

Modeling Twin Pregnancy: A Nonspherical Bioelectromagnetic Model

I. I. Doulgerakis¹, A. A. Varvari¹, D. I. Karatzidis¹, T. T. Zygidis², and N. V. Kantartzis¹

¹Dept. of Electrical & Computer Eng., Aristotle Univ. of Thessaloniki, Thessaloniki 54124, Greece, kant@auth.gr

²Dept. of Electrical & Computer Eng., Univ. of Western Macedonia, Kozani 50100, Greece, tzygidis@uowm.gr

This paper presents an effective methodology for constructing nonspherical models of the female torso being pregnant with twins and calculating the electric field when it is subjected to radiation from an external point source. The proposed model is described by spherical shapes for the representation of the various tissues, whereas the electric field is derived via a hybrid computational scheme, which involves dyadic Green's functions as well as the implementation of the appropriate surface boundary conditions and the superposition principle. Numerical results provide instructive deductions for a realistic model-antenna interaction and particularly for the precise evaluation of the electric-field intensity at every point in the domain with regard to diverse polarizations.

Index Terms—Bioelectromagnetics, computational electromagnetics, Green's functions methods.

I. INTRODUCTION

THE rapidly expanding wireless technologies have frequently been the subject of considerable debate regarding their potential negative impact to human health [1]. Recently, various studies have shown that a vulnerable group to the possible harmful effects of RF exposure is pregnant people and, by extension, fetuses [2]. As a consequence, there is an increasing need for simplified, accurate, and computationally affordable bioelectromagnetic models to thoroughly investigate the impact of RF technologies on such populations.

The objective of this paper is to present a simplified and yet accurate model for the effective computation of the electromagnetic fields surrounding the pregnant female torso in the case of twins. The presented model simulates the torso with spheres and spherical layers, enabling economical discretizations, while supporting the rigorous evaluation of the involved quantities via a dyadic Green's functions (dGfs) hybrid numerical technique, which provides fast, reliable, and very economical results.

II. DEVELOPMENT OF THE PROPOSED TORSO MODEL

A qualitative representation of the generalized model of the pregnant female torso with two fetuses is illustrated in Fig. 1. The first three layers simulate skin (S_1), fat (S_2), and muscle (S_3) tissues. Inside the muscle layer, two non-overlapping eccentric spheres depict the breasts (S_4, S_5). Moreover, at the core, another concentric host sphere describes the torso organs (S_6), the uterus (S_7) and the fetuses-amniotic fluid-placenta system (S_8, S_9). Each component of the model is defined by an outer radius ρ_i and/or a thickness w_i , for $i = 1, 2, \dots$, to characterize its maximum length/dimension. The concentric inclusions originate at origin O , while the eccentric ones at the O_j origin, defined by the $\mathbf{d}_j$ vectors, for $j = 4, 5, 7, 8, 9$. Each part is described by a lossy dielectric medium with complex electric permittivity $\tilde{\epsilon}_i$ and a wavenumber $k_i = \omega\sqrt{\mu_0\tilde{\epsilon}_i}$ for $i = 1, 2, \dots$, while $k_0 = \sqrt{\mu_0\epsilon_0}$ stands for the free space. Lastly, the point source is located at the $\mathbf{r}'$ point, originating from O . It is stressed that throughout our analysis, the harmonic time dependence $e^{-j\omega t}$ is assumed and suppressed for simplicity.

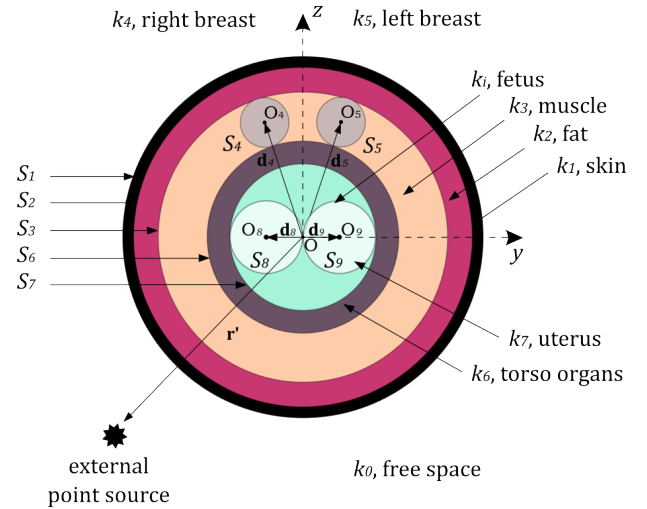


Fig. 1. Cross-section of the generalized model of a pregnant female torso with twins, described by the two non-overlapping spheres S_8 and S_9 .

III. DERIVATION OF THE HYBRID TECHNIQUE

The new hybrid formulation starts by defining the proper dGf in every layer of our scattering problem. In free space, the solution of the dyadic Helmholtz equation is $\bar{\bar{\mathbf{G}}}_{e,s}^{(0)}$, which generates the electric field of an external source. Thus we write $\nabla \times \nabla \times \bar{\bar{\mathbf{G}}}_{e,s}(\mathbf{r}, \mathbf{r}') + k_0^2 \bar{\bar{\mathbf{G}}}_{e,s}(\mathbf{r}, \mathbf{r}') = \bar{\bar{\mathbf{I}}} \delta(|\mathbf{r} - \mathbf{r}'|)$, where $\bar{\bar{\mathbf{I}}}$ is the unit dyad. Based on the main concepts of the Ohm-Rayleigh method [3], the required $\bar{\bar{\mathbf{G}}}_e$ function is written as

$$\bar{\bar{\mathbf{G}}}_e(\mathbf{r}, \mathbf{r}') = -\frac{1}{k_0^2} \hat{\mathbf{r}} \hat{\mathbf{r}}' \delta(\mathbf{r} - \mathbf{r}') + j \frac{k_0}{4\pi} \sum_{\alpha, m, n} c_{mn} \mathbf{F}_{\alpha, mn}^{(1)}(k_0 \mathbf{r}) \mathbf{F}_{\alpha, -mn}^{(3)}(k_0 \mathbf{r}'), \quad (1)$$

(for $r \leq r'$, otherwise $\iota = 1, 3$ must be interchanged) where $\hat{\mathbf{r}}, \hat{\mathbf{r}}'$ are unit vectors along $\mathbf{r}, \mathbf{r}'$, with $n = 1, 2, \dots$ and $m = -n, -n+1, \dots, n-1, n$, and $c_{mn} = (-1)^m \frac{2n+1}{n(n+1)} = c_{-mn}$. The α type index defines the kind of spherical harmonic and for $\alpha = M, N$, vector functions $\mathbf{F}_{\alpha, mn}^{(\iota)}(k\mathbf{r})$, in the different layers of the featured torso model, are given by

TABLE I
TORSO MODEL PARAMETERS AT THE FREQUENCY OF 2.6 GHz

Body part	Outer radius (mm)	Eccentricity or thickness (mm)	Complex relative permittivity
Skin	$\rho_1 = 292$	$w_1 = 1$	$\epsilon_1 = 37.8 + j10.6$
Fat	$\rho_2 = 291$	$w_2 = 5$	$\epsilon_2 = 10.8 + j2$
Muscle	$\rho_3 = 286$	$w_3 = 0$	$\epsilon_3 = 52.5 + j12.7$
Right breast	$\rho_4 = 58$	$d_4 = 200$	$\epsilon_4 = 5.1 + j1$
Left breast	$\rho_5 = 58$	$d_5 = 200$	$\epsilon_5 = 5.1 + j1$
Torso organs	$\rho_6 = 170$	$w_6 = 116$	$\epsilon_6 = 43.68 + j14$
Uterus	$\rho_7 = 160$	$w_7 = 10$	$\epsilon_7 = 57.6 + j16.3$
Fetus	$\rho_{8,9} = 80$	$d_{8,9} = 80$	$\epsilon_{8,9} = 43.4 + j12.86$

$$\mathbf{F}_{M,mn}^{(\iota)}(k\mathbf{r}) = \mathbf{M}_{mn}^{(\iota)}(k\mathbf{r}) = z_n^{(\iota)}(kr) \left(jm \frac{P_m^n(\cos \theta)}{\sin \theta} \hat{\theta} - \frac{dP_m^n(\cos \theta)}{d\theta} \hat{\varphi} \right) e^{jm\varphi}, \quad (2)$$

$$\mathbf{F}_{N,mn}^{(\iota)}(k\mathbf{r}) = \mathbf{N}_{mn}^{(\iota)}(k\mathbf{r}) = k^{-1} \nabla \times \mathbf{M}_{mn}^{(\iota)}(k\mathbf{r}), \quad (3)$$

where $z_n^{(\iota)}(kr)$ is a spherical Bessel ($\iota = 1$) or Hankel ($\iota = 3$) function of the first kind and $P_m^n(\cos \theta)$ is an associated Legendre function of the first kind [4].

Herein, the dGf depends on two spatial factors, $\mathbf{r}$ and $\mathbf{r}'$ for the model and point source region, respectively. The latter are independent, i.e. they may originate from different coordinate systems and end at different areas. According to [5] and by defining V_i ($i = 1, 2, \dots$) as the region of space between two surfaces, S_{in} and S_{out} , the electric dGf in V_i includes three terms and is expressed as $\bar{\mathbf{G}}_e^{(i)}(\mathbf{r}, \mathbf{r}') = \bar{\mathbf{G}}_{in}^{(i)}(\mathbf{r}, \mathbf{r}') + \bar{\mathbf{G}}_{out}^{(i)}(\mathbf{r}, \mathbf{r}') + \bar{\mathbf{G}}_s^{(i)}(\mathbf{r}, \mathbf{r}')$, with $\bar{\mathbf{G}}_{in}^{(i)}(\mathbf{r}, \mathbf{r}')$, $\bar{\mathbf{G}}_{out}^{(i)}(\mathbf{r}, \mathbf{r}')$, $\bar{\mathbf{G}}_s^{(i)}(\mathbf{r}, \mathbf{r}')$ due to S_{in} , S_{out} and the source, respectively. In this framework, the electric-field intensity (EFI) in V_i is obtained from

$$\mathbf{E}^{(i)}(\mathbf{r}) = j\omega\mu_0 \int_{V_i} \bar{\mathbf{G}}_e^{(i)}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{J}^{(i)}(\mathbf{r}') dV, \quad (4)$$

with $\mathbf{J}^{(i)}(\mathbf{r}')$ the electric-field current density of the external source at $\mathbf{r}'$.

IV. NUMERICAL VERIFICATION

To verify the proposed method, we select the dimensions and electric permittivity (at 2.6 GHz) for each torso part of Table I. All reference results are acquired through the ANSYS HFSS computational software [6] for a fully-discretized torso with twins of a realistic female human body, considering a dipole $\lambda/2$ near the body and oriented either parallel to the x -axis (parallel source) or parallel to the z -axis (perpendicular source). In this context, Fig. 2 illustrates the EFI in the free space, at ρ_1 , corresponding to the position of the waistline in the model, while Fig. 3 shows the EFI around the torso at the xOy plane (torso middle cross-section) for both sources. As observed, the outcomes of the hybrid method and the new torso model are in promising agreement with the reference data.

Comparing the free-space results with those acquired in the presence of the model, we can deduce that the EFI levels are significantly different. Furthermore, the patterns for both sources are found to be similar, with the EFI level following peaks and troughs along the waistline and receiving the highest

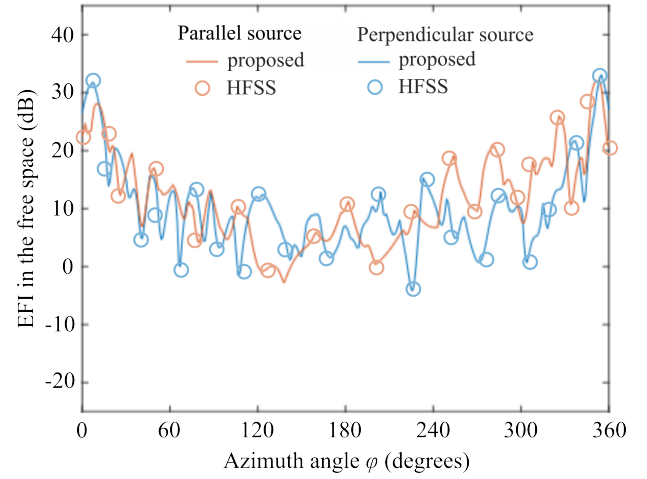


Fig. 2. Electric-field intensity in free space at $r = \rho_1$ (position of the waistline in the model), for parallel and perpendicular source, at $r = 1.1\rho_1$, $\varphi = 0$ (clockwise from y -axis), and $\theta = 90^\circ$ (clockwise from z -axis).

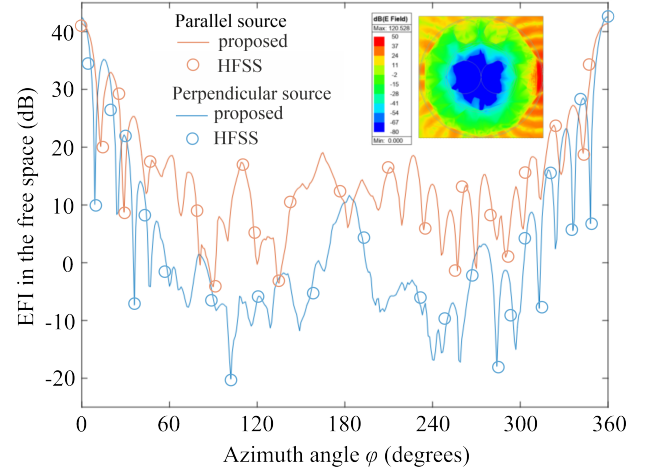


Fig. 3. Electric-field intensity for the pregnant, with twins, female torso on the waistline, for parallel and perpendicular source, at $r = 1.1\rho_1$, $\varphi = 0$ (clockwise from y -axis) and $\theta = 90^\circ$ (clockwise from z -axis). The inlet plot shows an EFI map at a cross-section of the proposed torso model.

value closest to the source. Note that the EFI of the parallel source is consistently higher throughout the angular space.

Finally, the inlet surface plot of Fig. 3 presents an EFI map of the model's cross-section. As promptly observed, the exterior layers experience higher levels of radiation, with the latter diminishing progressively through the internal layers.

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