OPTIMAL EXCITATION OF MULTIAPPLICATOR SYSTEMS FOR DEEP REGIONAL HYPERTHERMIA

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ABSTRACT

A method is proposed for determining the excitation amplitudes and phases of the elements of electromagnetic multiapplicator systems for forming a hot zone around a deep-seated tumor. The general principle is applied to a two-dimensional problem of a piecewise homogeneous cylinder heated by an array of electric current filaments placed outside the cylinder. Numerical simulations are performed to check the effectiveness of the approach. The results demonstrate that using this optimization method, an improved specific absorption rate (SAR) distributions can be achieved.

I. INTRODUCTION

Hyperthermia cancer therapy is a treating procedure in which the temperature of cancerous tumors embedded in healthy human tissue is elevated above 42°C. Among the sources of heat, multiapplicator arrays operating at microwave and radio frequencies are rapidly gaining utility in the clinic. A large body of previous work with multiapplicator arrays for hyperthermia purposes can be found in [1]. For a proper hyperthermia treatment, it is necessary to deliver maximum power to the region of the tumor to be treated while minimally heating surrounding healthy tissues. This can be effected by focusing electromagnetic field at the tumor. The concentrated field, helped by the fact that the tumor tends to accumulate more heat than the normal tissue because of sluggish blood flow, will form a hot zone in the tumor region. The inherent problem, of course, is that the electromagnetic field cannot penetrate deep if the frequency is high, while if the frequency is low, the focusing ability deteriorates.

We present an efficient method for determining the optimal excitation coefficients (amplitudes and phases) of the elements of a multiapplicator array aimed at forming a hot zone in a deep-seated tumor. The proposed approach follows Harrington's optimization procedure [2]. We characterize the multiapplicator system by a dimensionless performance index, which is a ratio of two quadratic forms, defined as the ratio of the power dissipated in the tumor region to a sum of this power and a weighted summation of the powers supplied to suitably selected surrounding regions. The maximization of this performance index leads to an eigenvalue matrix equation. The largest eigenvalue of this equation is the maximum value of the performance index and the eigenvector which corresponds to this eigenvalue itemizes the desired array excitation coefficients. In the course of the optimization process, the analysis of the electromagnetic field distribution in the body region produced by each array element needs the most lengthy numerical process. Once the fields due to each array element are known, the matrix eigenvalue equation can be easily solved for the largest eigenvalue and for the corresponding eigenvector resorting to an available IMSL routine.

In this paper, we consider a piecewise homogeneous cylindrical body as many parts of the human body can be very well represented by this model. Electric current filaments are used as applicators. To facilitate the solution for the fields in the various regions, we use a recently suggested simple and efficient method of moments procedure [2]. In this approach, instead of solving for conventional equivalent surface currents, we solve for sets of fictitious impulsive sources (line sources in the two-dimensional case), each set simulating the fields in a homogeneous region which corresponds to it. The numerical simulations illustrate that a better control of the SAR patterns can be attained using the proposed optimization strategy.

II. OPTIMIZATION PROCEDURE

Consider a piecewise homogeneous lossy body situated in free space as shown in Fig. 1. Our objective is to heat a tumor region within the body, referred to as region t, bounded by a closed surface S_t, while affecting the surrounding tissues as little as possible. The heating is attained by means of a multiapplicator array consisting of M sources placed around the body. A harmonic time dependence is assumed and suppressed throughout. Also, the magnitude of the complex quantity is the effective (root-mean-square) value of the instantaneous quantity. A general optimization procedure suggested by Harrington [2] is used to adjust the complex excitation coefficients $I_1, I_2, \cdots, I_M$ of the array elements. We define a dimensionless performance index as the ratio of the power dissipated in region t to a sum of this power and a weighted summation of the powers supplied to suitably selected surrounding regions. We denote the power dissipated in the desired region by P^t and the weighted summation by P^w. Letting the performance ratio be denoted by ρ, we have

$$\rho = \frac{P^t}{P^t + P^w} = \frac{P^t}{P^t + \sum_i a_i P^i} \tag{1}$$

where P^i denotes the power supplied to the surrounding region i and a_i ($a_i \geq 0$) is a dimensionless real weighting multiplier

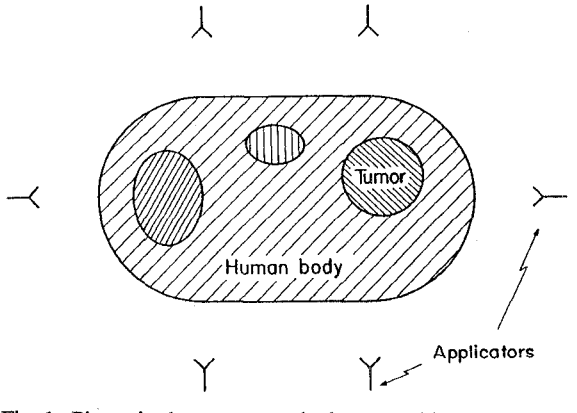

Fig. 1. Piecewise homogeneous body and multiapplicator array.

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associated with this region. Using straightforward algebraic steps, we obtain

$$\rho = \frac{\vec{I}^*[R^t]\vec{I}}{\vec{I}^*[R^t+R^w]\vec{I}} = \frac{\sum_p \sum_q I_p^* R_{pq}^t I_q}{\sum_p \sum_q I_p^*(R_{pq}^t + R_{pq}^w) I_q} \tag{2}$$

Here, $[R^t]$ and $[R^t+R^w]$ are square matrices of order M. The (p,q) elements R_{pq}^t and R_{pq}^w are given, respectively, by

$$R_{pq}^t = \frac{1}{2} \oint_{S_t} (\mathbf{E}_p \times \mathbf{H}_q^* + \mathbf{E}_q^* \times \mathbf{H}_p) \cdot \hat{\mathbf{n}}\, ds \tag{3}$$

and

$$R_{pq}^w = \sum_i \frac{a_i}{2} \oint_{S_i} (\mathbf{E}_p \times \mathbf{H}_q^* + \mathbf{E}_q^* \times \mathbf{H}_p) \cdot \hat{\mathbf{n}}\, ds \tag{4}$$

In (3) the integration is over the closed surface S_t bounding region t, while in (4) the integration is performed over the ith region boundary S_i. In both (3) and (4), $(\mathbf{E}_q, \mathbf{H}_q)$ is the electromagnetic field due to the qth array element when it is operating alone and driven by a unit excitation ($I_q = 1$), $\hat{\mathbf{n}}$ is a unit vector inwardly normal to the respective surface over which the integration is performed, and ds denotes a differential element of area. Also in (2), $\vec{I}$ is an M-element column vector whose qth element is I_q, and $\vec{I}^*$ denotes the transpose complex conjugate of the vector $\vec{I}$.

The maximization of (2) can be accomplished by treating each element of $\vec{I}$ and $\vec{I}^*$ as a variable and setting the necessary conditions

$$\frac{\partial \rho}{\partial I_k} = 0, \qquad k = 1,2,\cdots,M \tag{5}$$

and

$$\frac{\partial \rho}{\partial I_k^*} = 0, \qquad k = 1,2,\cdots,M \tag{6}$$

However, since ρ is real it is sufficient to impose one of these conditions, the other will follow immediately. Applying (6), we arrive at

$$\frac{\partial \rho}{\partial I_k^*} = \frac{1}{P^t + P^w}\left[\sum_q R_{kq}^t I_q - \rho \sum_q (R_{kq}^t + R_{kq}^w) I_q\right] = 0 \tag{7}$$

for $k = 1,2,\cdots,M$. Now, assuming $P^t + P^w \neq 0$ (else no power is being supplied to the body), equation (7) can be cast into the matrix form

$$[R^t]\vec{I} = \rho[R^t + R^w]\vec{I} \tag{8}$$

It is easily recognized that (8) is an eigenvalue equation with eigenvalue ρ and eigenvector $\vec{I}$. Hence, the maximum value of ρ would be the largest eigenvalue of (8) and the eigenvector $\vec{I}$ which corresponds to it would give the desired array excitation coefficients. With a view towards deriving a solution to (8), attention should be given to the fact that the elements of $[R^t]$ satisfy $R_{pq}^t = (R_{qp}^t)^*$ and those of $[R^w]$ satisfy $R_{pq}^w = (R_{qp}^w)^*$. Thus, $[R^t]$ and $[R^w]$ are Hermitian and consequently the matrix eigenvalue equation (8) can be solved applying a well stabilized IMSL routine.

III. NUMERICAL SIMULATIONS

As a study case, we treat a two-dimensional problem. We consider an infinitely long penetrable cylinder of circular cross section situated in free space. The cross section of the cylinder is shown in Fig. 2. The cylinder is composed of a 6 cm in diameter circular tumor region embedded in a 32 cm in diameter homogeneous muscle region. The center of the tumor region is moved 4 cm

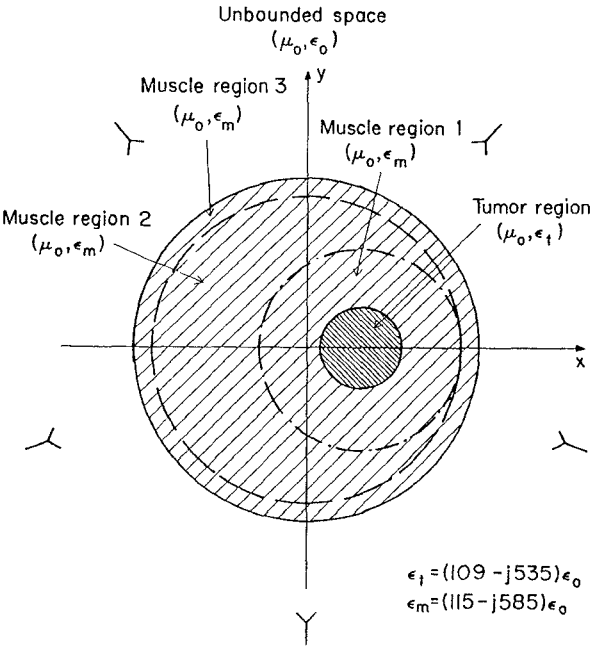

Fig. 2. Tissue model and suggested auxiliary optimization regions.

along the x axis from the center of the muscle region. The illumination of the cylinder is due to a 5 electric current filaments equispaced on a 90 cm in diameter cylindrical surface concentric with the cylindrical muscle region. The excitation is at 25 MHz. The values of the electric parameters of the muscle and the tumor at the excitation frequency were specified according to [5].

To determine the optimal excitation currents, we execute the procedure outlined in the preceding section. As a first step, we should solve successively for each electromagnetic field $(\mathbf{E}_q, \mathbf{H}_q)$ appearing in (3) and (4). Specifically, we solve for the fields in the tumor, muscle, and exterior regions when in turn only the respective qth applicator is operating while the others are absent. Towards this end, we use the method that has been recently proposed in [3] and [4]. In this approach, we solve for sets of fictitious impulsive sources (line sources in this two-dimensional case), each set simulating the fields in a corresponding homogeneous region. The sources of yet unknown complex amplitudes associated with a given region are situated outside the region (so that their fields are regular on and within the surface bounding the region) and are assumed to radiate into a homogeneous unbounded space having constitutive parameters equal to those of their respective region. The sources associated with the exterior free space region are only assumed to simulate the electromagnetic field scattered by the cylinder in the original situation. To obtain the total field in the exterior free space region, the incident field due to the qth applicator when it is operating alone and driven by a unit excitation ($I_q = 1$) must be superposed. Simulated equivalences for the tumor, the muscle, and the external free space are shown in Fig. 3. The electromagnetic fields in the various regions are related by the continuity conditions for the tangential components of the electric and magnetic fields across the boundaries between the regions. We impose the boundary conditions at a sufficient number of points on the boundaries to obtain a solution within a reasonably low error. Consequently, the functional equations are reduced to the matrix equations

$$[Z]\vec{I}_q = \vec{V}_q, \qquad q = 1,2,\cdots,M \tag{9}$$

where $[Z]$ is the generalized impedance matrix, $\vec{I}_q$ is the fictitious

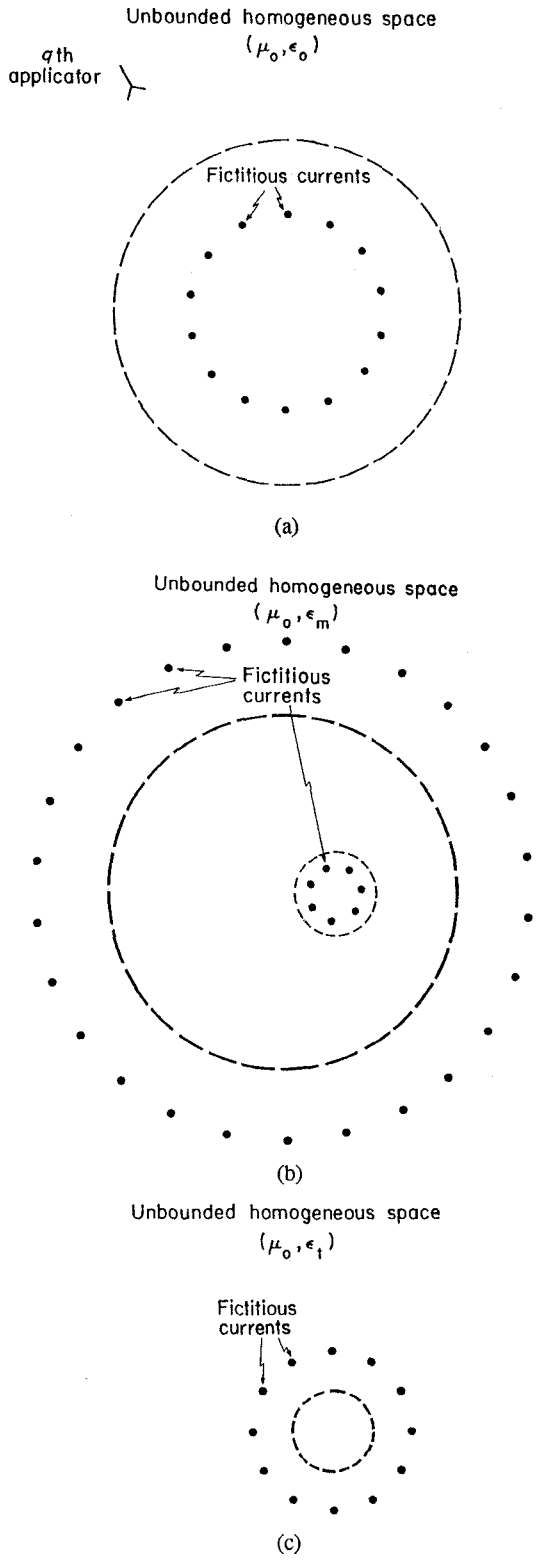

Fig. 3. Simulated equivalences for the (a) exterior unbounded free space, (b) muscle region, and (c) tumor region, when the q th applicator alone is operating.

current vector and $\vec{V}_q$ is the excitation vector corresponding to the qth applicator. If the matrix $[Z]$ is invertible, the M matrix equations in (9) can be readily solved for the unknown fictitious filamentary currents by inversion. Note that matrix $[Z]$ of (9) depends on the geometry and on the electrical properties of the body, but not on the excitation. Thus the same matrix $[Z]$, whose construction and subsequent inversion are the most time consuming operations, is used for solving the unknown current vectors due to each of the independent excitations. Once these currents are revealed, approximate values for the fields due to each of the M applicators at any point in space, in general, and those produced in regions of interest within the body, in particular, can be easily evaluated exploiting the analytically known fields of line sources.

To proceed with the optimization process, the muscle region is subdivided into three auxiliary regions as shown in Fig. 2. Different weighting multipliers have been assigned to each of these auxiliary regions. For region 1, which is concentric with the tumor, we set $a_1 = 1$. For the intermediate region, we choose $a_2 = 0.02$, and, finally, for the outer shell (region 3) we let $a_3 = 0.015$. Here, by choosing a_1 to be relatively high compared with the weights associated with the rest of the body, we direct the optimization process to bring down the field strength in the healthy tissues adjacent to the tumor. Less weight has been given to the peripheral region because this region can be cooled by external means. The SAR distribution obtained with the optimal excitation is shown in Fig. 4. This distribution should be compared with the one for uniform excitation shown in Fig. 5. Clearly, the uniform excitation focuses the heat energy in the central part of the body and thus heats both the center and the half of the body which does not include the tumor much more than the optimal currents. It should be emphasized that the optimization results are not highly sensitive to the choice of the auxiliary regions and their respective weights, though an unwise choice might lead to an undesired power absorption in healthy tissues. For example, if we regard the whole muscle region as a single reference region and thus optimize the ratio of the power dissipated in the tumor to the total power supplied to the body, the SAR distribution shown in Fig. 6 results. If on the other hand we assign a zero weight to the two auxiliary muscle regions designated 2 and 3, the SAR distribution of Fig. 7 results. Finally, SAR distributions in the $y = 0$ cross section for some of the above cases are compared in Fig. 8. Note that both Fig. 6 and Fig. 7 illustrate undesired SAR patterns as in the two examples local overheating of healthy tissues

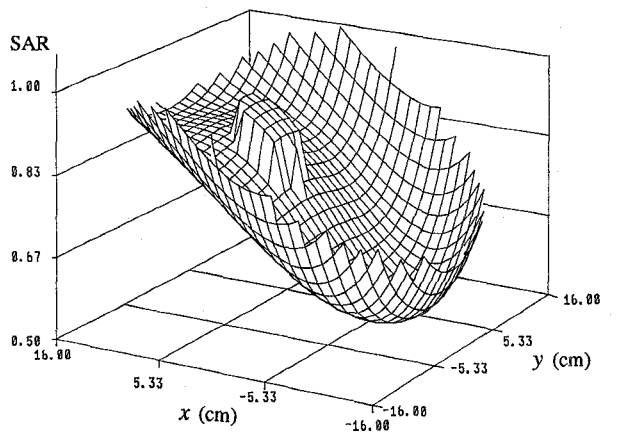

Fig. 4. Normalized SAR distribution for the excitation coefficients obtained with $a_1 = 1$, $a_2 = 0.02$, and $a_3 = 0.015$.

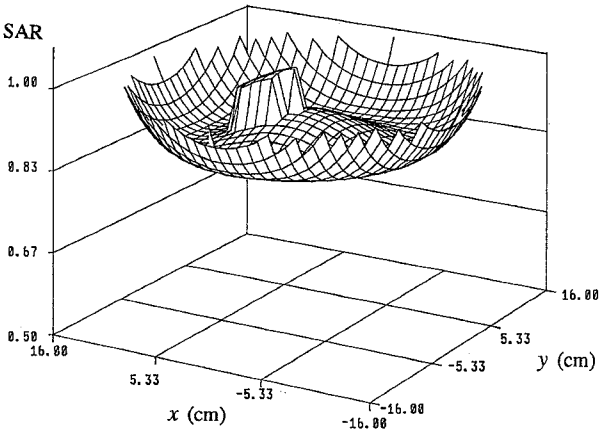

Fig. 5. Normalized SAR distribution for uniform excitation.

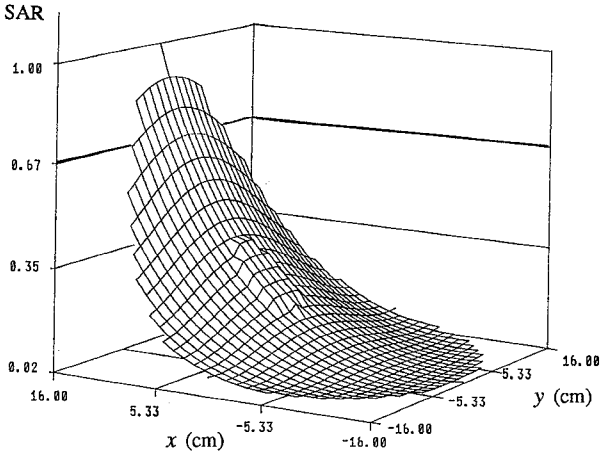

Fig. 6. Normalized SAR distribution for the excitation coefficients obtained with $a_1=a_2=a_3=1$.

occurs. It may be added that in any event one should examine the SAR distribution produced by the optimization procedure. Then, if an unwanted excessive local heating is observed, it can be diminished by giving more weight to the regions surrounding the hot spots.

IV. CONCLUSION

An optimization method for determining the excitation amplitudes and phases of the elements of electromagnetic multiapplicator systems for forming a hot zone around a deep-seated tumor has been proposed. The method has been demonstrated through a numerical study of a simple two-dimensional case to be effective. We believe that this simple case highlights the main features of the proposed method. Application of the method to more realistic models corresponding to computer tomography images as well as studies of more practical applicators remain to be done.

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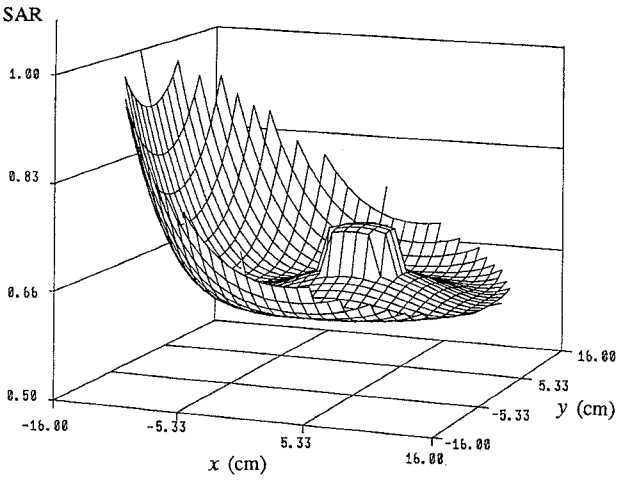

Fig. 7. Normalized SAR distribution for the excitation coefficients obtained with $a_1=1$ and $a_2=a_3=0$.

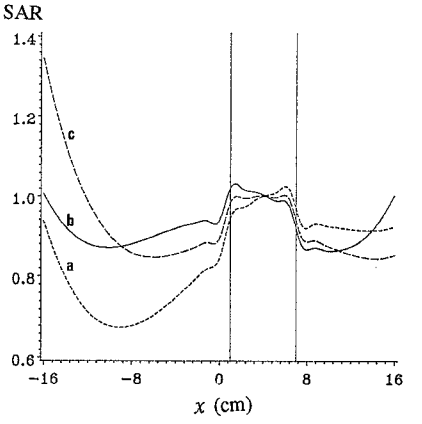

Fig. 8. SAR distributions in the $y=0$ cross section for the cases of Fig. 4 (curve a), Fig. 5 (curve b), and Fig. 7 (curve c). The vertical reference lines indicate the boundaries of the tumor.

REFERENCES

[1] Special issue on phased arrays for hyperthermia treatment of cancer, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 481-648, May 1986.

[2] R. F. Harrington, *Field Computation by Moment Methods*. New York: Macmillan, 1968, ch. 10.

[3] Y. Leviatan and A. Boag, "Analysis of electromagnetic scattering from dielectric cylinders using a multifilament current model," *IEEE Trans. Antennas Propagat.*, vol. AP-35, pp. 1119-1127, October 1987.

[4] Y. Leviatan, A. Boag, and A. Boag, "Generalized formulations for electromagnetic scattering from perfectly conducting and homogeneous material bodies-theory and numerical solution," *IEEE Trans. Antennas Propagat.* (to appear).

[5] R. Peloso, D. T. Tuma, and R. K. Jain, "Dielectric properties of solid tumors during normothermia and hyperthermia," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 725-728, November 1984.