SAR DISTRIBUTION FROM RUTILE-LOADED MODIFIED BOX-HORN APPLICATOR FOR HYPERTHERMIA

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ABSTRACT

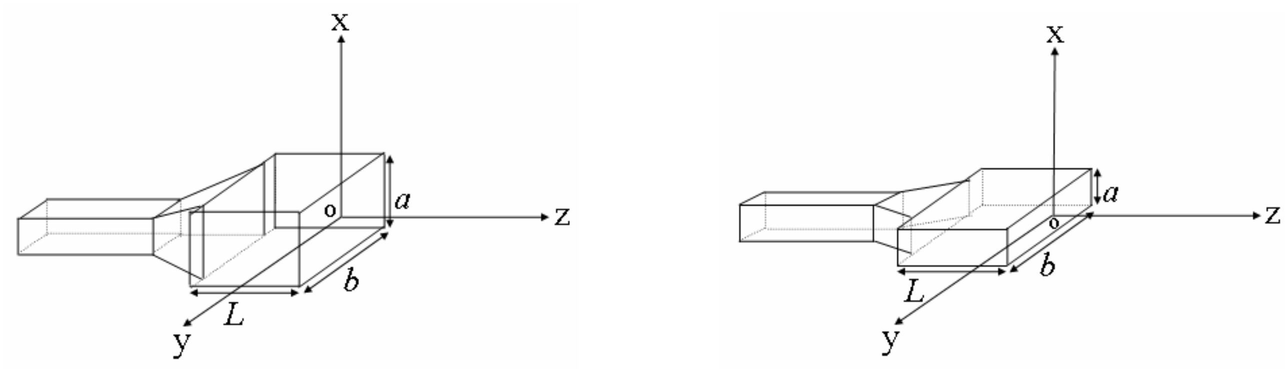
In this paper, the authors have analyzed a rutile-loaded modified box-horn terminated in a bio-medium for hyperthermia treatment of cancer. Modified box-horn is a novel and improved version of conventional box-horn, in which the horn exciting the box waveguide is also flared in E-plane to increase its aperture size. The field over the box-horn aperture is a combination of the TE_{10} and TE_{30} modes and hence field distribution over the H-plane of the aperture is a closer approximation to the uniform distribution. The modified box-horn is filled with rutile or titanium dioxide (TiO_2) to provide good impedance match between the horn and muscle medium, which ensures good transmission into the tissue. Theoretical analysis of electric field and specific absorption rate (SAR) distribution in different planes in muscle medium due to modified box-horn is carried out. SAR distribution in muscle medium as well as penetration depth and power absorption coefficient is computed at 2450 MHz. The SAR distributions are also compared with those for conventional box-horn. The modified box-horn has larger aperture and gives higher values of SAR in muscle in comparison to the conventional box-horn.

INTRODUCTION

Numerous types of hyperthermia applicators have been investigated by many researchers and are described in the literature including waveguide applicators [1]-[2], multimodal applicator [3], conical horn antenna [4] etc. The type of applicator selected depends on the production of sufficient thermal field distributions at different depths of the tumor in a variety of anatomical sites. In this paper, the authors have analyzed rutile-loaded modified box-horn applicator terminated in muscle medium for hyperthermia. The modified box-horn is a novel and improved version of conventional box-horn, which consists of a TE_{10} mode pyramidal horn coupled to a length L of rectangular waveguide of same E-plane height but whose H-plane width is large enough to support the TE_{30} mode. The field over the horn aperture is then due to a combination of the TE_{10} and TE_{30} modes [5] and therefore the amplitude distribution over the H-plane of the aperture is a closer approximation to the uniform distribution, whereas fundamental TE_{10} mode provides cosine variation of the field. It has greater directivity in the H-plane than a flared horn of the identical aperture carrying TE_{10} mode. The modified box-horn is filled with rutile or titanium dioxide (TiO_2) which has negligible medium loss. Hence, it is conceivable that by using a relatively lossless matching material, sufficient energy deposition at the tumor site can be achieved. Loading the box-horn with rutile provides a good impedance match and ensures good transmission into the tissue. Also, it reduces the size of the modified box-horn, which makes it suitable for array configuration. The expression for the electric field in the tissue is derived and SAR distributions in different planes are computed and presented at 2450 MHz. The SAR distributions in muscle medium due to modified box-horn have been compared with those for conventional box-horn.

THEORY

The present analysis is based on plane wave spectra technique [6]-[7]. The three-dimensional views of modified and conventional box-horns are shown Figs. 1(a) and 1(b) respectively. The narrow and broad dimensions of the aperture of each box-horn are denoted as a and b respectively. The length of box-horn along z-direction is denoted as L. In present analysis, muscle is considered to be extending upto infinity along z-direction and each box-horn aperture is assumed to be in direct contact with the muscle surface.



(a) (b)

Fig. 1. Three-dimensional view of (a) modified box-horn and (b) conventional box-horn

Analysis of SAR in muscle layer due to modified box-horn

The analysis of fields in the bio-medium presented here follows the plane wave spectral technique discussed by Compton [6] and Harrington [7]. The x-component of electric field at the aperture of the modified box-horn [5] is represented by

$$E_x(x,y,0) = a_{10}(1+\Gamma_{10})\cos\left(\frac{\pi y}{b}\right)e^{-j\beta_{10}L} + a_{30}(1+\Gamma_{30})\cos\left(\frac{3\pi y}{b}\right)e^{-j\beta_{30}L} \quad (1)$$

where a_{10} and a_{30} are amplitude coefficients, Γ_{10} and Γ_{30} are reflection coefficients at the interface between rutile-loaded box-horn aperture and muscle layer, β_{10} and β_{30} are the phase constants for TE_{10} and TE_{30} modes, respectively.
With the aperture electric field as given in (1), the fields in bio-medium are every-where TE to y [6]. Hence, the fields may be represented by an electric vector potential

$$\overline{F} = \hat{y}\psi \quad (2)$$

where ψ is the solution of the wave equation

$$\nabla^2\psi + k_m^2\psi = 0\,. \quad (3)$$

where k_m is the complex propagation constant of muscle. The solutions for ψ may be constructed as the sum of a continuous spectrum of eigenvalues as follows:

$$\psi(x,y,z) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(k_x,k_y)\cdot e^{-jk_z z}e^{-jk_x x}e^{-jk_y y}\,dk_x dk_y\,. \quad (4)$$

where $k_z = \sqrt{k_m^2 - k_x^2 - k_y^2}$, and $f(k_x,k_y)$ is the Fourier transform of $\psi(x,y,z)$.

The electric field may found from the relation

$$\overline{E} = -\nabla\times\overline{F}\,. \quad (5)$$

The x-, y- and z-components of electric field in muscle are derived and are given below

$$E_x(x,y,z) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} -jk_z f(k_x,k_y)\cdot e^{-jk_z z}e^{-jk_x x}e^{-jk_y y}\,dk_x dk_y \quad (6)$$

$$E_y(x,y,z) = 0 \quad (7)$$

$$E_z(x,y,z) = \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} jk_x f(k_x,k_y)\cdot e^{-jk_z z}e^{-jk_x x}e^{-jk_y y}\,dk_x dk_y \quad (8)$$

Substituting the expression for $E_x(x, y, 0)$ from (1) and taking inverse Fourier transform of (6) at $z = 0$ gives

$$f(k_x,k_y)=\frac{j.4\pi b}{k_x k_z}\sin\left(\frac{k_x a}{2}\right)\cos\left(\frac{k_y b}{2}\right)\cdot\left[\frac{a_{10}(1+\Gamma_{10})e^{-j\beta_{10}L}}{\pi^2-b^2k_y^2}-\frac{3a_{30}(1+\Gamma_{30})e^{-j\beta_{30}L}}{9\pi^2-b^2k_y^2}\right]. \tag{9}$$

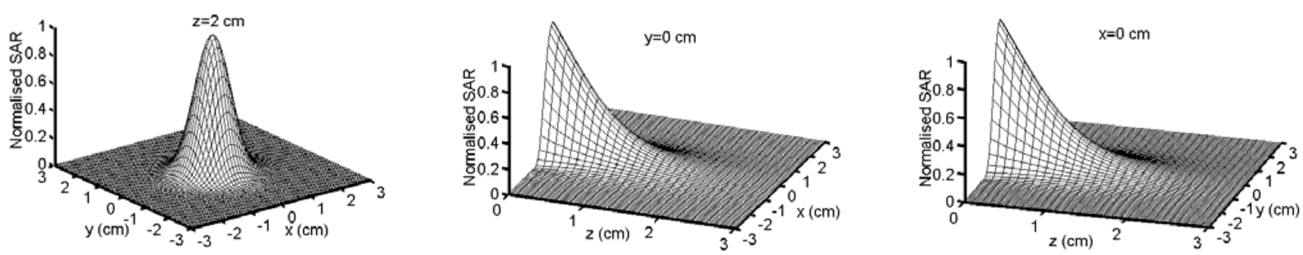
The x-, y- and z-components of electric field, E_x , E_y and E_z are found by substituting for $f(k_x,k_y)$ from (9) into (6)-(8),. The Specific absorption rate (SAR) in muscle is evaluated using the formula $SAR=\sigma_m|E_t|^2/2\rho_m$, where $\sigma_m=\omega\varepsilon_0\varepsilon''_m$, ρ_m and ε''_m are the conductivity, density and imaginary part of relative permittivity of muscle layer respectively, and the total electric field E_t due to modified box-horn is evaluated by $|E_t|=\sqrt{|E_x|^2+|E_y|^2+|E_z|^2}$.

Design of rutile- loaded Modified Box-horn

For Modified box-horn, both E- and H-plane flared-horn (pyramidal horn) exciting the box waveguide is designed as discussed by Terman [8] and box waveguide is designed as per Silver [5] at the frequency of 2450 MHz. The complex relative permittivity of the rutile is taken to be 80 – j 0 [9]. The computed dimensions of rutile-loaded modified box-horn are a=1.61 cm, b=2.19 cm, L =1.14 cm and flare angles of the pyramidal horn exciting the box are 30^0 in both H-and E-planes. The rutile-loaded conventional box-horn applicator is designed as discussed by Silver [5]. The computed dimensions of the conventional box-horn at 2450 MHz, are a=0.43 cm, b=2.19 cm and L =1.14 cm. The flare angle of the horn exciting the box is 30^0 in H-plane.

NUMERICAL RESULTS AND DISCUSSION

The spatial distributions of SAR in muscle layer for rutile-loaded box-horn are computed at 2450 MHz using MATLAB and results are presented in Figs. 2, 3 and 4. The complex permittivity [10] and density [11] of muscle are taken to be $\varepsilon_m^*=47.5-j13.5$ and $\rho_m=1050\,Kg/m^3$ respectively in the computation of SAR distribution.
Fig. 2(a)-(c) illustrate the three-dimensional SAR distributions in muscle in x-y, x-z and y-z planes respectively for rutile-loaded modified box-horn. The SAR values are normalized to the maximum value of SAR in muscle layer.

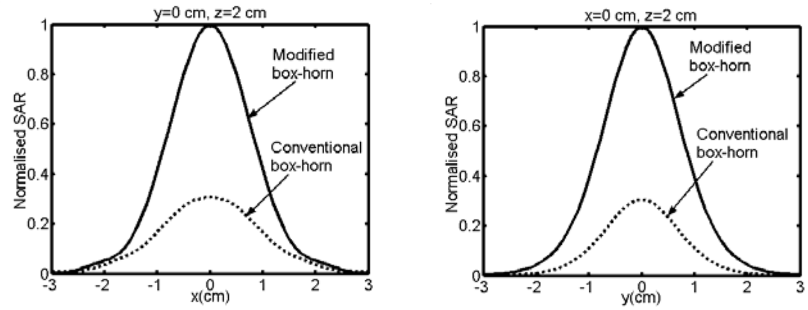


(a) (b) (c)

Fig. 2. SAR distribution in muscle due to modified box-horn along (a) x-y directions, (b) x-z directions and (c) y-z directions

In Figs 3(a)-(b) SAR distributions in muscle in x- and y-directions due to modified box-horn are compared with corresponding distributions that for conventional box-horn. The SAR value is normalized with maximum value of SAR for modified box-horn in muscle layer. It is observed from Fig. 3 that modified box-horn has higher peak value of SAR in x- and y-directions.

Comparison of SAR distributions of modified box-horn and conventional box-horn along z-direction is given in Fig. 4. The penetration depth in muscle (depth where SAR value is down to 13.5 percent of the maximum in the muscle) is found to be 1.3 cm for modified box-horn and 0.8 cm for conventional box-horn. The power absorption coefficient of muscle defined as inverse of penetration depth in muscle is found to be 76.92 m^{-1} for modified box-horn and 125.00 m^{-1} for conventional box-horn. To increase penetration depth further, modified box-horn can be arranged in phased array configuration. By dielectric-slab-loading in the centre of modified box-horn, penetration depth can also be improved.



(a) (b)

Fig. 3. Comparison of SAR distributions in muscle due to modified and conventional box-horns along (a) x-direction and (b) y-direction

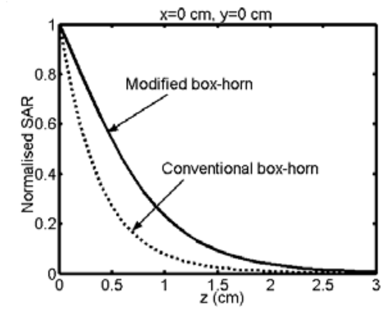


Fig. 4. SAR distributions in muscle due to modified and conventional box-horns along z-direction

CONCLUSION

An analytical solution has been presented for SAR distribution in muscle layer illuminated by modified box-horn, a new type of multi-mode applicator. It is shown that modified box-horn can produce higher SAR values in comparison to conventional box-horn. The analysis and results presented here may be useful in analyzing, designing and developing a new type of multi-mode applicator for hyperthermia.

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