Numerical Analysis of Printed Strip Dipole Hyperthermia Applicators

Steven L. Dvorak and David J. Aziz

Abstract— **The performance of a planar printed strip dipole hyperthermia applicator is simulated using a computer. The applicator is modeled using an exact integral equation formulation, and Galerkin's method is used to obtain the approximate current distribution on the dipole antenna. These currents are then used to compute the input impedance and heating pattern for the applicator. The computer model is used to investigate, and eliminate, the problem of "hot-spots" in the fat layer.**

I. Introduction

A NUMBER of recent studies have shown hyperthermia to be a promising method for the treatment of certain types of cancerous tumors [1]. Additionally, hyperthermia enhances the efficacy of several treatment modalities including x-rays and chemotherapy.

Hyperthermia entails raising the temperature of the tumor above a threshold temperature for an extended period of time [1]. In noninvasive hyperthermia, where the radiating source is located outside the tissue, one attempts to focus the energy in the tumor, thereby avoiding damage to the surrounding healthy tissue. This is referred to as localized heating [2]–[4].

Methods for localized hyperthermia currently use either ultrasonic or electromagnetic waves [3]. Electromagnetic waves, which are the topic of this paper, produce hyperthermia through Joule heating, $\sigma|\boldsymbol{E}|^2$. The distribution of power in the tissue, which is equivalent to the applicator's heating pattern if the heat transfer properties of the tissue are ignored, depends on the electrical properties of the tissue, i.e., the complex-valued permittivity $\hat{\epsilon} = \epsilon - j\sigma/\omega$. The energy must be delivered to the tumor, which is sometimes located deep within the muscle tissue, without excessive heating at the surface of the skin or in the fat. Tissue damage in the fat occurs when applicators produce a large electrical field component normal to the fat/muscle interface [3].

In this paper, we describe the method and results of a theoretical study of a printed strip dipole antenna radiating into a layered tissue model. Although the human body is not a simple layered structure, studying layered models provides valuable insight into the design of applicators. The applicator under study consists of a single center-driven dipole located on a dielectric substrate backed with a perfectly conducting ground plane (see Fig. 1). The tissue is modeled as a layer of fat above a semi-infinite layer of muscle. Additionally, a layer of water (a bolus) is included between the antenna and the surface of the fat (the skin layer being neglected). The currents on the antenna are computed using Galerkin's method, and these currents are used to compute the electric field pattern within the tissue. The applicator and tissue parameters are then varied to determine the applicability of this antenna design to hyperthermia treatment. Finally, the insight gained by the numerical studies is used to develop a set of guidelines for the design of printed dipole applicators. It is demonstrated that there are optimal thicknesses for the substrate and bolus. Furthermore, the optimal substrate thickness is not a quarter wavelength as previously believed.

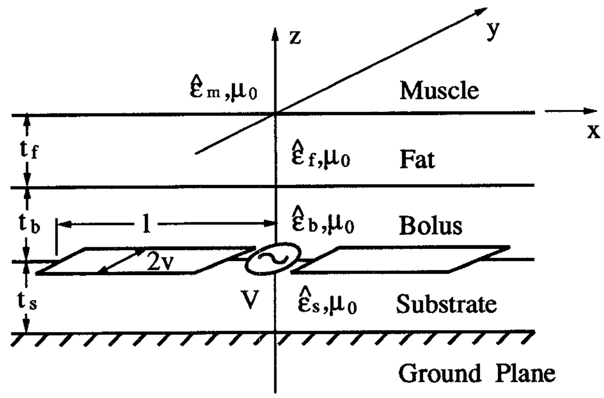

Fig. 1. Layered tissue model for a printed strip dipole applicator.

II. Overview of Relevant Work

Simplified tissue models, which can be analyzed using efficient quasi-analytical techniques, include separable geometries, e.g., planar, cylindrical, and spherical. For example, a number of authors have investigated rectangular waveguides radiating into planar layered tissue models [5]–[8]. In these papers, it is assumed that only the dominant mode of the rectangular waveguide is present in the aperture. A theoretical study that included higher-order modes was carried out in [9].

Microstrip antenna applicators have also been shown to be useful as hyperthermia applicators [10]–[16]. Since microstrip antennas are relatively inexpensive, easy to fabricate, compact, and can be made flexible enough to conform to nonplanar surfaces, they are ideally suited for use in hyperthermia arrays. Furthermore, the ground plane, which backs the microstrip antennas, provides shielding for the medical personnel. Examples of microstrip array applicators are shown in [10], [12], [16]. In [12], it was demonstrated that an applicator consisting of

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four spiral microstrip antennas can provide controlled heating to a depth of 2 cm. In [16], a computer model was used to investigate an array of printed strip dipoles.

The papers [10]–[14] demonstrate that microstrip antennas are well suited for microwave hyperthermia applications. However, elements in the design of these applicators, such as the thickness and the electrical properties of the substrate and the bolus can be optimized to provide superior applicators. A detailed theoretical study of a printed strip dipole applicator radiating into a planar tissue model is carried out in this paper.

III. Applicator Model

The layered applicator model employed in this paper is shown in Fig. 1. The assumption that the tissue can be modeled as a layered medium allows the spectral domain technique to be employed to formulate an electric field integral equation for the unknown current distribution on the antenna [20]. The method of moments is then used to numerically solve the integral equation, thereby providing an approximate current distribution on the dipole antenna. This current distribution is used to find the input impedance and the near-zone electric field pattern for the applicator. A knowledge of the near-zone electric field distribution is used to assess the applicator's performance. Likewise, the input impedance is used to determine the resonant frequency of the applicator and investigate the sensitivity of the applicator to changes in the dimensions and electrical properties of the tissue.

Since a study of the near-zone electric fields is required for the characterization of hyperthermia applicators, the currents on the antenna (or the equivalent currents in the case of apertures) must be accurately determined. Techniques starting with an assumed current distribution can lead to solutions that do not show the true near-zone field behavior. Once an accurate and efficient computer model has been developed for computing the currents, the effects of the various parameters on the performance of the applicator can be studied in great detail.

A rigorous analysis of the printed dipole applicator requires a large amount of computation time. To reduce the amount of computation time, we employ in this paper the efficient numerical techniques developed in [20]–[22]. These techniques are general and can be applied to other microstrip applicators as well as aperture radiators.

We assume that a dipole antenna (Fig. 1), is driven at a frequency of $f = 915$ MHz by an idealized delta-function gap voltage source. The antenna sits on a substrate of variable thickness and permittivity (t_s and $\hat{\epsilon}_s$) and is covered by a variable thickness water bolus (t_b and $\hat{\epsilon}_b = 80.0\epsilon_0$). The water bolus provides cooling at the fat surface, but the effects of heat transfer are not accounted for in this paper. The applicator radiates into a two-layer tissue model (the thin skin layer is neglected) composed of a variable thickness fat layer (t_f and $\hat{\epsilon}_f = (6.0 - j2.0)\epsilon_0$) and a half-space filled with lossy muscle tissue ($\hat{\epsilon}_m = (58.0 - j12.0)\epsilon_0$). The width of the antenna is chosen as $2v = 0.4$ cm and the length of the antenna is chosen for operation at the first resonance (the shortest length providing a zero input reactance). Our studies have shown that operating at higher resonances do not improve the applicator's heating characteristics. We utilize Galerkin's method with roof-top basis functions to obtain an approximate current distribution on the antenna [22]. Since the antenna width is much smaller than a wavelength, we neglect the transverse component of the current (i.e., $J_y = 0$). We also only subdivide the antenna along the length to reduce the amount of computation time.

An initial study, which excluded the fat layer (i.e., $t_f =$ 0.0 cm), was carried out in [20] to compare the printed strip dipole applicator to the rectangular microstrip applicator in [15]. In that study, a printed strip dipole antenna of length $2l = 2.34$ cm was placed on a rexolite substrate ($t_s = 0.5$ cm and $\hat{\epsilon}_s = 2.53\epsilon_0$), and a $t_b = 0.5$ cm water bolus was employed. The material parameters were chosen to be the same as those used in [15]. The current distribution on the antenna was obtained using Galerkin's method with five piecewise-sinusoidal basis functions employed along the length of the antenna. Once the current distribution was obtained, the near-zone fields were computed and the specific absorption ratio (SAR), which was assumed to be proportional to $\sigma_m|\boldsymbol{E}|^2$, was plotted at various depths, z, in the muscle tissue. It should be noted that $z = 0.0$ cm is at the location of the antenna in [20], whereas $z = 0.0$ cm is at the fat-muscle interface in this paper. It was determined that the printed strip dipole applicator under investigation in [20] exhibited a relatively small penetration depth, and its performance was further degraded by "hot-spots," which were attributed to the fringing fields at the ends of the dipole antenna. The fringing fields are only present in the near zone of the antenna as can be seen by looking at [20, Fig. 5]. The goal of this paper is to determine whether the performance of the printed strip dipole applicator can be improved through changes in its design.

Reference [20, Fig. 5] shows that the heating pattern is fairly well behaved in the y-direction, so future plots will only show the dependence on x and z. If a 1.0-cm-thick fat layer is added to the model in [20], one finds that the fat is excessively heated near the ends of the antenna and very little energy reaches the muscle tissue (Fig. 2). Since the heating pattern is symmetric about $x = 0.0$ cm, a plot of the heating pattern as a function of positive x for muscle and negative x for fat is given for various locations in the fat and muscle layers on the same plot to facilitate comparison (see Fig. 2). The different curves correspond to different depths in the tissues. This plotting format was first employed in [5]. The addition of the fat layer also changes the resonance length to $2l =$ 2.56 cm. The dramatic difference in the heating patterns in [20, Table II and Fig. 5] and Fig. 2 clearly demonstrates the need to include the fat layer when significant normal components of the electric field are present.

IV. Improvements in the Applicator Design

The substrate and bolus thicknesses are two parameters that can be utilized to improve the applicator's heating pattern. We will work with the same applicator as was previously described, except we will now assume that the dipole antenna is fabricated on a grounded alumina substrate ($\hat{\epsilon}_s = 9.5\epsilon_0$). The parameters t_s and t_f are varied to study their influence on

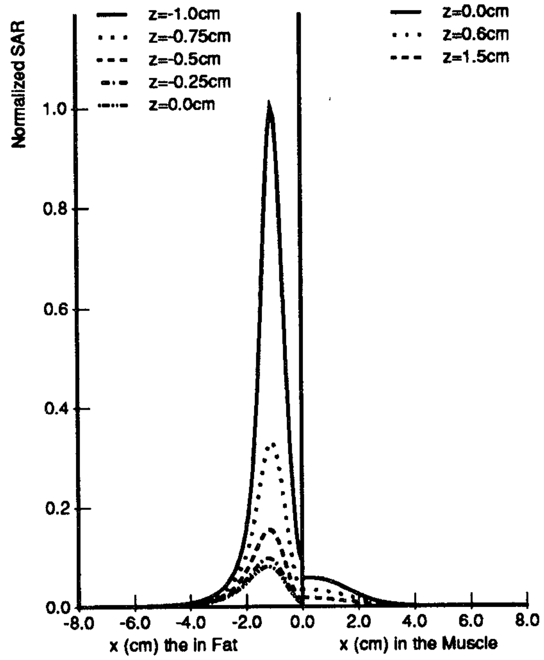

Fig. 2. Relative heating patterns for the printed strip dipole applicator at various depths in the muscle and fat tissues for $\hat{\epsilon}_s = 2.53\epsilon_0, t_s = 0.5$ cm, $\hat{\epsilon}_b = 80.0\epsilon_0, t_b = 0.5$ cm, $\hat{\epsilon}_f = (6.0-j2.0)\epsilon_0$, $t_f = 1.0$ cm, $\hat{\epsilon}_m = (58.0 - j12.0)\epsilon_0, f = 915$ MHz, $2l = 2.56$ cm, and $2v = 0.4$ cm.

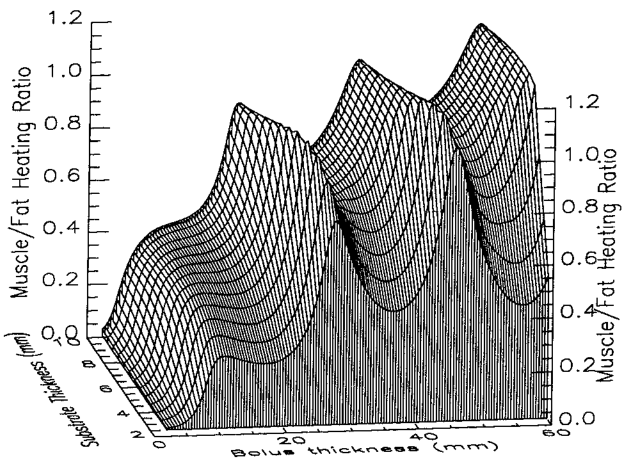

Fig. 3. The ratio of the maximum SAR in the muscle to the maximum SAR in the fat (muscle/fat heating ratio) plotted as a function of substrate (alumina) and bolus (water) thicknesses. Parameters are $\hat{\epsilon}_s = 9.5\epsilon_0, \hat{\epsilon}_b = 80.0\epsilon_0, \hat{\epsilon}_f = (6.0 - j2.0)\epsilon_0, t_f = 1.0$ cm, $\hat{\epsilon}_m = (58.0 - j12.0)\epsilon_0, f = 915$ MHz, $2l = 2.21$ cm, and $2v = 0.4$ cm.

the heating pattern (Fig. 3). As was previously demonstrated, changes in the substrate or bolus thicknesses also change the resonant length of the antenna. For example, a resonant length of $2l = 2.17$ cm was obtained for the case $t_s = 0.5$ cm and $t_b = 2.5$ cm using Fig. 4.

The antenna length is held constant in Fig. 3 to assess the effect of changes in the bolus and substrate thicknesses on the applicator. An antenna length of $2l = 2.21$ cm was picked because it is the mean of the lengths for the first resonances over the range of bolus and substrate thicknesses in Fig. 3. Since we were primarily interested in removing the "hot-spots" in the fat, we plotted the muscle/fat heating ratio, which is the ratio of the maximum SAR in the muscle to the maximum SAR in the fat. The following procedure was applied for each value of t_s and t_b to obtain the muscle/fat heating ratio:

1) Compute the current distribution on the dipole using Galerkin's method. Five rooftop basis functions were used to approximate the current.
2) Use the approximate current distribution to compute the SAR ($\propto \sigma_m|\boldsymbol{E}|^2$) in the muscle at a number of points along the x-axis next to the muscle-fat interface (note: the maximum SAR in the muscle occurs at $y = 0.0$ cm and $z = 0.0$ cm).
3) Use the approximate current distribution to compute the SAR ($\propto \sigma_f|\boldsymbol{E}|^2$) in the fat at a number of points along the x-axis next to the fat-bolus interface (note: the maximum SAR in the fat occurs at $y = 0.0$ cm and $z = -1.0$ cm for the case of a 1.0-cm-thick fat layer).
4) Choose the maximum SAR for the muscle and fat regions and use these values to compute the muscle/fat heating ratio.

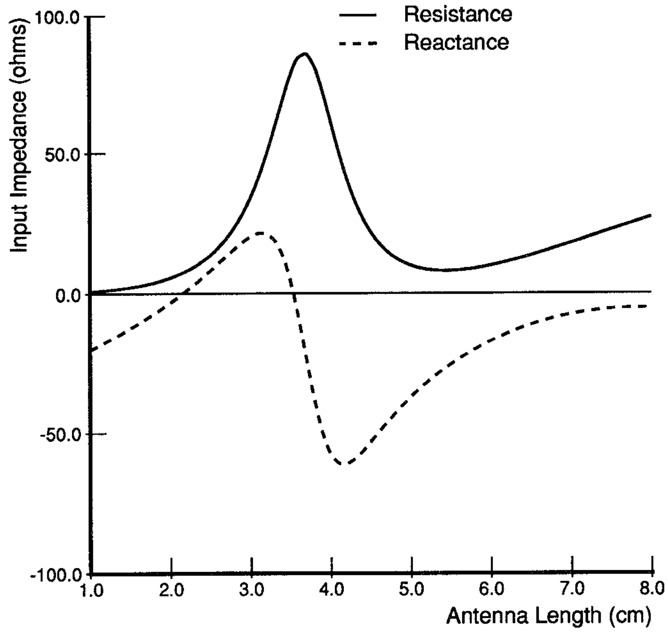

Fig. 4. Input impedance as a function of antenna length for $\hat{\epsilon}_s = 9.5\epsilon_0, t_s = 0.5$ cm, $\hat{\epsilon}_b = 80.0\epsilon_0, t_b = 2.5$ cm, $\hat{\epsilon}_f = (6.0 - j2.0)\epsilon_0$, $t_f = 1.0$ cm, $\hat{\epsilon}_m = (58.0 - j12.0)\epsilon_0, f = 915$ MHz, and $2v = 0.4$ cm.

Fig. 3 shows that the local maxima of the muscle/fat heating ratio are separated by $\Delta t_b = \lambda_b/2 = 18.3$ mm. This resonance behavior should be accounted for when designing an applicator with a thick bolus. Fig. 3 also shows that "hot spots" occur in the fat regardless of the substrate thickness when the bolus is too thin and that the performance of the applicator drops off for $t_s < 0.5$ cm.

To get a better feeling for the performance of the dipole applicator, we fix $t_s = 0.5$ cm and plot the computed relative SAR distributions for various values of t_b in Fig. 5. Fig. 5(a) shows the "hot-spots" present in the fat when the bolus is too thin. As previously discussed, these "hot-spots" are caused by the large normal component of the electric field which is

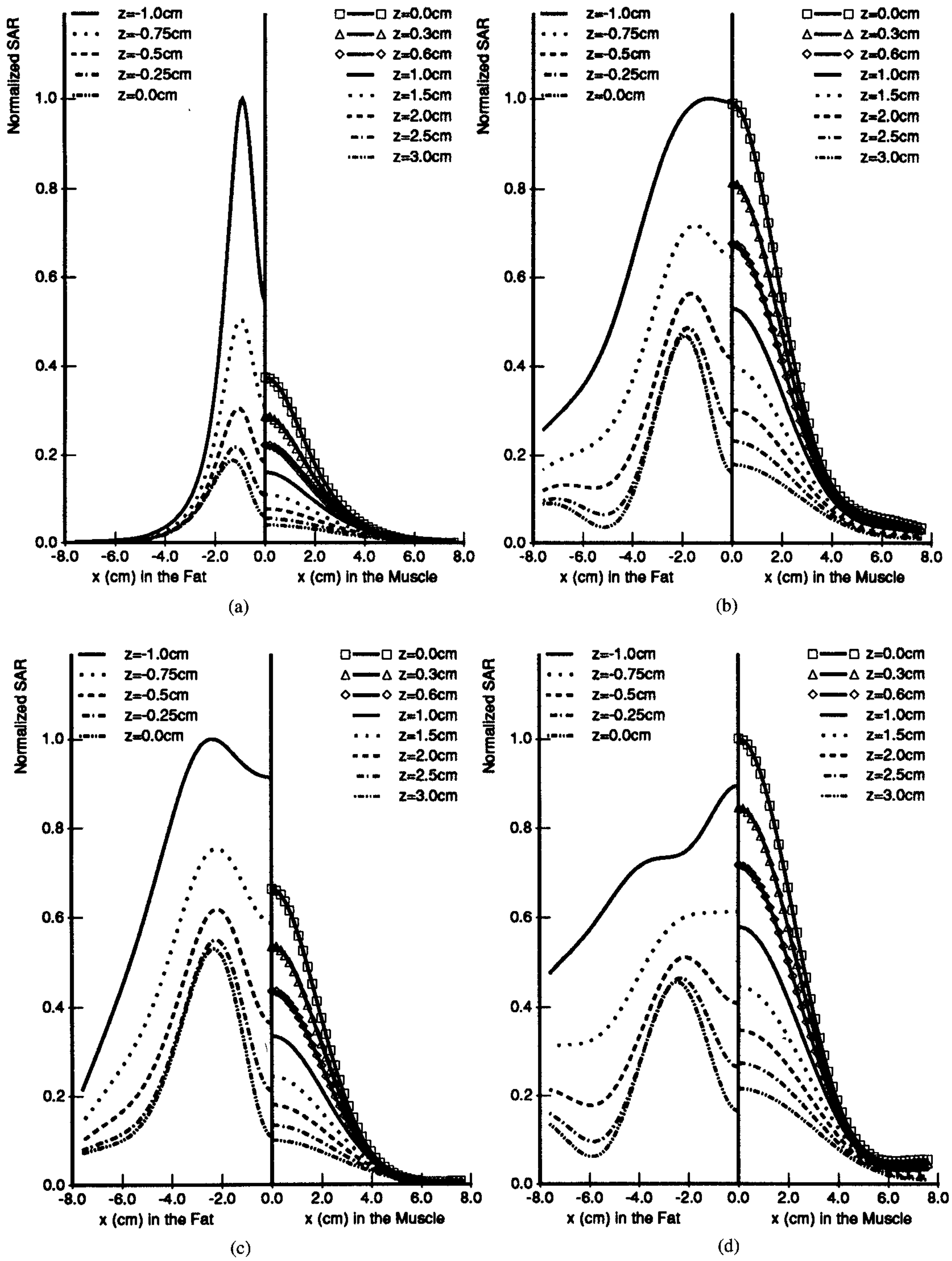

Fig. 5. Relative heating patterns for the printed strip dipole applicator at various depths in the muscle and fat tissues for four different bolus thicknesses: (a) $t_b = 1.0$ cm; (b) $t_b = 2.5$ cm; (c) $t_b = 3.5$ cm; (d) $t_b = 4.3$ cm. Parameters common to all four figures are $\hat{\epsilon}_s = 9.5\epsilon_0, t_s = 0.5$ cm, $\hat{\epsilon}_b = 80.0\epsilon_0, \hat{\epsilon}_f = (6.0 - j2.0)\epsilon_0, t_f = 1.0$ cm, $\hat{\epsilon}_m = (58.0 - j12.0)\epsilon_0, f = 915$ MHz, $2l = 2.17$ cm, and $2v = 0.4$ cm.

associated with the fringing fields at the ends of the dipole antenna. This is especially true for thicker fat layers as will be shown later.

The problem of overheating the fat can be eliminated by increasing the thickness of the bolus so that the applicator is operating at either the second or third peak in Fig. 3 (see Fig. 5(b) and (d)). Fig. 5(c) serves as a worst case scenario assuming that the applicator is designed with a bolus thickness in the range $2.5 \text{ cm} < t_b < 4.3$ cm. Additionally, excessive heat at the fat-bolus interface may be dissipated in the bolus (e.g., by circulating chilled water).

The effect of fat thickness on the heating pattern is demonstrated in Figs. 6(a), (b), and 5(d) where $t_f = 0.5$, 1.0, and 1.5 cm, respectively. These figures demonstrate that increasing the thickness of the fat layer increases the chance of burning the fat. As expected, our studies have also shown that increasing the conductivity of the fat also increases the chance of burning the fat.

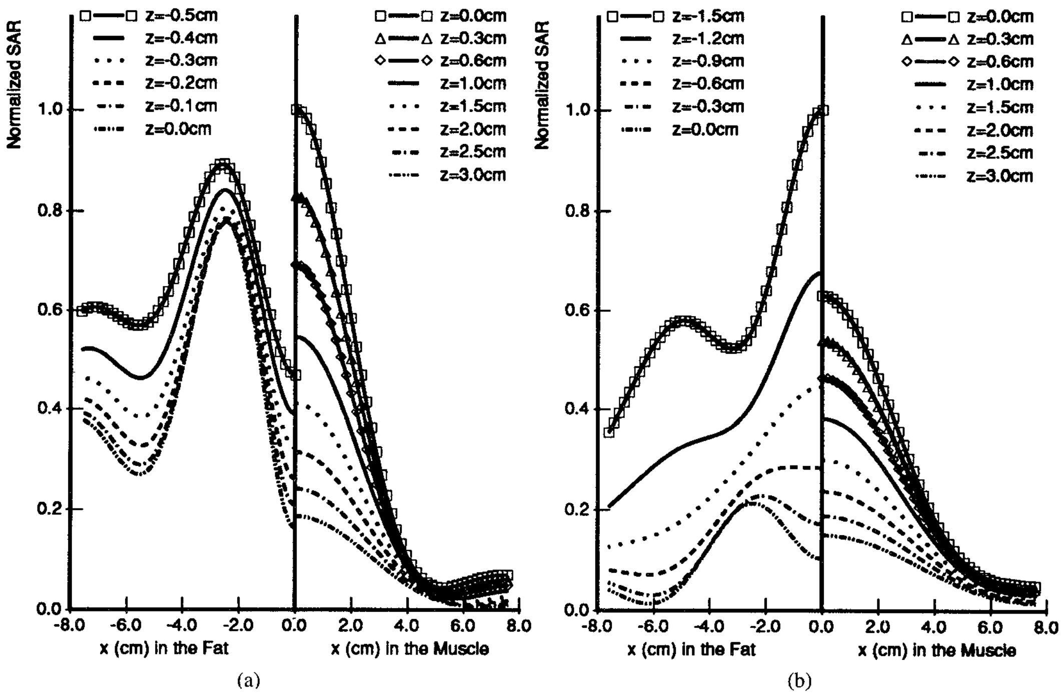

Fig. 6. Relative heating patterns for the printed strip dipole applicator at various depths in the muscle and fat tissues for different fat thicknesses: (a) $t_f = 0.5$ cm. (b) $t_f = 1.5$ cm. Parameters common to both figures are $\hat{\epsilon}_s = 9.5\epsilon_0, t_s = 0.5$ cm, $\hat{\epsilon}_b = 80.0\epsilon_0, t_b = 4.3$ cm, $\hat{\epsilon}_f = (6.0 - j2.0)\epsilon_0$, $\hat{\epsilon}_m = (58.0 - j12.0)\epsilon_0, f = 915$ MHz, $2l = 2.17$ cm, and $2v = 0.4$ cm.

When we first started working on this problem, we were under the impression that the optimal substrate thickness would be $t_s = \lambda_s/4$ [23]. The argument was that if the substrate is a quarter wavelength thick, then the unwanted normal component of the direct electric field will interfere destructively with the field which is reflected off of the ground plane. On the other hand, the tangential components (the desired components) of the direct and reflected electric fields add constructively. Quarter wavelength slabs were also used in [16], [17]. We have found, however, that better heating patterns can be obtained using $t_s = 0.5$ cm $= 0.047\lambda_s$. The use of a thin substrate has the following advantages over the quarter wavelength substrate:

1) The applicator is more compact.
2) Quarter wavelength substrates have to be specially manufactured whereas thin substrates are off-the-shelf items.
3) Less power is lost in surface waves with the thin substrate.
4) A quarter wavelength substrate is rigid and will not conform to the body as well as a thinner substrate.

V. Conclusion

The performance of the planar printed strip dipole hyperthermia applicator in Fig. 1 has been simulated using a computer. The applicator was modeled using an exact integral equation formulation and Galerkin's method was used to obtain the approximate current distribution on the antenna. The approximate currents were then used to compute the heating pattern for the applicator. The following observations were made:

- The fat layer must be included to correctly assess the performance of the applicator.
- The fringing fields near the ends of the dipole antenna can cause "hot-spots" in the fat layer.
- The "hot-spots" can be controlled through proper design of the substrate and bolus.
- Thin substrates can be used provided the applicator is properly designed.
- The muscle/fat heating ratio possesses a resonance behavior which is related to the bolus thickness.

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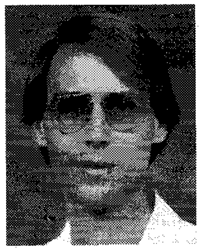

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