Development of a FDTD Simulator for the Calculation of Temperature Rise in Human Heads from Mobile Phones Operation

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Abstract. In this work a complete software tool, which uses the finite-difference time-domain (FDTD) method, was developed from scratch. This tool comprises a full three-dimensional (3D) wave electromagnetic simulator and a bioheat equation solver. The application of this tool, using an anatomically based model of the human head, allows the electromagnetic and thermal analysis of a head exposed to the radiation of a mobile phone, through the determination of the specific absorption rate (SAR). Preliminary results show good agreement with previous published numerical and measurement results taken for similar formulations.

Keywords: Biological effects of electromagnetic radiation, Finite difference time domain (FDTD), bioheat equation, anatomic model of the head, cellular telephones, temperature increase, specific absorption rate (SAR).

1 Introduction

In recent years, the generalized use of mobile radio systems had as a result to increase the public concern regarding the hazards from handheld terminals. These terminals, known as mobile phones, emit electromagnetic fields and operate in close proximity to the human head. Although a lot of work has been done on SAR estimations, only in a few recent studies there have been attempts to include the biological and physical mechanisms of heat transfer in conjunction with the Maxwell equations, which describe the electromagnetic energy propagation around and within the exposed human head. Wang [1] calculated the SAR and temperature increase distributions due to an approximate mobile phone model consisting of a quarter-wavelength monopole over a conducting box. Bernardi [2] calculated SAR and temperature increase for four different approximate mobile phone models irradiating an anatomical model of the human head. Hirata [3], Rodriguez [4] and Kim [5] examined the influence of a half-wavelength dipole near head models. In all of these studies the anatomical models (when used) were simplified consisting of 6-18 tissue types. In addition, most of these

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studies [1-5] do not agree with each other in their findings, which calls for additional investigations to be performed with more detailed anatomical models. In this work, both electromagnetic and thermal simulations of a highly detailed anatomical head model exposed to the fields of an approximate mobile phone model were performed. The resulting SAR and temperature increase where extracted and compared to results from other studies.

2 Description of the Process

The used human head is based on a segmented anatomical model obtained from [6]. This model, developed from Computer Tomography (CT) image data of a human head, has a resolution of 4×4×4 mm cubic cells. In the form that it was used in this work it includes 26 distinct different tissues and every cubic cell contains only one tissue, which makes it very efficient for FDTD simulation. The dielectric and thermal parameters of the involved tissues for the desired frequency were based on similar studies found in bibliography [7]. The handheld phone is modeled as a monopole antenna on a dielectric covered metal box and it is the same used in previous works [1, 2]. The temperature rise in this work is computed in two steps. During the first step, the electromagnetic problem is solved, where from the solution of Maxwell equations using the FDTD method the electromagnetic fields are calculated [1]. From these fields the distribution of SAR in the human head is evaluated. On the second step, the thermal problem is treated, where the determination of temperature rise is evaluated by solving the bioheat equation. The temperature increase is calculated as the difference between the temperature distribution of the head during thermal equilibrium with and without exposure to the EM fields of the mobile phone. The Pennes bioheat equation [2], which accounts for various heat-exchange mechanisms such as heat conduction, blood flow and electromagnetic heating, is also solved through the FDTD method. Considering the fact that the temperature rise due to handheld phones operation is not sufficient to cause a significant change on the electric parameters of tissues, the steady state SAR distribution is used as the input electromagnetic heating source into the bioheat equation. Validation of the EM solver was performed by calculating the complex input impedance of dipoles for different frequencies and comparing it to analytically derived results provided by textbooks and the numerically calculated results from commercial FDTD software packages. The observed error was less than 5%.

3 Simulation Results

For the purposes of this work, as well as for other similar cases, an electromagnetic and a thermal simulator were developed from scratch. Based on Python, the open source programming libraries NumPy and SciPy for the core computational and numerical needs, and the Visual Tool Kit for visualization and post processing needs were used.

The electromagnetic solver is a full wave 3D FDTD electromagnetic simulator, capable of solving the Maxwell equations, based on the standard E-H paradigm. It was flexibly developed to simulate any properly defined electromagnetic problem, such as waveguide and antenna design cases, or to evaluate biomedical applications, such as wave-tissue interaction to biomedical implant safety assessment. The discretized partial differential equations were solved on a uniform rectangular grid. The truncation of the generally unbounded computational domain was achieved using a combination of 1st and a modified version of the 2nd order Mur absorptive boundary conditions in order to keep the computational resource requirements to a minimum. These were discretized using upwind finite differences to counter the late-time instabilities, that is the spurious values at the domain boundaries which occur when using centered finite differences to discretize the Mur equations, effectively countering this error source. The power radiated from the phone has been computed on the basis of the feed point impedance.

The thermal solver implementing the bioheat equation for the calculation of the absolute temperature and the temperature increase of a 3D electromagnetically irradiated geometry was also developed from the ground-up. Starting from the evaluated SAR distribution, the thermal response as a function of time, until the steady state is reached, has been calculated through an explicit finite difference formulation on the bioheat equation. This equation was formulated to account for the metabolic heat generation as well as the cooling effect of blood according to the model proposed in [8]. Figs. 1-3 present some results from the application of the method. For a 910 MHz mobile phone with antenna output of 250 mW, which is the output of a GSM900 mobile phone, Fig. 1 shows the total electric field distribution in a vertical cross section, Fig. 2 shows the 1-gr-averaged SAR's distributions and Fig. 3 shows the temperature rise distributions, all for a vertical cross section which includes the monopole antenna. The achieved values are compared well with results found in literature for similar cases. Using a mobile phone operating at 900 MHz with antenna output at 600 mW, which radiates at a distance of 16 mm from the head, the 1-gr-averaged SAR maximum value was evaluated to 3.2 W/kg while the maximum temperature rise was 0.43 ºC, for the whole head. Table 1 shows the comparison between the results of this study and those from other publications.

Table 1. Comparison between the results of this study and those from other publications

	Head 1g SAR [W/Kg]	**Head Temperature Increase [C]**	**Brain 1g SAR [W/Kg]**	**Brain Temperature Increase [C]**
Current Study	3.20	0.43	2.03	0.16
Wang [1]	1.60	0.16	0.89	0.05
Bernardi [2]	2.74	0.33	1.85	0.19
Hirata [3]	2.10	0.80	1.20	0.8
Kim [5]	2.84	0.50	1.76	0.24

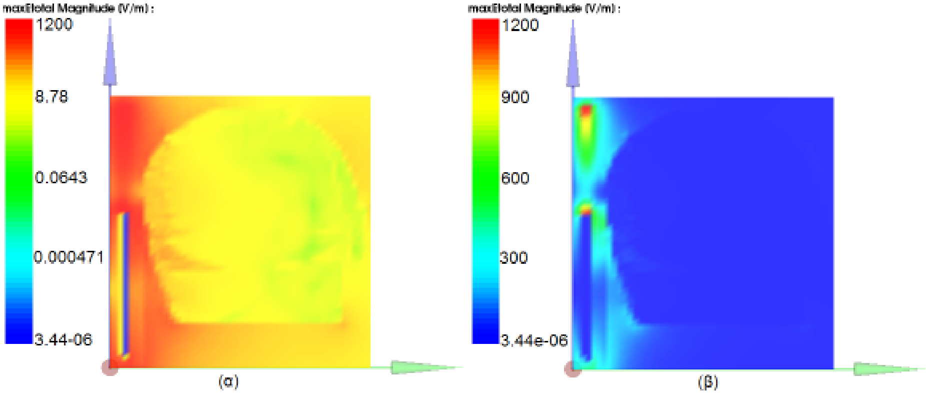

Fig. 1. Total electric field distributions in a vertical cross section for a 910 MHz mobile phone with antenna output of 250 mW (a) linear and (b) chromatic view

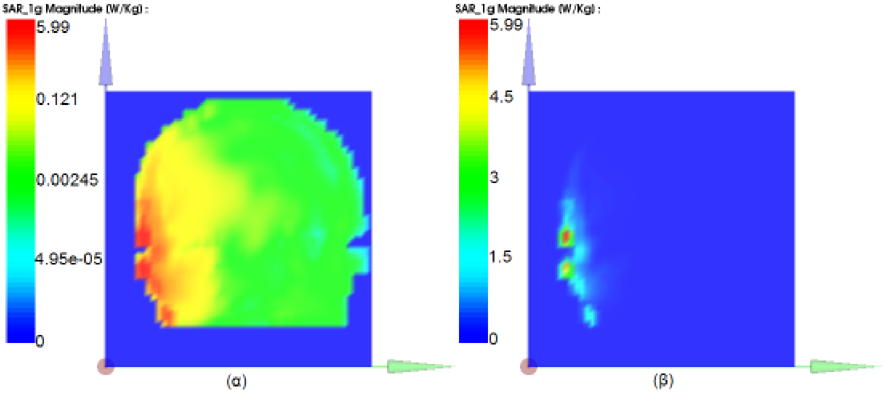

Fig. 2. 1-gr- averaged SAR's distributions in a vertical cross section, for a 910 MHz mobile phone with antenna output of 250 mW (a) linear and (b) chromatic view

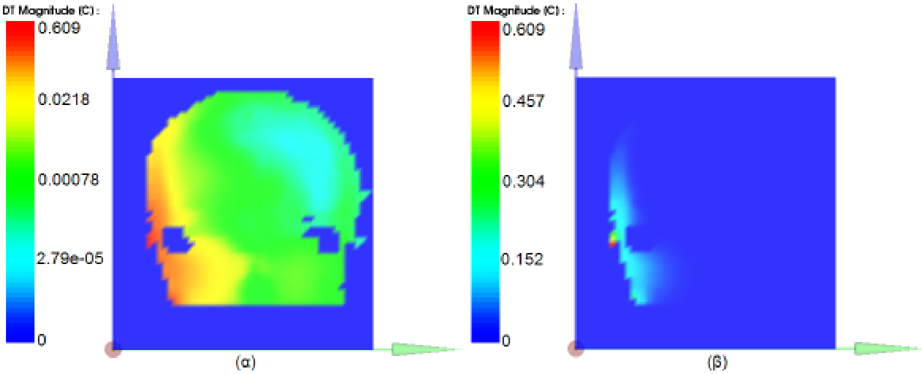

Fig. 3. Temperature distributions in a vertical cross section, for a 910 MHz mobile phone with antenna output of 250 mW (a) log and (b) linear scale

4 Conclusions

The electromagnetic and thermal analysis of a head exposed to the radiation of a mobile phone, through the determination of the specific absorption rate (SAR) was performed, by using a combination of an electromagnetic and thermal solver, both working using the FDTD method. These solvers were developed from the beginning and their application proved their validity. Preliminary results show good agreement with previous published numerical and measurement results [1-5].

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