DESIGN OPTIMIZATION OF INTERSTITIAL ANTENNAS FOR MICROWAVE HYPERTHERMIA

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ABSTRACT

Theoretical and experimental results illustrating the design optimization of interstitial antennas for microwave hyperthermia are presented. New numerical models which calculate current distribution and the radiation characteristics of multisection insulated antennas in conductive tissue are developed. Numerical predictions are verified experimentally by making heating patterns measurements and by mapping the various near- and far-field components.

I. INTRODUCTION

Hyperthermia treatment using microwave and RF applicators has proven effective in delivering therapeutic heating to malignant tumors. A wide variety of hyperthermia applicators have been designed and clinically tested for regional, whole body, and localized hyperthermia. Recently, however, the use of more direct ways for heating deep-seated tumors using interstitial antennas has gained popularity. This is because of the advantages of directly depositing the electromagnetic energy to cancerous tissue with minimum heating of the surrounding healthy tissue, and the relative ease of achieving good impedance matching for these antennas. In addition, the increased utilization of invasive treatment techniques using ionizing radiation has greatly helped the expanded use of interstitial antennas.

To improve the design performance of interstitial antennas, parameters such as the uniformity of the heating pattern, the depth of penetration, and the impedance matching properties must be optimized. Such an optimization, however, requires identifying and quantifying the tradeoffs between various design parameters, including the diameters of the center conductor and the insulation, the type of insulation, and the feasibility of using multisection antennas to achieve the desired optimum design.

In this paper we developed two numerical models to calculate the current distribution and radiation characteristics of multisection insulated antennas in conductive media. The first model is new and is based on generalizing the rigorous solution developed by R. P. W. King, et al., for uniformly-insulated antennas, and extending it to the case of multisection antennas. The other model is approximate and provides a more computationally efficient way for characterizing multisection antennas. The numerical predictions were verified experimentally both by making heating patterns measurements and by mapping the various near- and far-field components of these antennas. The developed numerical models as well as the experimental measurements will be described in the following sections.

II. NUMERICAL MODELS

As indicated earlier we developed two numerical models to calculate the current distribution and the radiation characteristics of multisection insulated antennas in conductive media. The first model is rigorous and is based on extending the theory developed by King, et al., [1,2] for uniformly-insulated antennas.The other, however, is approximate but more computationally efficient and may be used to calculate heating patterns as close as 1 mm away from the insulation. The following is a brief description of these models:

A. Theory of multisection insulated antennas in conductive media:

One of the most important conclusions derived from the extensive analysis conducted by R. W. P. King and his coworkers on insulated antennas [3], is that such antennas when placed in dissipative media may be treated as sections of lossy transmission line with generalized propagation constant that accounts for the ohmic losses in the conductors as well as for the losses due to radiation from the antenna to the ambient medium. Hence, a possible procedure for analyzing a multisection insulated antenna in dissipative medium is through the representation of the antenna by a multisection transmission line, each terminated with a load impedance equal to the input impedance of the preceding section. Hence, for the ith section of the antenna, the input impedance and current distribution are given by

$$Z_{in}(i) = j\, Z_c(i)/\tan\left[K_{Li}\, h_i + j\, \theta_{h(i-1)}\right]$$

$$I_{zi}(z) = Y_{in}(z)\frac{\sin\left[K_{Li}\left(h_i - |z|\right) + j\,\theta_{h(i)}\right]}{\sin\left(K_{Li}\, h_i + j\theta_{h(i)}\right)}$$

where $\theta_{h(i)} = \mathrm{Coth}^{-1}\,[Z_{in(i-1)}/Z_{c(i)}]$ is the angle used to take into account the termination of the ith section of the antenna which is of length $h_{(i)}$, characteristic impedance $Z_{C(i)}$ and complex propagation constant $K_{L(i)}$ with the load impedance $Z_{in(i-1)}$. In this case $Z_{in(i-1)}$ is clearly the input impedance of the preceding section of the antenna. The propagation constant K_L and characteristic impedance Z_c are given elsewhere [3].

The above procedure is used to calculate the input impedance and the current distribution of multisection antennas. To calculate the radiation characteristics, we relate the electric and magnetic field components in the insulation to the current and charge (through continuity equation) distributions on the antenna. The electromagnetic field at any point in the ambient medium can be determined from the electromagnetic field at the surface of the insulation. Since these equations will not be included here, it suffices to indicate that this procedure is the same utilized by King, et al., except that it is generalized here for the case of multisection antenna [1]. Results from the generalized computer code showed excellent agreement with the data reported by King for the special case of uniformly-insulated antennas.

B. Approximate analysis of the radiation characteristics of insulated antennas in conductive media

In this approximate analysis the input impedance and the current distribution are calculated as described above. The radiated fields from the multisection insulated antennas are calculated based on an assumed array point source (infinitesimal electric dipoles) distribution along the insulation. The amplitude and phase distribution among these point sources is determined by:

1. The amplitude and phase of the current distribution along the antenna, and
2. the amplitude is further multiplied by what we call "radiation efficiency term," which is equal to α/β, where α and β are the

real and imaginary parts of the complex propagation constant K_L. It should be noted that this radiation efficiency term is proportional to the radiation loss to the ambient medium per wavelength. The inclusion of this intensity -modifying factor was found to be particularly important for accurately calculating the power deposition pattern in the near-zone of the interstitial antennas.

III. EXPERIMENTAL MEASUREMENTS

To confirm the numerical observations regarding the optimum design of interstitial antennas, we constructed several multisection insulated antennas and tested their performance experimentally. The parameters measured include the power deposition pattern, the near-and far-field components, and the input impedance as a function of frequency.

The input impedance was measured using an HP 8510B Network Analysis System. The three-dimensional electric field maps were obtained using an implantable electric field probe. This probe consists of three orthogonal diode-loaded dipoles which are connected to digital voltmeters via high resistance leads. Both the dipoles and the resistive leads were coated with a thin layer of insulating material. Finally, the heating pattern was measured using a semiconductor temperature probe with optical fiber leads [4,5].

IV. RESULTS

The rigorous numerical solution was first checked by artificially dividing a uniformly insulated antenna into four sections and comparing the obtained results from the multisection antenna code with those reported by King, et al., [1] for a uniform case of insulation . The results agreed very well and we hence used the code to calculate field components and heating patterns of typical experimentally-design multisection antennas. Regarding checking the accuracy of the approximate theory, Fig. 1 shows comparison between the obtained results and those published by Trembley [2] for an array of four uniformly-insulated antennas. The results are in very good agreement except for distances less than one millimeter away from the insulation. For such close distances we, therefore, used the computer code based on the rigorous theory.

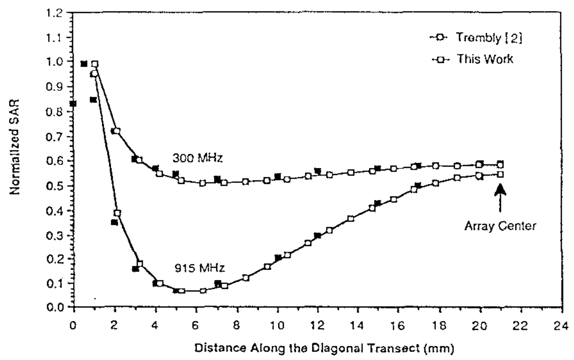


Fig. 1. Comparison between the results obtained using the approximate numerical model and the data reported by Trembley [2]. The results represent the power deposition pattern along the diagonal plane of an array of four insulated antennas. The side length of the square array is 3 cm, and the antenna length is $\lambda_2/4$. Results were calculated at both 300 and 915 MHz.

Numerical results for uniformly insulated and multisection antennas are shown in Fig. 2. Comparison between the various antenna designs show that a multisection arrangement with the thinnest insulation near the antenna tip has superior performance (uniform pattern and an improved depth of penetration) compared with the uniform insulation. These results were confirmed experimentally as shown in Fig. 3.

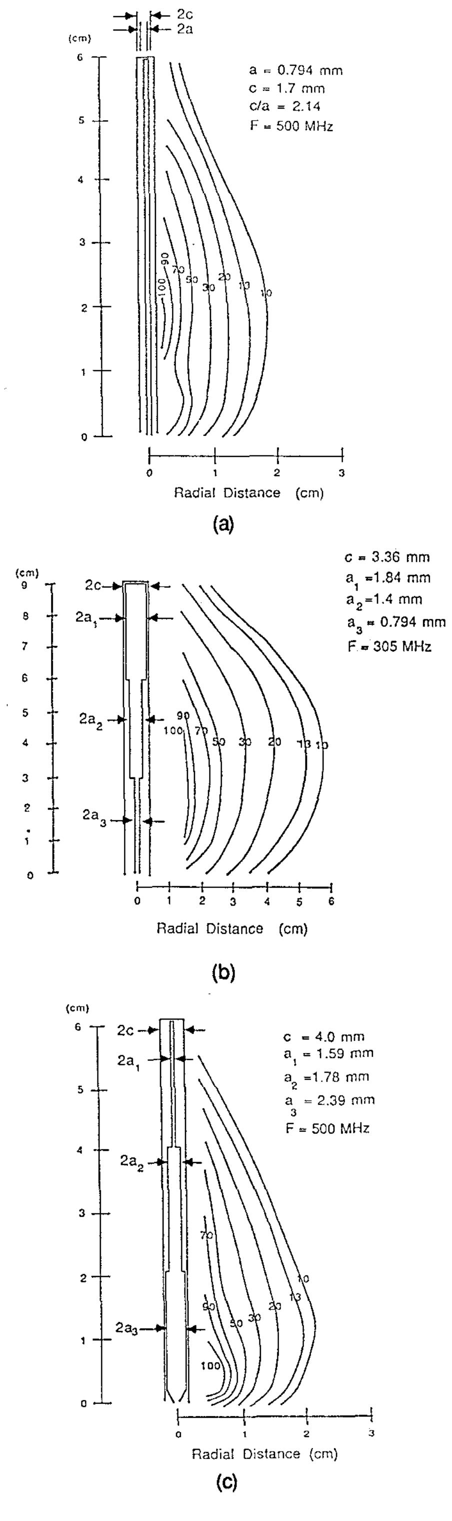
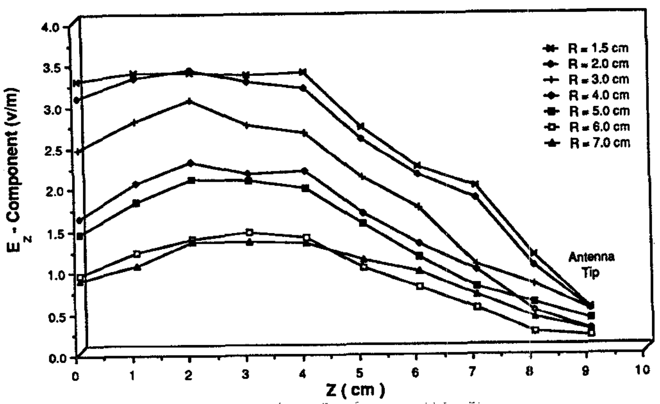
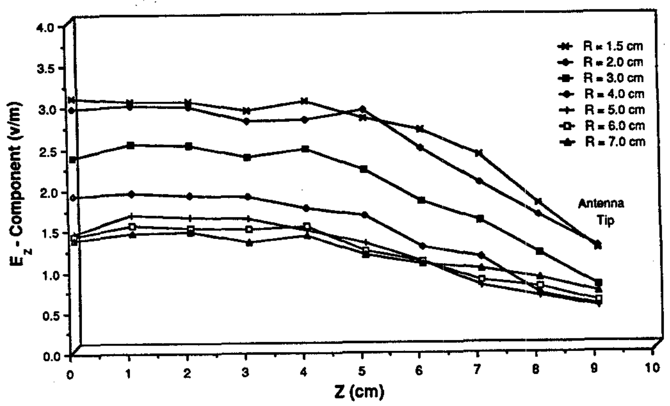


Fig. 2. Comparison between the power deposition patterns of uniformly-insulated and multisection antennas. A multisection design with thinnest insulation near the antenna tip has better pattern uniformity and an improved depth of penetration. Thin insulation at the feed, on the other hand, makes the power pattern localized near the feed and zero heating near the tip.



(a) Multi-section design of Fig. 2(c).



(b) Multi-section design of Fig. 2(b).

Fig. 3 Experimental results illustrating the axial field component for multisection antennas. More uniform pattern is observed for multisection design with thinnest thickness of insulation near the tip (b). These results, thus, confirms numerical predictions. Results for other field components we omitted to prevent cluttering the figure.

Several other results illustrating the tradeoffs in designing multisection antennas will be presented. Also the effect of the thickness, type of insulation, as well as the presence of an air gap between the center conductor and the insulation on the radiation characteristics and the input impedance of uniformly insulated and multisection antennas, will be examined.

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