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 optimizing the specific absorption rate (SAR) distribution around a deep-seated tumor. In this method, the ratio of the power dissipated in the tumor to a weighted summation of the powers supplied to the surrounding regions is optimized. The optimization procedure is combined with a recently proposed effective technique for analysis of various electromagnetic scattering and interaction problems. 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, improved SAR distributions can be achieved. The extension to three-dimensional configurations is discussed.

I. INTRODUCTION

HYPERHERMIA cancer therapy is a treating procedure in which the temperature of cancerous tumors embedded in healthy human tissue is elevated. Among the sources of heat, multiapplicator arrays operating at microwave and radio frequencies are rapidly gaining utility in the clinic. For a proper hyperthermia treatment, it is necessary to deliver time-average power such that the tumor is maximally heated while the surrounding healthy tissues are kept below their maximally tolerable temperatures. This can be effected by focusing electromagnetic field at the tumor. The inherent problem is that the electromagnetic field cannot penetrate deep if the frequency is high, while if the frequency is low, the focusing ability deteriorates.

Phased arrays, also referred to as multiapplicator systems, promise to be effective in concentrating the electromagnetic energy on the tumor. A large body of previous work reporting theoretical analysis and experimental verification of various specific applicators and human body configurations can be found in [1]. While many researchers have exploited the main feature of phased arrays, i.e., the freedom in choosing the relative amplitudes and phases of applicators in the array, to obtain improved field patterns, [2] is perhaps the only work proposing a method for determining an optimal excitation for a multiapplicator system which applies a full wave analysis to the electromagnetic problem. In this work, Morita et al. have tried to induce a specified electric field distribution in the body, choosing the simple zero-order Bessel function, optimal for heating the center of homogeneous circular cylinder, as the target field distribution in a rather complicated piecewise homogeneous cylindrical structure.

This paper presents a simple and efficient procedure for optimizing the relative electromagnetic power absorbed by a deep-seated tumor region, which is a quantity of interest in hyperthermia treatment. The outputs of the procedure are the optimal excitation coefficients (amplitudes and phases) of the elements of the applicator array. The proposed approach employs an optimization sequence similar in principle to the general optimization procedure pursued by Harrington [3]. We characterize the multiapplicator system by a dimensionless performance index, which is a ratio of two quadratic forms, defined as the ratio of the time-average power dissipated in the tumor region to a weighted summation of the time-average 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 specifies the desired array excitation coefficients.

In the course of the optimization process, the evaluation of the electromagnetic field in the body region due to each array element needs the most lengthy numerical treatment. Once the fields due to each array element are known, the matrix eigenvalue equation can be easily solved for the eigenvalue which is greatest in value and for the corresponding eigenvector using an available IMSL routine. To facilitate the solution for the fields in the various regions, we use a recently suggested simple and efficient procedure [4]–[7]. Central to this approach is the use of sets of fictitious impulsive sources (line sources in two-dimensional cases and elemental dipoles in three-dimensional cases) instead of using conventional equivalent surface currents. Each set of sources is associated with one homogeneous region and is assumed to simulate the fields in that region. The sources associated with a given region are situated outside the region and are assumed to radiate into a homogeneous unbounded space having con-