FDTD Simulation of Interstitial Arrays of Sleeved-Slot Antennas for Hyperthermic Cancer Therapy

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Abstract — **In this paper, a graded-mesh FDTD code is used for studying triangular arrays of sleeved-slot antennas immersed in a brain-equivalent phantom. The code allows accurate modeling of the fine structure of each antenna and of a sufficiently wide surrounding region with acceptable computational costs. The study performed illustrates the ability of a triangular array with 15 mm inter-antenna spacing to produce a fairly uniform power deposition in a spherical volume around the center of the array.**

I. INTRODUCTION

Microwave interstitial techniques are used to produce localized deposition of electromagnetic energy in hyperthermia treatments [1]. In these treatments the antenna must be able to produce a uniform power distribution in the target tissue without affecting the surrounding regions. In [2], triangular arrays of sleeved-slot antennas have been proposed for brain tumor hyperthermia treatments. These arrays have been studied both experimentally and analytically in order to verify their ability in producing a spatial power deposition which is uniform within a centimeter [2].

In this paper a FDTD code employing a graded mesh is used for studying the same geometry proposed in [2]. The aim of the present work is to study the electromagnetic power deposition inside a brain-equivalent phantom, considering the antenna fine structure, and the mutual interaction among antennas, in order to test the SAR distribution uniformity evidenced by the analytical model proposed in [2].

II. MATERIALS AND METHODS

A previously developed 3D graded-mesh FDTD code [3] has been improved in order to deal with multiple fine regions. In this manner both a single and an array of sleeved-slot antennas have been studied. In the implemented code, the graded mesh is generated along the three Cartesian directions independently. Considering a given axis, a small spatial step is used in the region where the antenna is located. Starting from this region, the spatial step is successively multiplied by a constant factor (geometric series) up to the largest spatial step. This procedure is repeated wherever an antenna is located. In the present study the fine region cell dimensions are 0.06×0.06×0.12 mm, while the largest cell sizes are 0.6×0.6×0.6 mm. In this way, the real array geometry is modelled with an adequate number of cells but with limited memory occupation.

The considered sleeved slot antenna was proposed in [2] for operation at 2450 MHz. The antenna is mounted on a UT-34 coaxial cable that is used for power delivery to the antenna. In Fig. 1(a) a longitudinal section of the antenna is depicted, while Fig. 1(b) reports a horizontal section in correspondence of the AA' plane of Fig. 1(a).

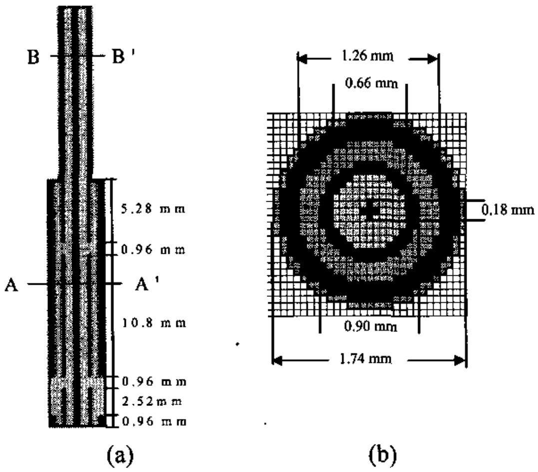

Fig. 1. Longitudinal (a) and horizontal (b) sections of the sleeved-slot antenna.

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Since for the considered staircase structure of the coaxial cable the solution for the TEM mode is not analytically available, it was obtained with a 2D FD code. This distribution has then been used as spatial excitation at the BB' section of Fig. 1(a) together with a gaussian-modulated sine-wave time behavior. This time behaviour allows to study the structure on a wide frequency range with a single FDTD run. Simulations are interrupted when the total energy in the studied domain reduces of 30 dB with respect to its maximum value. At this time the antenna radiation impedance is evaluated as the ratio between the Fourier transforms of the voltage and the current at the feed (BB' section in Fig. 1(a)).

The radiating structure has been inserted in a brain tissue phantom (sigma=1.23 S/m, eps=33.5) of 60×60×50 mm. The truncation of the computational domain has been performed by using the uniaxial perfectly matched layer (UPML) absorbing boundary condition [4], [5]. Both a single antenna and triangular arrays have been studied by using the graded-mesh FDTD code. In particular, the triangular arrays were formed by locating the antennas at the vertices of three equilateral triangles whose sides are 10, 15, and 20 mm, respectively.

III. RESULTS

Figure 2 shows, in logarithmic scale, the SAR distribution for a single sleeved-slot antenna radiating a power of 1.0 W. The SAR data are sampled with a spatial step of 0.2 mm along the three axes and are reported on a vertical plane passing through the antenna axis. For the isolated antenna, the magnitude of the reflection coefficient at 2.45 GHz is 0.48. The SAR distribution shows a pear shaped behavior with a maximum in correspondence of the first slot placed 4 mm from the antenna tip.

After that, three arrays made of 3 identical antennas placed at the vertices of equilateral triangles of 10, 15 and 20 mm side, respectively, have been simulated. The ratio between the magnitude of reflected and incident waves, evaluated at the excitation section when all the three antennas are equally fed, is the same for the three antennas of each array, and is equal to 0.55, 0.52 and 0.48 for the 10, 15 and 20 mm cases, respectively. These results show that increasing the distance among the antennas, the radiation impedance of the single antenna of the array approaches the one of the isolated antenna.

Fig. 3 shows, for the three array configurations, the SAR distribution over a horizontal section, perpendicular to the antenna axes, for a total radiated power of 1.0 W. The considered section is placed 4 mm above the antenna tip.

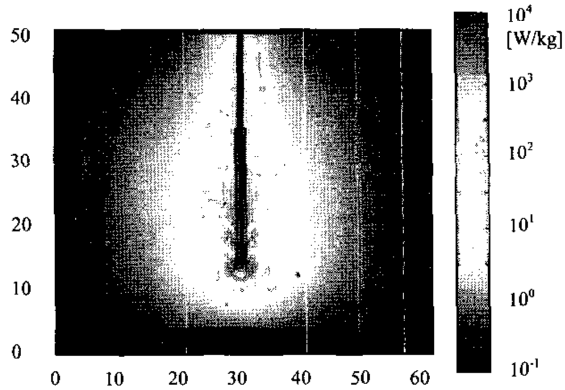

Fig. 2. Local SAR distribution for 1.0 W of radiated power in a vertical plane passing through the antenna axis. Dimensions are in mm.

The figure shows that the power deposition is mainly concentrated in the region among the antennas. The shape of the high absorption region is strongly dependent on the antenna spacing, while a fast decay is always evident in the array external region.

Fig. 4 shows the SAR distribution over a vertical section including a side of the equilateral triangle defined by the three antennas. The figure evidences the ability of the triangular array to concentrate the power deposition in the region between the antennas, in proximity of their tip. This is particularly true for the 10 and 15 mm spacing.

In order to investigate the ability of the antenna arrays in producing uniform power deposition in a localized region, a spherical volume of 3-mm radius, with its center placed 4 mm above the antenna tip at the center of the array, was considered.

Table I reports, for each array configuration and a total radiated power of 1.0 W, the maximum (SAR_{MAX}) and minimum (SAR_{MIN}) SAR values, the average SAR (SAR_{MED}) with its standard deviation (SAR_{SD}), and the ratio between SAR_{SD} and SAR_{MED} obtained inside the sphere.

From the Table it can be noted that, increasing the spacing between antennas, the obtained SAR values reduce. However, as evidenced by the SAR_{SD} / SAR_{MED} parameter, the 15-mm spacing produces the most uniform power absorption in the region contained inside the sphere. The same conclusion was drawn in [2] by analyzing the SAR values obtained analytically in correspondence of different antenna sections.

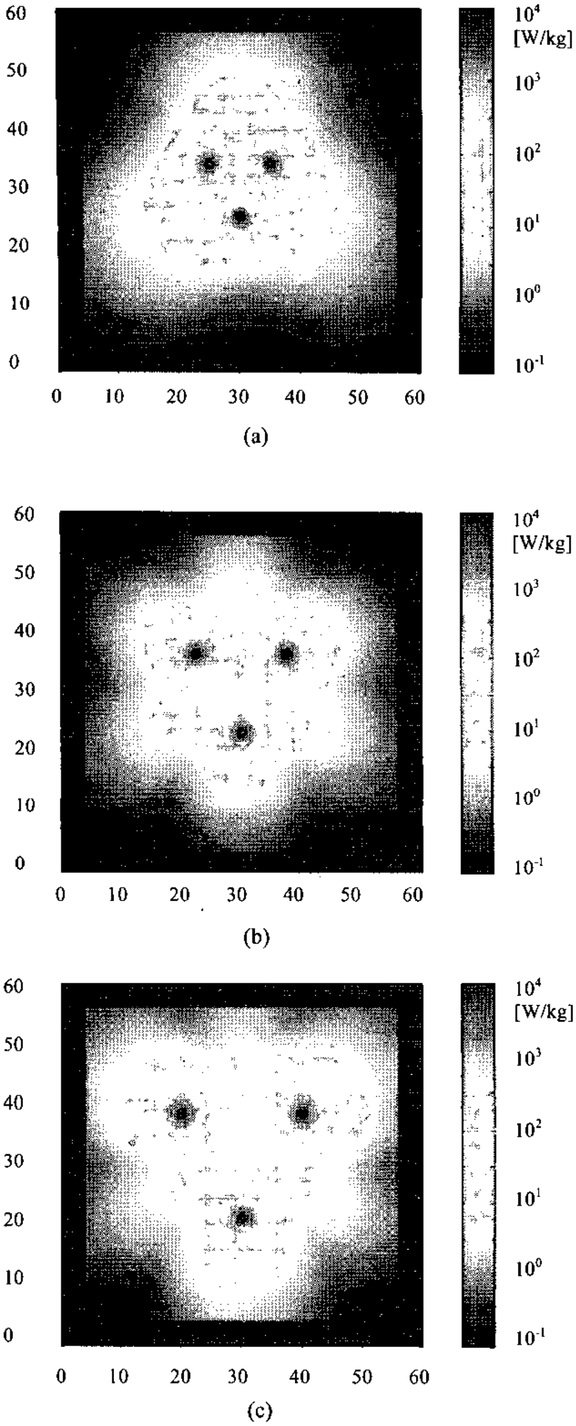

Fig. 3. SAR distribution over horizontal sections perpendicular to the antenna axes for a total radiated power of 1.0 W. (a) 10 mm, (b) 15 mm, (c) 20 mm antenna spacing. Dimensions are in mm.

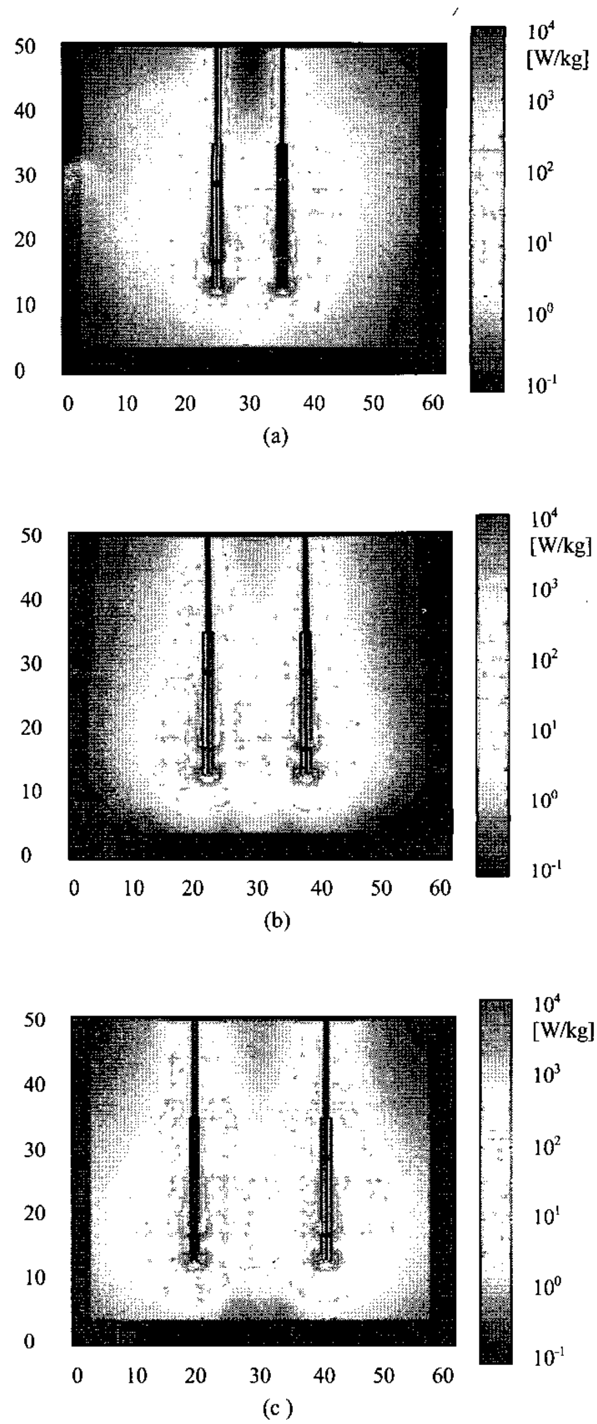

Fig. 4 SAR distribution over vertical sections for a total radiated power of 1.0 W. (a) 10 mm, (b) 15 mm, (c) 20 mm antenna spacing. Dimensions are in mm.

TABLE I
VARIATION OF SAR INSIDE A 3-MM RADIUS SPHERE

Antenna spacing (mm)	**SAR_{MAX} (W/kg)**	**SAR_{MIN} (W/kg)**	**SAR_{MED} (W/kg)**	**SAR_{SD} (W/kg)**	**SAR_{SD} / SAR_{MED}**
10	700	130	202.16	41.45	0.20
15	71	40	56.81	6.82	0.12
20	25	7.8	17.03	4.30	0.25

IV. CONCLUSIONS AND DEVELOPMENTS

A graded-mesh FDTD code has been used for studying triangular arrays of sleeved-slot antennas. The study demonstrates the ability of a triangular array of 15 mm spacing to produce the most uniform power deposition, with respect to the 10 and 20 mm cases, in a spherical volume placed at the center of the array.

As a further development, the graded-mesh FDTD code will be used for studying anatomical inhomogeneous phantoms in which a tumor region will be modeled. Moreover, an alternate direction implicit (ADI) solution of the bio-heat equation is under development and it will be applied to evaluate temperature increase induced by interstitial arrays in inhomogeneous phantoms. Purpose will be the optimization of the array geometry towards uniform temperature increases in a brain tumor region.

REFERENCES

[1] B. Stea, J.Kittleson, and J.R. Cassady, "Treatment of malignant glioma with interstitial irradiation and hyperthermia," *Int. J. radiat. Oncol. Biol. Phys.*, vol. 24, pp. 657-667, 1992.

[2] J.C. Lin, S.Hirai, C.L. Chiang, W.L. Hsu, Y.J.Wang, "Computer simulation and experimental studies of SAR distributions of interstitial arrays of sleeved-slot microwave antennas for hyperthermia treatment of brain tumors," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-48, no. 11, pp. 2191-2197, November 2000

[3] P. Bernardi, M. Cavagnaro, S. Pisa, and E. Piuzzi, "A graded-mesh FDTD code for the study of human exposure to cellular phones equipped with helical antennas", *ACES Journal*, vol.16, pp. 90-96, July 2001.

[4] A. Taflove and S.C. Hagness, *Computational Electrodynamics: the Finite-Difference Time-Domain Method*, Artech House: Boston, MA, 2000.

[5] S.D. Gedney, "An anisotropic perfectly matched layer-absorbing medium for the truncation of FDTD lattices," *IEEE Transactions on Antennas and Propagation*, vol. AP-44, pp. 1630-1639, 1996.