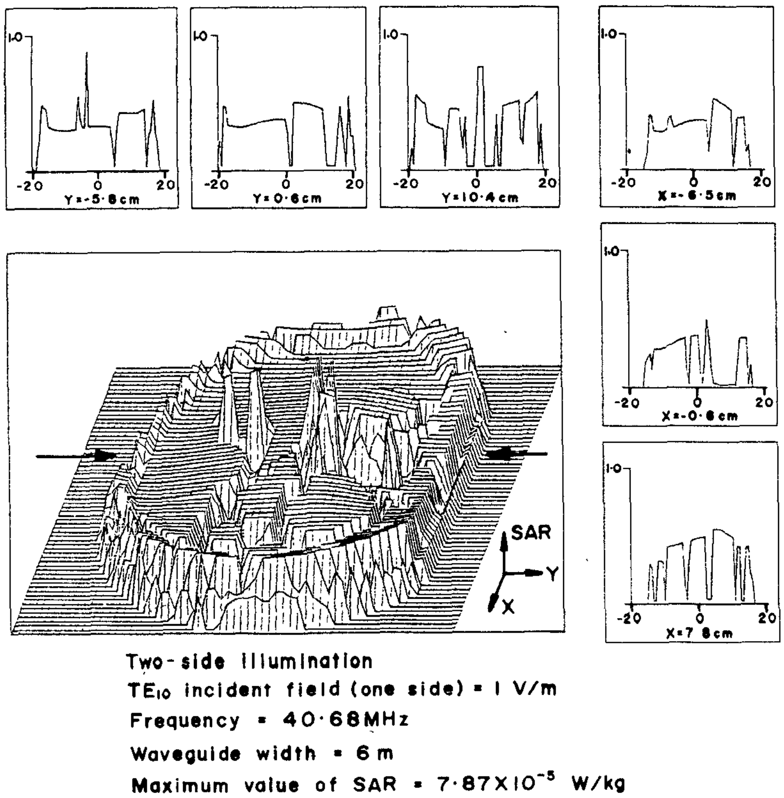


Fig. 7. SAR distribution in the inhomogeneous model of a human body of Fig. 5. The SAR distribution corresponds to the smooth field distribution of Fig. 6.

appropriate for deep heating, provided that it is in the TE_{10}-mode propagation range, without an external shielding arrangement.

Using the results of 2-D field analysis, a thermal analysis is underway to estimate the temperature distribution in a body. In addition, an extension of the field analysis to the three-dimensional case seems possible in view of the availability of the necessary Green's function for the rectangular waveguide [19], [20]. We also plan to experiment on the applicator at around 40 MHz. Our plan includes the development of a frequency tunable source and a method of controlling bidirectional excitation.

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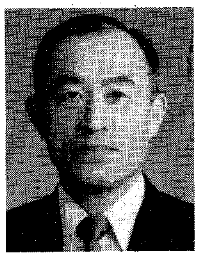

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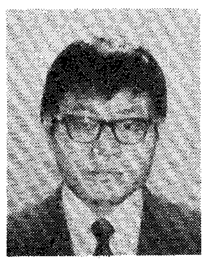

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