Synthesis of an Array Antenna for Hyperthermia Applications

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Abstract—In the present work the synthesis of an array antenna for hyperthermia treatment is developed. The selected antenna is an array antenna surrounded by a semicircular reflector which has shown to ease the penetration and focalization in malignant biological tissues. A bolus is introduced as a protection in order to avoid an increasing heat hazard of superficial healthy tissues. The electric field within the biological medium will be modeled by means of the well known method of moments. The electromagnetic coupling problem is expressed in a closed form, enabling both a synthesis and an optimization procedure to be performed. Numerical results are included, illustrating the capabilities of the array antenna.

Index Terms—Biomedical applications of electromagnetic radiation, hyperthermia, microwave antennas, moment methods.

I. INTRODUCTION

THE electrical processes inherent to biological systems together with several medical and biological applications of electromagnetic fields have been extensively studied. Currently, electromagnetic hyperthermia (heating of biological tissues) offers a promising modality for treating cancer in humans.

The use of an array antenna [1]–[4], and even the introduction of a perfectly electric conducting (PEC) reflector [5]–[8] to enhance penetration in biological medium, is not new in hyperthermia applications. Special mention is due to Rappaport's [4], in which a spherical and homogeneous tissue is employed to look for an optimal source distribution with an additional power constraint imposed on the superficial area. Otherwise, a 915 MHz monopole phased array antenna designed with a conducting reflector is used for brain tumor heating in [5] and for breast cancer in [6]. Recently, a similar design working between 70 and 100 MHz [8] has been employed to improve the conventional therapy of deep seated pelvic tumors by additive use of regional hyperthermia.

The main point of the present work is to synthesize the amplitude and phase of each component of the array antenna trying to focalize the electromagnetic (EM) energy over a particular region of the biological tissue, i.e. over the damaged tissue or tumor. Otherwise, surrounding healthy tissues may be affected by this EM energy so the biological safety limitations must be also taken into account. The influence over superficial tissues is critical and hazardous because while trying to induce heat in deeper tissues, a dangerous temperature rise stays in this area. Therefore, a dielectric protecting layer, or a bolus, is included

Fig. 1. Geometry of the problem: Biological tissue protected by a dielectric layer in front of the antenna array. $d = 9.58$ cm, $r_a = 18.3$ cm and $r_{pec} = r_a + 0.25\lambda$ cm.

and considered in the synthesis and optimization process to diminish or even avoid the excessive dangerous heating of these superficial healthy tissues.

The proposed technique applies the *method of moments* (MoM) [9] to achieve a rigorous and accurate model of the whole EM problem. Then an optimization procedure is applied enforcing the concentration of the EM energy over malignant tissues. The performed synthesis procedure has demonstrated a good capability to focalize the EM field not only in superficial biological tissues but also in deeper regions.

In the following section, the EM modeling of the whole problem is described. Section III is devoted to describe the synthesis procedure employed to determine the coefficients of the array antenna. Numerical results are presented in Section IV, showing the capabilities of the suggested method. Finally, a few conclusions summarizing the paper are presented in Section V.

II. ELECTROMAGNETIC MODELING OF THE PROBLEM

Let us consider an N -elements array antenna with a PEC semicircular reflector around and a biological tissue within its near field region (Fig. 1). For the sake of simplicity, the analysis is restricted to two-dimensional (2D) problems with a transversal magnetic (TM) polarized electric field. However, the proposed synthesis procedure can be straightforward extended to three-dimensional (3D) problems and other geometries and biomedical applications.

The EM coupling between the array antenna and the tissue is formulated through the *electric field integral equation* (EFIE), which is solved using the conventional *method of moments* (MoM) [9]. The MoM implies a discretization process, that, in this case, is performed through the application of a point

Manuscript received October 25. This work was supported by the Spanish CICYT, Project Ref. TIC97-0821-C02-01.

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Publisher Item Identifier S 0018-9464(00)04966-9.

matching procedure (Dirac delta weighting functions) together with the choice of pulse basis functions.

The fields and currents will be assumed to have a time-harmonic dependence of the form $e^{j\omega t}$ (ω is the angular frequency), which will be suppressed in the rest of the paper.

The boundary condition on the PEC surface and the boundary condition within the biological medium are discretized, leading to the following matrix systems,

$$Z_{\text{PEC}} j_{\text{PEC}} = -Z_{\text{PEC}}^a a - Z_{\text{PEC}}^d e_d \quad (1)$$

$$(Z_d - I)e_d = -Z_d^a a - Z_d^{\text{PEC}} j_{\text{PEC}}, \quad (2)$$

that can be easily managed in the synthesis procedure. The column-vectors a , j_{PEC} and e_d are, respectively, the array excitations, the superficial electric currents over the PEC and the total electric field within the tissue. Z_{PEC} and Z_d are self-impedance matrices concerning the PEC surface and the dielectric area. The remaining terms are mutual impedance matrices, whose elements show the mutual influence between the components of the whole EM problem. For instance, Z_d^a represents the influence of the array over the dielectric region.

Combining (1) and (2), the total electric field within the tissue is obtained as a function of the array coefficients as follows,

$$e_d = [(Z_d - I) - Z_d^{\text{PEC}}(Z_{\text{PEC}})^{-1}Z_{\text{PEC}}^d]^{-1} \cdot [-Z_d^a + Z_d^{\text{PEC}}(Z_{\text{PEC}})^{-1}Z_{\text{PEC}}^a] a, \quad (3)$$

This equation will be the core of the synthesis procedure that will be described in the following section in detail.

III. SYNTHESIS PROCEDURE

In order to achieve the optimum excitations of the array elements, i.e., in order to synthesize the antenna, two methods have been applied: the *conjugate field matching* (CFM) [3] and the proposed *near field power maximization* (NFPM). The CFM together with an enhancement called *gain optimization*, which is similar to NFPM, has been already used in [3] in order to focalize the electric near field inside a dielectric material.

When applying CFM, the excitation assigned to each element is just the conjugate of the field radiated by this element in the desired focus (a set of matching points). Particularizing, the excitation coefficient will be the conjugate of (3) in the selected directions. Therefore, defining the uniform excitation vector l , as,

$$l = \begin{cases} 1 & \text{matching point in tumor} \\ 0 & \text{matching point in healthy tissue,} \end{cases} \quad (4)$$

and applying the near field reciprocity approach to (3), the array excitations are obtained as,

$$a_{\text{CFM}} = (l[(Z_d - I) - Z_d^{\text{PEC}}(Z_{\text{PEC}})^{-1}Z_{\text{PEC}}^d]^{-1} \cdot [-Z_d^a + Z_d^{\text{PEC}}(Z_{\text{PEC}})^{-1}Z_{\text{PEC}}^a])^H. \quad (5)$$

However, though CFM gets a directive pattern from the radiation in the focus of each array element, it does not consider the power coupling between elements.

On the other hand, the proposed NFPM method solves this problem introducing a power-coupling matrix G , which does

Fig. 2. Dimensions of the tissue layers and the bolus. $a = 2.5$ cm, $b = 6.75$ cm, $c = 7.75$ cm, $d = 8$ cm, $e = 11$ cm, $f = 1.5$ cm, $g = 5.75$ cm, $h = 6.75$ cm, $i = 7$ cm, $j = 10$ cm.

not depend on the array excitations and whose components g_{ij} represent the coupling among the primary patterns, $f_i(\phi)$ and $f_j(\phi)$ corresponding to the i -element and the j -element of the array,

$$g_{ij} = \frac{1}{2\nu_0} \int_0^{2\pi} f_i^*(\phi) f_j(\phi) d\phi. \quad (6)$$

Finally, the solution achieved by the NFPM method is expressed as,

$$a_{\text{NFPM}} = (G^H)^{-1} \left(l[(Z_d - I) - Z_d^{\text{PEC}}(Z_{\text{PEC}})^{-1}Z_{\text{PEC}}^d]^{-1} \cdot [-Z_d^a + Z_d^{\text{PEC}}(Z_{\text{PEC}})^{-1}Z_{\text{PEC}}^a] \right)^H. \quad (7)$$

Paying attention to (5) and (7), the following relationship is deduced in a straightforward manner,

$$a_{\text{NFPM}} = (G^H)^{-1} a_{\text{CFM}}, \quad (8)$$

which relates the coefficients provided by both synthesis procedures.

IV. NUMERICAL RESULTS

In this section, some numerical results will illustrate the capabilities of the suggested antenna array synthesis procedure. A two-dimensional example is presented for the TM case (see Fig. 2). Four elliptical concentric layers of biological tissue (bone, muscle, fat and skin) protected by a bolus are radiated by an array antenna with a semicircular PEC reflector surround. The choice of such a shape for the PEC reflector enables the antenna array feeding and diminishes the power concentration. Otherwise, the PEC reflector enhances focalization and allows power to be delivered to deeper tissues.

The working frequency is 915 MHz, which provides penetration and focalization compatible with medical constraints. At 915 MHz, the characteristics of the dielectric protecting layer and the biological tissues under proof, i.e. density (ρ), relative permittivity (ϵ_r) and conductivity (σ), are shown in Table I.

The normalized *specific absorption rate* (SAR) is the magnitude selected to show the results,

$$\text{SAR} = \frac{\sigma}{\rho} |E^{\text{tot}}|^2 \quad (\text{W/Kg}), \quad (9)$$

where E^{tot} is the total electric field within the biological tissue.

TABLE I
PROPERTIES OF BIOLOGICAL TISSUES AND BOLUS AT WORKING FREQUENCY,
915 MHz. DENSITY, ρ , RELATIVE PERMITTIVITY, ϵ'_r , AND CONDUCTIVITY, σ

	ρ (10^3 Kg/m^3)	ϵ'_r	σ (S/m)
Muscle	1.04	58	1.4
Fat	0.92	6	0.08
Bone	1.85	8	0.11
Skin	1.10	35	0.6
Bolus	2.07	4	0.1

Fig. 3. Normalized SAR (dB) within biological tissue without bolus. Grid of dots represents the tumor region.

In the following pictures, the dark colors represent low SAR values and the light colors represent high SAR values. The tumor is indicated by a grid of dots. The results are presented for both methods: CFM and NPFM.

Fig. 3 shows the SAR within the biological tissue when there is no additional protection. Though the electromagnetic energy reaches the whole tumor, it is also observed that the surrounding healthy tissue is affected dangerously.

As a feasible alternative, previously suggested and tested, a dielectric protecting layer is introduced. Due to this additional bolus, the undesired heating of superficial tissues is reduced considerably. Comparing the percentage of biological tissue exposed to a particular level of SAR with and without protecting layer this statement is clarified; i.e., given a SAR threshold of -15 dB, the percentage of biological tissue exposed to higher levels, diminishes from 20.2% without protecting layer to 10.9% with it (a 46.2% reduction in the affected area).

In Fig. 4, a bolus is clearly distinguished and the tumor is supposed in a deep muscle area close to the edge of the bone. Subjectively, the scale of colors shows that the NPFM concentrates better the energy in the tumor, delivering less power to faraway regions. Quantitatively, the maximum level of SAR in the zone just opposite the tumor is -25 dB in the CFM case and -27.4 dB in the NPFM. Therefore, the NPFM achieves an improvement of 2.4 dB with regard to the CFM.

Fig. 4. Normalized SAR (dB) within biological tissue surrounded by a bolus. Grid of dots represents the tumor region.

It is worth mentioning that it is considerably easier to obtain a selective increment in temperature when we are concerned with superficial tumors. This fact is illustrated in Fig. 5.

V. CONCLUSION

The main aim of the exposed work was to achieve localized hyperthermia over malignant human tissues by means of EM energy at microwave frequencies. The solution proposed was to synthesize an antenna array with a semicircular PEC reflector around. A closed formulation combining the MoM method with optimization techniques has been developed in order to obtain the desired increasing heat in tumor region.

The proposed synthesis has been demonstrated to provide a good focalization of the EM energy within superficial and intermediate biological tissues. Nevertheless, it has not been possible to reach the deepest regions, namely the bone, because of the excessive power losses in the previous tissue layers.

Fig. 5. Normalized SAR (dB) within biological tissue surrounded by a bolus. Grid of dots represents the tumor region. Superficial tumor.

For the sake of simplicity, only 2D simulations have been presented. Nevertheless, the synthesis technique can be extended and adapted to 3D problems in a straightforward manner. Besides, this method could be also extended to complex geometries including other kinds of tissues and other applications.

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