ANALYSIS OF AN ARRAY OF TWO WATER-LOADED MODIFIED BOX-HORNS FOR HYPERTHERMIA TREATMENT OF TUMOR

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Abstract

In this paper, the theoretical analysis of fields in three-layered bio-media (skin, fat and muscle layers) in direct contact with an array of two modified box-horns suitable for hyperthermia treatment of cancerous tumor has been carried out using plane wave spectral technique. The proposed modified box-horn applicator has relatively uniform field distribution across the aperture as compared with flared horn of identical aperture dimensions. The modified box-horn is a novel applicator, in which the horn is flared in both E-and H-planes, while in conventional box-horn, the horn is flared only in H-plane. Each modified box-horn of the array is assumed filled with de-ionized water to reduce its size and to provide a better impedance match to a high dielectric constant medium representative of human skin. The specific absorption rate (SAR) distribution in different bio-layers (*viz.* skin, fat and muscle layers) are computed and presented at an ISM frequency of 2450 MHz. The results of SAR values in different layers for array of two modified box-horns and single modified box-horn are calculated and compared for same output power. It is shown that an array of two modified box-horns gives relatively higher SAR values in different layers in comparison to single modified box-horn. The SAR distribution in different layers for an array of two conventional box-horns is also obtained and compared with that for an array of modified box-horns for same output power. The result with phase steering of the SAR pattern is also presented in the paper. The result has been validated against available published result in the literature.

Keywords: Bio-media, Hyperthermia, Modified box-horn, Plane wave Spectra, Specific absorption rate (SAR).

1. INTRODUCTION

Microwave Hyperthermia is one of the more promising techniques for treating cancer. Hyperthermia is a technique, wherein the tumor is heated upto the therapeutic temperature (about 43-50° C) so that the cancer cells can be selectively killed without damaging surrounding normal tissue. A major characteristics of the hyperthermia applicator is the ability to focus heat energy in a small region around the tumor to be treated.

Different types of hyperthermia applicators have been developed and used practically such as, rectangular waveguide, circular waveguide, ridged waveguide, conical horn antenna, coaxial antenna, microstrip antenna, antenna arrays *etc*. The type of applicator selected depends on the production of sufficient thermal field distribution at different depths of the tumor in a variety of anatomical sites. For superficial tumors, single contact applicators at 915 and 2450 MHz have been used to treat well localized tumors extending upto a depth of 3 cm. Waveguide and horn antennas are also put under this category of hyperthermia applicators. Since bio-media are usually quite lossy, there is a fundamental trade-off between penetration-depth and localization (high resolution or narrower half-power width of SAR distribution in transverse direction) of the field [1] inside the body. In hyperthermia, it is often desirable to concentrate the internal fields at the tumor, thereby heating it without appreciably affecting the surrounding normal tissue. To restrict physical sizes of the aperture of the array convenient for use with patients and still get narrower half-power width of SAR distribution in transverse direction, higher frequency operation such as 2450 MHz is required. The penetration depth at higher frequency (2450 MHz) is relatively low (3 cm), which is useful for treatment of tumors at relatively smaller depth. Greater penetration depth can be obtained by increasing number of box-horns in the array. To increase the penetration depth a little more, the illumination frequency may also be reduced further. For uniform heating of these tumors properly designed multi-mode waveguides / horns can be used.

In an extensive analysis of the internal fields produced by a TE_{10} mode rectangular aperture in a two-layer semi-infinite tissue model, Guy [2] calculated internal fields as a function of the size of the aperture and thickness of the fat layer. A direct contact 915 MHz microwave applicator for effective deep-tissue heating was proposed by Lehmann and colleagues [3]. Uzunoglu and colleagues [4] have shown that water-loaded waveguide applicator at UHF is useful for tumors due to small reflection between waveguide and skin and high penetration depth. Further, Nikita *et al.* [5] reported an analytical model for power coupling from a water-loaded waveguide applicator (carrying TE_{10} mode) into a three-layered tissue model and presented the results at 144 and 432 MHz. Paglione and colleagues [6] developed a large ridged-waveguide applicator that operates at 27.12 MHz. It is loaded with de-ioned water to further reduce its size, but it is still so large that the patient must sit or lie on the aperture. Recently, Samaras *et al.* [7] presented analytical model of a Lucite cone applicator for hyperthermia and investigated SAR distribution of the same applicator at 433 MHz.

In this paper, the authors have proposed an array applicator consisting of two modified box-horns for hyperthermia treatment. The fields in different layers of the bio-media are analyzed for array of two modified box-horns. The modified box-horn is a new type of applicator which is an improved version of conventional box-horn [8]. The modified box-horn 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 [8]. The amplitude distribution over the H-plane of the aperture is a closer approximation to the uniform distribution whereas 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. The box-horn is loaded with de-ionized water so that no energy dissipation takes place in it and efficiency of the system does not reduced. Also loading the modified box-horn with dielectric (de-ionized water) having permittivity approximately equal to that of skin layer of bio-media, provides a good impedance match and ensures good transmission into the tissue [4, 5]. The de-ionized water-loading also reduces the size of the box-horn, which is useful for array applicator. The effective heating of the bio-media depends strongly on the size of the aperture and the field distribution across it. The specific absorption rate (SAR) distribution in skin, fat and muscle layers are computed and presented for an array of two modified box-horns as well as an array of two conventional box-horns. In an array environment, the element pattern is affected by the mutual coupling between the elements. This effect is generally considered to be secondary and is neglected in this study, since experimentally it is investigated that coupling between adjacent waveguide elements is on the order of -30 dB, presumably low due to high medium losses [9]. Thus, effect of mutual coupling on SAR distribution is negligible. This approximation (neglecting mutual coupling) in present theory gives satisfactory results for SAR distribution in different layers. The array of two modified box-horns is superior to the array of two conventional box-horns for effective heating of superficial tumors at the ISM frequency of 2450 MHz. It is also shown that higher SAR values in skin, fat and muscle layers are obtained for an array of two modified box-horns when the results of the array were compared with those of single modified box-horn for same output power. The effect of phase excitation of each modified box-horn of the array on SAR distribution is also reported.

2. ANALYSIS OF SPECIFIC ABSORPTION RATE IN SKIN, FAT AND MUSCLE LAYERS

Two arrays – the first one consisting of two modified box-horns terminated in three-layered bio-media (skin, fat and muscle layers) and the second one consisting of two conventional box-horns in direct contact with bio-layers are shown in fig.1 (a) and (b) respectively. Each box-horn aperture is assumed to be in direct contact with the skin surface. The narrow and broad dimensions of the aperture of each modified box-horn are denoted as *a* and *b* respectively. *L* is the length of box-horn along *z*-direction. Skin and fat layers considered are of finite thickness, while muscle layer is considered to be of infinite thickness in present analysis. ε_1^*, ε_2^* and ε_3^* are complex permittivities of skin, fat and muscle layers, respectively.

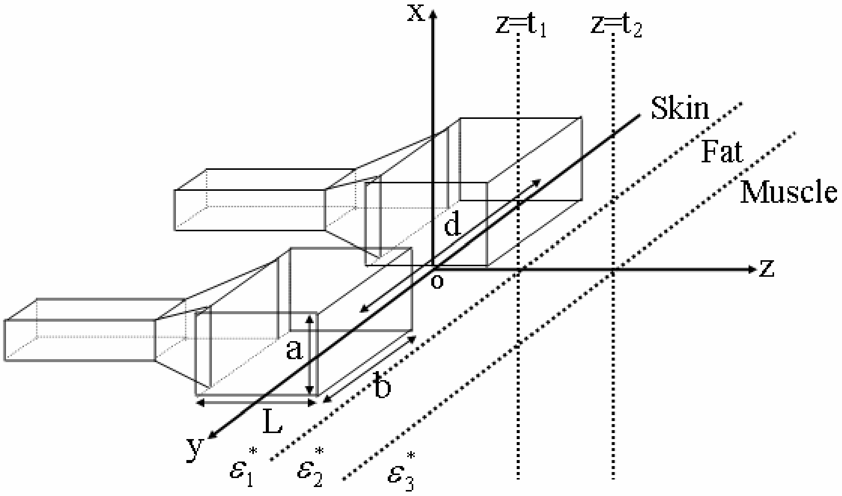

Fig. 1 a. Array of two de-ionized water-loaded modified box-horns in three-layered tissue.

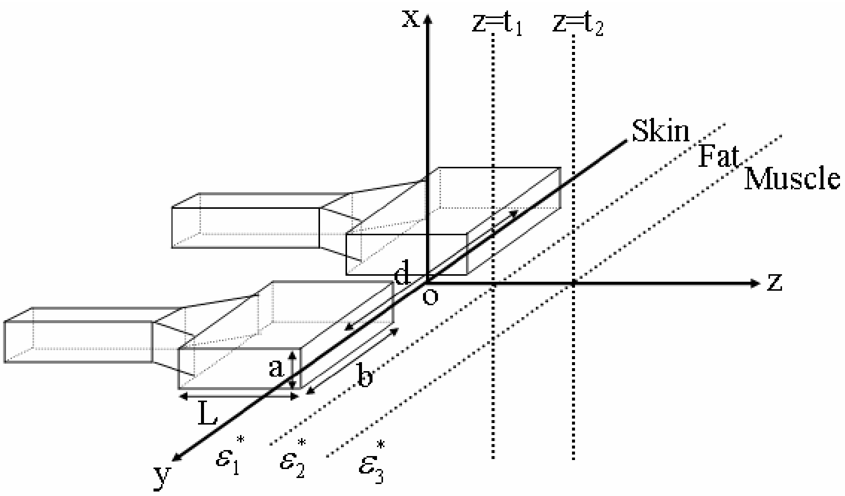

Fig. 1 b. Array of two de-ionized water-loaded conventional box-horns in three-layered tissue.

The analysis of fields in different layers of the bio-media is carried out using plane-wave spectral technique. Through the use of plane-wave spectral technique [10, 11], spectral integral representations of the fields in different layers are obtained. The *x*-component of electric field at point (*x*, *y*, 0) in the aperture plane of the array is represented by

$$E_{x1}(x,y,0)=\left[(1+\Gamma_{10})a_{10}\cos\left(\frac{\pi(y+d/2)}{b}\right)e^{-j\beta_{10}L}e^{-\alpha_{10}L}+(1+\Gamma_{30})a_{30}\cos\left(\frac{3\pi(y+d/2)}{b}\right)e^{-j\beta_{30}L}e^{-\alpha_{30}L}\right].e^{j\delta_1}$$
$$+\left[(1+\Gamma_{10})a_{10}\cos\left(\frac{\pi(y-d/2)}{b}\right)e^{-j\beta_{10}L}e^{-\alpha_{10}L}+(1+\Gamma_{30})a_{30}\cos\left(\frac{3\pi(y-d/2)}{b}\right)e^{-j\beta_{30}L}e^{-\alpha_{30}L}\right].e^{j\delta_2} \tag{1}$$

Where Γ_{10} and Γ_{30} are reflection coefficients at the interface between water-loaded modified box-horn aperture and skin layer for TE_{10} and TE_{30} modes respectively, a_{10} and a_{30} are corresponding amplitude coefficients, β_{10} and β_{30} are the phase constants, α_{10} and α_{30} are the attenuation constants in de-ionized water for corresponding modes, *L* is the length of modified box-horn along *z*-direction, and *d* is separation between the centers of two modified box-horns along y-direction. δ_1 and δ_2 are phases of excitation of the two modified box-horns respectively. With the field as given in equation (1), the field in bio-media is every-where TE to *x* and TE to *y* [10]. Hence the fields may be represented in terms of an electric vector potential

$$\overline{F}=\phi\,\hat{x}+\psi\,\hat{y} \tag{2}$$

where ϕ and ψ are both solutions to the wave equation

$$\left(\nabla^2+k_{1,2,3}^2\right)\begin{Bmatrix}\psi\\ \phi\end{Bmatrix}=0 \tag{3}$$

where $k_{1,\,2,\,3}$ are respectively the wave-numbers in layers 1, 2 and 3 (skin, fat and muscle layers). The solutions for ϕ and ψ may be constructed as the sum of a continuous spectrum of eigenvalues, as follows

$$\psi_1(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[I_{\psi 1}e^{-jk_{z1}z}+R_{\psi 1}e^{+jk_{z1}z}]\cdot e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{4}$$

$$\phi_1(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[I_{\phi 1}e^{-jk_{z1}z}+R_{\phi 1}e^{+jk_{z1}z}]\cdot e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{5}$$

$$\psi_2(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[T_{\psi 1}e^{-jk_{z2}z}+R_{\psi 2}e^{+jk_{z2}z}]\cdot e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{6}$$

$$\phi_2(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[T_{\phi 1}e^{-jk_{z2}z}+R_{\phi 2}e^{+jk_{z2}z}]\cdot e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{7}$$

$$\psi_3(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}T_{\psi 2}e^{-jk_{z3}}e^{-jk_x x}\cdot e^{-jk_y y}dk_x dk_y \tag{8}$$

$$\phi_3(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}T_{\phi 2}e^{-jk_{z3}z}e^{-jk_x x}\cdot e^{-jk_y y}dk_x dk_y \tag{9}$$

where plane wave spectra are $I_{\psi 1}, I_{\phi 1}, R_{\psi 1}, R_{\phi 1}$ in skin layer (layer 1), $T_{\psi 1}, T_{\phi 1}, R_{\psi 2}, R_{\phi 2}$ in fat layer (layer 2) and $T_{\psi 2}$, $T_{\phi 2}$ in muscle layer (layer 3). The propagation constants along *z*-direction in the three layers are given by $k_{z1}=\sqrt{k_1^2-k_x^2-k_y^2}$, $k_{z2}=\sqrt{k_2^2-k_x^2-k_y^2}$ and $k_{z3}=\sqrt{k_3^2-k_x^2-k_y^2}$.

The electric and magnetic fields in different layers can be found from the relations

$$\overline{E}=-\nabla\times\overline{F} \tag{10}$$

$$\overline{H}=\frac{1}{j\omega\mu_0}\left[k_{1,2,3}^2\overline{F}+\nabla\left(\nabla\cdot\overline{F}\right)\right]. \tag{11}$$

The *x*-, *y*- and *z*-components of electric field in different layers (skin, fat and muscle layers) are derived and are given below:

$$E_{x1}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[-jk_{z1}I_{\psi 1}e^{-jk_{z1}z}+jk_{z1}R_{\psi 1}e^{+jk_{z1}z}]e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{12}$$

$$E_{y1}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[+jk_{z1}I_{\phi 1}e^{-jk_{z1}z}-jk_{z1}R_{\phi 1}e^{+jk_{z1}z}]e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{13}$$

$$\begin{aligned}E_{z1}(x,y,z)=&\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[I_{\phi 1}e^{-jk_{z1}z}+R_{\phi 1}e^{+jk_{z1}z}]\cdot e^{-jk_x x}(-jk_y)e^{-jk_y y}dk_x dk_y\\&-\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[I_{\psi 1}e^{-jk_{z1}z}+R_{\psi 1}e^{+jk_{z1}z}]\cdot(-jk_x)e^{-jk_x x}e^{-jk_y y}dk_x dk_y\end{aligned} \tag{14}$$

$$E_{x2}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[-jk_{z2}T_{\psi 1}e^{-jk_{z2}z}+jk_{z2}R_{\psi 2}e^{+jk_{z2}z}]e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{15}$$

$$E_{y2}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[+jk_{z2}T_{\phi 1}e^{-jk_{z2}z}-jk_{z2}R_{\phi 2}e^{+jk_{z2}z}]e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{16}$$

$$\begin{aligned}E_{z2}(x,y,z)=&\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[T_{\phi 1}e^{-jk_{z2}z}+R_{\phi 2}e^{+jk_{z2}z}]\cdot e^{-jk_x x}(-jk_y)e^{-jk_y y}dk_x dk_y\\&-\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[T_{\psi 1}e^{-jk_{z2}z}+R_{\psi 2}e^{+jk_{z2}z}]\cdot(-jk_x)e^{-jk_x x}e^{-jk_y y}dk_x dk_y\end{aligned} \tag{17}$$

$$E_{x3}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}-jk_{z3}T_{\psi 2}e^{-jk_{z3}z}\ e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{18}$$

$$E_{y3}(x,y,z)=\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}+jk_{z3}T_{\phi 2}e^{-jk_{z3}z}\cdot e^{-jk_x x}e^{-jk_y y}dk_x dk_y \tag{19}$$

$$\begin{aligned} E_{z3}(x,y,z) = {} & \frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} T_{\phi 2}e^{-jk_{z3}z}\; e^{-jk_x x}(-jk_y).e^{-jk_y y}dk_x dk_y \\ & -\frac{1}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} T_{\psi 2}e^{-jk_{z3}z}\;(-jk_x)\cdot e^{-jk_x x}e^{-jk_y y}dk_x dk_y \end{aligned} \tag{20}$$

Similarly, the *x*-, *y*- and *z*-components of magnetic field in different layers (skin, fat and muscle layers) are derived utilizing Eqns. (4)-(9) and (11). The expressions for magnetic field components are not given here for brevity.

Taking inverse Fourier transform of equations (12) and (13) at $z = 0$ gives

$$\begin{aligned} jk_{z1}[-I_{\psi 1}+R_{\psi 1}] = {} & \frac{2}{k_x}\sin\left(\frac{k_x a}{2}\right)\cdot[a_{10}(1+\Gamma_{10})e^{-j\beta_{10}L}e^{-j\alpha_{10}}\left\{f_1(k_y)e^{j\delta_1}+g_1(k_y)e^{j\delta_2}\right\} \\ & +a_{30}(1+\Gamma_{30})e^{-j\beta_{30}L}e^{-j\alpha_{30}}\left\{f_3(k_y)e^{j\delta_1}+g_3(k_y)e^{j\delta_2}\right\}] \end{aligned} \tag{21}$$

where

$$\begin{aligned} f_1(k_y) = {} & \frac{be^{jk_y b/2}}{\pi^2-b^2k_y^2}\left[\pi\sin\left\{\frac{\pi}{2b}(b+d)\right\}+jbk_y\cos\left\{\frac{\pi}{2b}(b+d)\right\}\right] \\ & -\frac{be^{-jk_y b/2}}{\pi^2-b^2k_y^2}\left[\pi\sin\left\{\frac{\pi}{2b}(-b+d)\right\}+jbk_y\cos\left\{\frac{\pi}{2b}(-b+d)\right\}\right] \end{aligned}$$

$$\begin{aligned} g_1(k_y) = {} & \frac{be^{jk_y b/2}}{\pi^2-b^2k_y^2}\left[\pi\sin\left\{\frac{\pi}{2b}(b-d)\right\}+jbk_y\cos\left\{\frac{\pi}{2b}(b-d)\right\}\right] \\ & -\frac{be^{-jk_y b/2}}{\pi^2-b^2k_y^2}\left[\pi\sin\left\{\frac{\pi}{2b}(-b-d)\right\}+jbk_y\cos\left\{\frac{\pi}{2b}(-b-d)\right\}\right] \end{aligned}$$

$$\begin{aligned} f_3(k_y) = {} & \frac{be^{jk_y b/2}}{9\pi^2-b^2k_y^2}\left[3\pi\sin\left\{\frac{3\pi}{2b}(b+d)\right\}+jbk_y\cos\left\{\frac{3\pi}{2b}(b+d)\right\}\right] \\ & -\frac{be^{-jk_y b/2}}{9\pi^2-b^2k_y^2}\left[3\pi\sin\left\{\frac{3\pi}{2b}(-b+d)\right\}+jbk_y\cos\left\{\frac{3\pi}{2b}(-b+d)\right\}\right] \end{aligned}$$

$$\begin{aligned} g_3(k_y) = {} & \frac{be^{jk_y b/2}}{9\pi^2-b^2k_y^2}\left[3\pi\sin\left\{\frac{3\pi}{2b}(b-d)\right\}+jbk_y\cos\left\{\frac{3\pi}{2b}(b-d)\right\}\right] \\ & -\frac{be^{-jk_y b/2}}{9\pi^2-b^2k_y^2}\left[3\pi\sin\left\{\frac{3\pi}{2b}(-b-d)\right\}+jbk_y\cos\left\{\frac{3\pi}{2b}(-b-d)\right\}\right] \end{aligned}$$

$$jk_{z1}[I_{\phi 1}-R_{\phi 1}] = 0 \tag{22}$$

Applying the boundary conditions, *i.e.*, the continuity of tangential electric and magnetic fields at $z = t_1$ (the skin-fat interface) and $z = t_2$ (the fat-muscle interface) gives the necessary remaining eight equations as follows:

$$-jk_{z1}I_{\psi 1}e^{-jk_{z1}t_1}+jk_{z1}R_{\psi 1}e^{+jk_{z1}t_1} = -jk_{z2}T_{\psi 1}e^{-jk_{z2}t_1}+jk_{z2}R_{\psi 2}e^{+jk_{z2}t_1} \tag{23}$$

$$+jk_{z1}I_{\phi 1}e^{-jk_{z1}t_1}-jk_{z1}R_{\phi 1}e^{+jk_{z1}t_1} = +jk_{z2}T_{\phi 1}e^{-jk_{z2}t_1}-jk_{z2}R_{\phi 2}e^{+jk_{z2}t_1} \tag{24}$$

$$-jk_{z2}T_{\psi 1}e^{-jk_{z2}t_2}+jk_{z2}R_{\psi 2}e^{+jk_{z2}t_2} = -jk_{z3}T_{\psi 2}e^{-jk_{z3}t_2} \tag{25}$$

$$+jk_{z2}T_{\phi 1}e^{-jk_{z2}t_2}-jk_{z2}R_{\phi 2}e^{+jk_{z2}t_2} = +jk_{z3}T_{\phi 2}e^{-jk_{z3}t_2} \tag{26}$$

$$\begin{aligned} & (k_1^2-k_x^2)[I_{\phi 1}e^{-jk_{z1}t_1}+R_{\phi 1}e^{+jk_{z1}t_1}]-k_xk_y[I_{\psi 1}e^{-jk_{z1}t_1}+R_{\psi 1}e^{+jk_{z1}t_1}] \\ & =(k_2^2-k_x^2)[T_{\phi 1}e^{-jk_{z2}t_1}+R_{\phi 2}e^{+jk_{z2}t_1}]-k_xk_y[T_{\psi 1}e^{-jk_{z2}t_1}+R_{\psi 2}e^{+jk_{z2}t_1}] \end{aligned} \tag{27}$$

$$\begin{aligned}&(k_1^2-k_y^2)[I_{\psi 1}e^{-jk_{z1}t_1}+R_{\psi 1}e^{+jk_{z1}t_1}]-k_xk_y[I_{\phi 1}e^{-jk_{z1}t_1}+R_{\phi 1}e^{+jk_{z1}t_1}]\\&=(k_2^2-k_y^2)[T_{\psi 1}e^{-jk_{z2}t_1}+R_{\psi 2}e^{+jk_{z2}t_1}]-k_xk_y[T_{\phi 1}e^{-jk_{z2}t_1}+R_{\phi 2}e^{+jk_{z2}t_1}]\end{aligned} \tag{28}$$

$$\begin{aligned}&(k_2^2-k_x^2)[T_{\phi 1}e^{-jk_{z2}t_2}+R_{\phi 2}e^{+jk_{z2}t_2}]-k_xk_y\cdot[T_{\psi 1}e^{-jk_{z2}t_2}+R_{\psi 2}e^{+jk_{z2}t_2}]\\&=(k_3^2-k_x^2)T_{\phi 2}e^{-jk_{z3}t_2}-k_xk_yT_{\psi 2}e^{-jk_{z3}t_2}\end{aligned} \tag{29}$$

$$\begin{aligned}&(k_2^2-k_y^2)[T_{\psi 1}e^{-jk_{z2}t_2}+R_{\psi 2}e^{+jk_{z2}t_2}]-k_xk_y\cdot[T_{\phi 1}e^{-jk_{z2}t_2}+R_{\phi 2}e^{+jk_{z2}t_2}]\\&=(k_3^2-k_y^2)T_{\psi 2}e^{-jk_{z3}t_2}-k_xk_yT_{\phi 2}e^{-jk_{z3}t_2}\end{aligned} \tag{30}$$

Equations (21) through (30) can be solved for plane-wave spectra in different layers. The field distribution in different layers of bio-media can then be obtained for given parameters of the array of two modified box-horns and the given physical properties of the layers. Electric field in ith layer is given by

$$|E_i|^2=|E_{xi}|^2+|E_{yi}|^2+|E_{zi}|^2 \tag{31}$$

The specific absorption rate (SAR) in ith layer (i=1, 2, 3) can be evaluated by

$$SAR=\frac{\sigma_i|E_i|^2}{2\rho_i} \tag{32}$$

where E_i, $\sigma_i(=\omega\varepsilon_0\varepsilon_i'')$, ρ_i and ε_i'' are the electric field intensity, conductivity, density and imaginary part of relative permittivity of ith layer respectively.

3. DESIGN OF ARRAY OF TWO MODIFIED BOX-HORNS

For Modified box-horn, the pyramidal horn (E- and H-plane flared-horn) exciting the box waveguide is designed as per Terman [12] and box waveguide is designed as discussed in reference [8]. To investigate the effect of flare angle in E-plane on SAR values, two arrays consisting of modified box-horns of different dimensions are considered at 2450 MHz. In first array, the dimensions of each water-loaded modified box-horn are a=1.06 cm, b=2.23 cm, L =1.16 cm with the flare angles of the pyramidal horn exciting the box, $\phi_H = 30^0$ in H-plane and $\phi_E = 20^0$ in E-plane. While in the second array for each water-loaded modified box-horn a=1.61 cm, b=2.23 cm, L =1.16 cm with flare angle of the pyramidal horn exciting the box=30^0 in both H-and E-planes.

The water-loaded conventional box-horn applicator is designed at 2450 MHz as discussed in reference [8]. The computed dimensions of the box-horn are a=0.43 cm, b=2.23 cm and L =1.16 cm. The flare angle of the horn exciting the box is 30^0 in H-plane.

In the proposed array, center of each box-horn is at a distance 'd/2' along y-direction from reference point 'O'. The separation between two box-horns can be taken as $d = n\lambda_e/2$, where λ_e is wavelength in bio-media, n = 1, 2, 3, 4… Due to aperture dimension constraints, n is chosen to be 4.

4. VALIDATION OF THE ANALYSIS

Electric field distribution at the aperture of the waveguide applicator carrying TE$_{10}$ mode in direct contact with three-layered tissue model obtained with the help of present theory has been compared with that computed by Nikita and Uzunoglu [5] at 432 MHz. These results are in agreement with each other within maximum 2 percent deviation as shown in fig. 2.

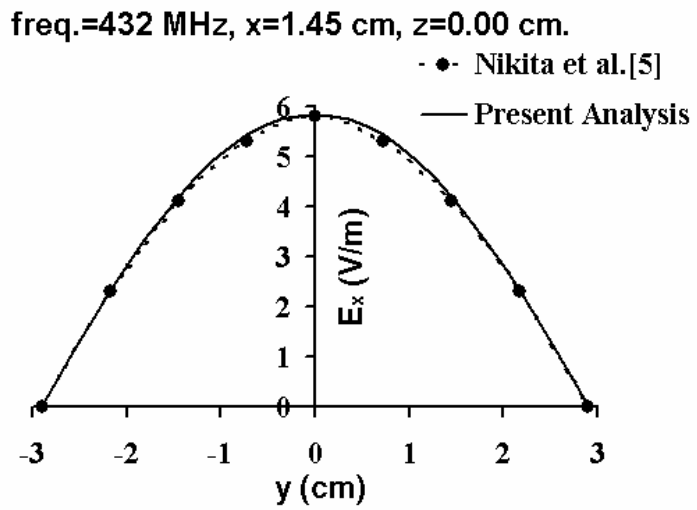

Fig. 2. Aperture electric field versus *y* obtained by present analysis and reference [5].

5. NUMERICAL RESULTS AND DISCUSSION

The SAR distributions in skin, fat and muscle layers for an array of de-ionized water-loaded modified box-horn are numerically solved at 2450 MHz using MATLAB.The thicknesses [13] of the skin and fat layers are taken to be t_1 = 0.1 cm, $t_2 - t_1$ = 0.5 cm, and the complex relative permittivities [14] of bio-layers at 2450 MHz are ε_1^* = 40-j12 (skin), ε_2^* =3.9-j0.67 (fat) and ε_3^* = 47.5-j13.5 (muscle), permittivity of de-ionized water [15] filling the modified box-horn is taken as 77.0-j0.0.

Fig. 3 shows a three-dimensional plot of SAR distribution along *x*- and *y*-directions in skin, fat and muscle layers from an array applicator consisting of two de-ionized water-loaded modified box-horns at 2450 MHz. Both modified box-horns have same phase excitation ($\delta_1 = \delta_2 = 0^0$). The SAR values are normalized with maximum SAR value that occurs in muscle layer. The normalized SAR is for the same output power from the array applicator. The value of normalized SAR is the minimum (=0.0437 at $x = y = 0$ cm, z=0.35 cm) in fat layer due to its poor conductivity (0.0913 mhos/m) and is the highest (=1.0 at $x = y = 0$ cm, z=0.61 cm) in muscle region because muscle is highly conducting (=1.84 mhos/m).

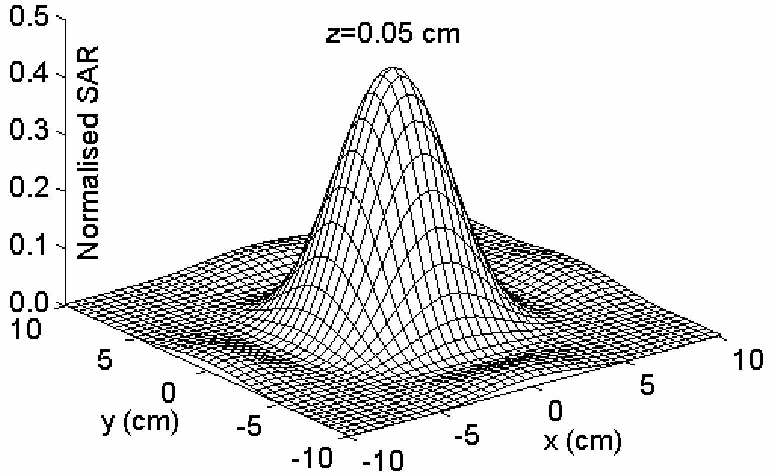

Fig. 3 a. SAR distribution along x- and y-directions in skin layer for array of two modified box-horns ($\phi_E = \phi_H = 30^0$ for each modified box-horn).

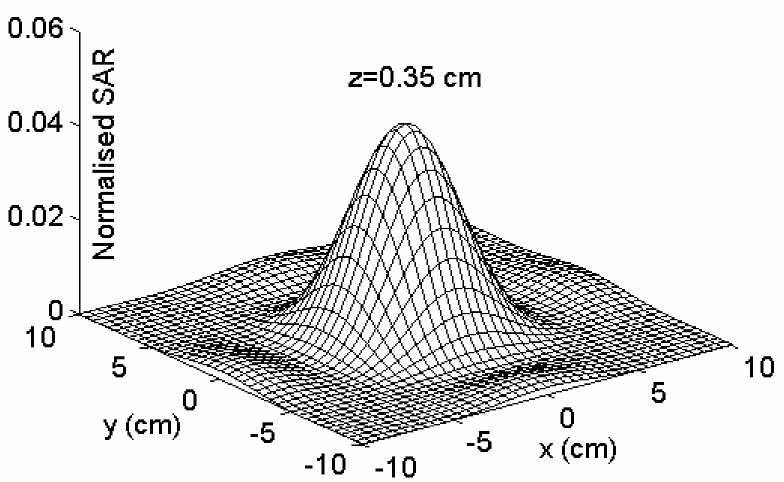

Fig. 3 b. SAR distribution along x- and y-directions in fat layer for array of two modified box-horns ($\phi_E = \phi_H = 30^0$ for each modified box-horn).

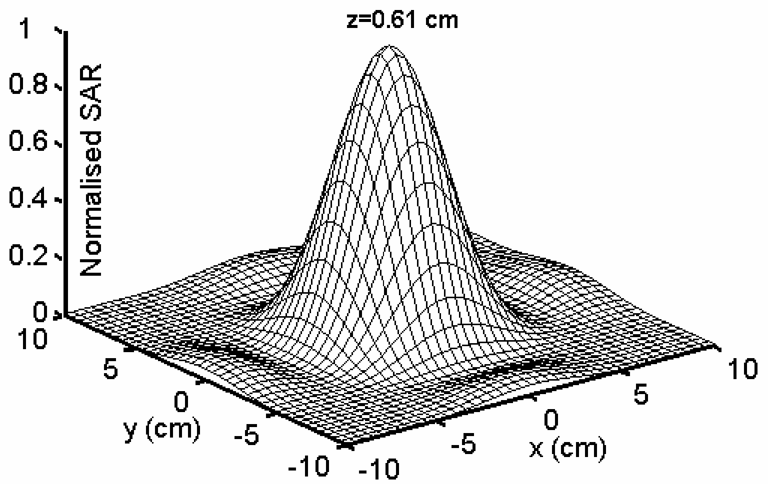

Fig. 3 c. SAR distribution along x- and y-directions in muscle layer for array of two modified box-horns ($\phi_E = \phi_H = 30^0$ for each modified box-horn).

SAR distributions along *x*- / *y*- and *z*-directions for an array of two modified box-horns for different flare angles in E-plane (ϕ_E=20^0, 30^0) and fixed flare angle in H-plane (ϕ_H=30^0) are depicted in Fig. 4 along with those for an array of two conventional box-horns (ϕ_E=0^0, ϕ_H=30^0). Both modified box-horns operate on equal phase excitation ($\delta_1 = \delta_2 = 0^0$). The SAR values are normalized with maximum value of SAR that occurs for the array of two modified box-horns (ϕ_E=30^0, ϕ_H=30^0). The normalized SAR is for the same output power from the array applicators. It can be seen from fig. 4, that array of two modified box-horns gives much higher values of SAR (1 and 0.6644 at *x* = *y* = 0 cm, *z*=0.61 cm with ϕ_E=30^0 and 20^0 respectively) in *x*- / *y*- and *z*-directions in comparison with those for the array of two conventional box-horns (=0.3554 at *x* = *y* = 0 cm, *z*=0.61 cm). Thus, higher values of SAR can be obtained by increasing flaring angle of the horn which is coupled to the box waveguide in E-plane also.

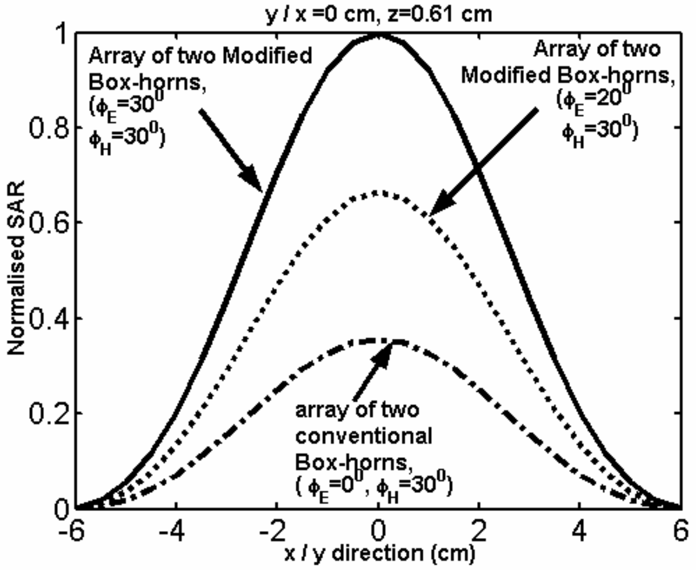

Fig. 4 a. SAR distribution along x / y-direction at 2450 MHz for array of two modified box-horns and array of two conventional box-horns.

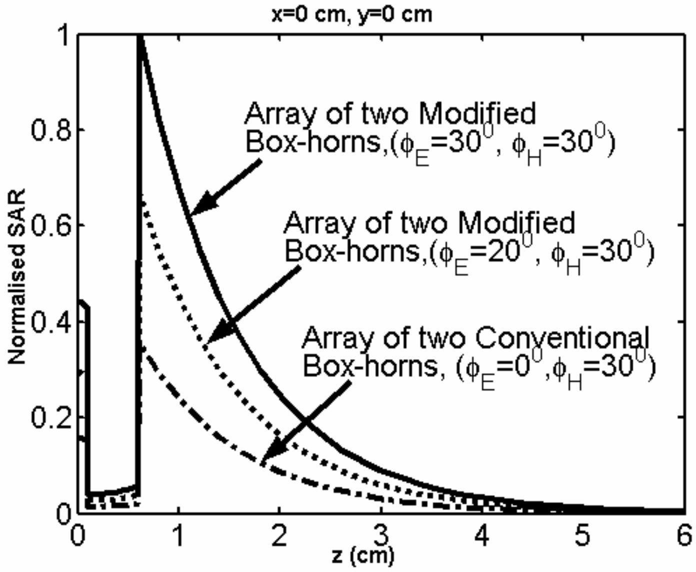

Fig. 4 b. SAR distribution along z-direction at 2450 MHz for array of two modified box-horns and array of two conventional box-horns.

SAR distributions for array of two de-ionized water-loaded modified box-horns and single de-ionized water-loaded box-horn are compared in *x*- / *y*-direction in muscle layer. The phase excitations of the elements of the array are $\delta_1 = \delta_2 = 0^0$.The SAR values are normalized with the maximum value of SAR that occurs for the array. The normalized SAR is for the same output power from array of two modified box-horns and single modified box-horn. The SAR distribution for array of two modified box-horns is similar to that for single modified box-horn, but the value of normalized SAR for any *x*- / *y*-coordinate is higher (1 at $x = y = 0$ cm) for array of two modified box-horns as compared to that for a single box-horn (0.9332 at $x = y = 0$ cm). Fig. 5(b) illustrates the results for a wave transmitted through subcutaneous skin and fat media into muscle medium in *z*-direction at 2450 MHz for the array of two modified box-horns and single modified box-horn. The SAR is normalized to unity in the muscle at the fat-muscle interface.

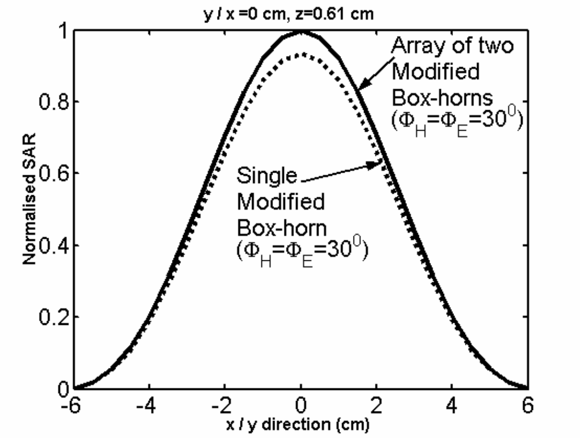

Fig. 5 a. SAR distribution along x / y-direction for array of two modified box-horns and single modified box-horn.

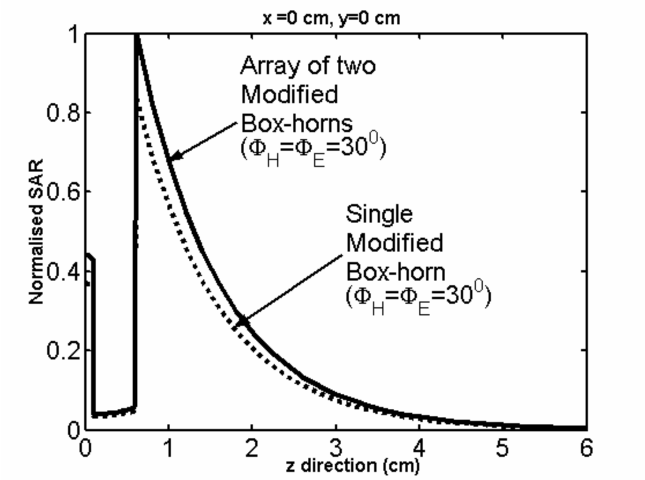

Fig. 5 b. SAR distribution along z-direction for array of two modified box-horns and single modified box-horn.

The results for SAR distribution of phase-steered array of two modified box-horns is presented in fig. 6 along with the SAR distribution of unfocused array of two modified box-horns. The phase excitations of two modified box-horns are $\delta_1 = -5\pi/12$ and $\delta_2 = 5\pi/12$ respectively for focused array. The maximum SAR value occurs at y = 1.5 cm for focused array instead of y = 0 cm for unfocused array.

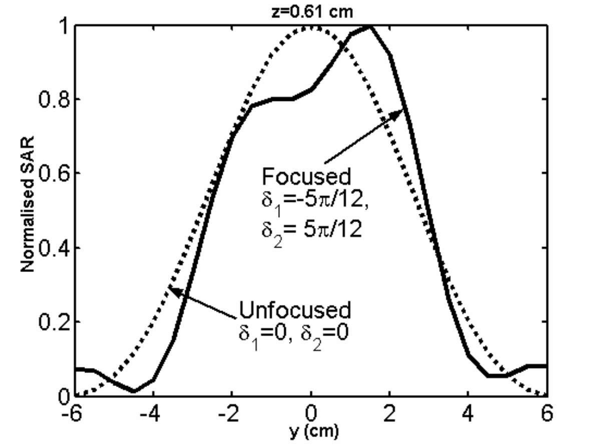

Fig. 6. SAR distribution along y-direction in muscle layer for phased array of two modified box-horns ($\phi_E = \phi_H = 30^0$ for each modified box-horn).

6. CONCLUSION

An analytical solution has been presented for SAR distributions in skin, fat and muscle layers illuminated by an array of two de-ionized water-loaded modified box-horns at 2450 MHz. The array of two modified box-horns gives higher SAR values in skin, fat and muscle layers as compared with single modified box-horn for same output power. Therefore, an array of two water-loaded modified box-horns is better for hyperthermia treatment of cancerous tumor at somewhat greater depth inside the body. The array of two modified box-horns has larger aperture (aperture of each modified box-horn=1.61cm×2.23cm with $\phi_E=30^0$, $\phi_H=30^0$) and gives higher values of SAR (=1.0 at $x = y = 0$ cm, z=0.61 cm) in comparison to the array of two conventional box-horns (aperture=0.43cm×2.23cm and normalized SAR=0.3554 at $x = y = 0$ cm, z=0.61 cm) for same output power. By appropriate phase excitation of each modified box-horn of the array, the SAR pattern can be steered in desired direction. The analysis and results presented here may be useful in designing multi-mode applicators and in analyzing the performance of multi-applicator phased array for hyperthermia treatment of cancer.

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