Numerical SAR and Temperature Analysis in RF EM Fields Exposed Vial Set-ups of Peripheral Blood Lymphocytes

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Numerical electromagnetic and thermal dosimetry is carried out in order to characterize the exposure conditions of blood cells in a GTEM cell. Blood cell suspension stored in 15 ml test tubes is subjected to radiofrequency electromagnetic waves. Specific absorption rate calculations are performed for tubes being E-, H-, and K-polarized at 900 MHz, 1800 MHz and 2450 MHz. For a selected arrangement that shows satisfactory SAR uniformity, SAR and temperature distributions inside cell medium are presented and discussed.

Long Abstract

I. INTRODUCTION

Mobile communication systems have characterized the technological development of the whole world. Consequently, intense public concern has been triggered about the potential adverse health effects of radiofrequency (RF) electromagnetic radiation. In this basis, numerous scientific research studies have been carried out in order to assess possible health hazards due to human's exposure to RF electromagnetic fields (EMF).

In particular, the evaluation of potential biological effects of RF electromagnetic waves at cellular level has attracted scientific interest since DNA damage can lead to cancer. Several research studies have been conducted in order to estimate possible biological damage at cellular level due to exposure to EMF at mobile communication frequencies [1], [2].

In our study, a gigahertz transverse electromagnetic wave (GTEM) cell will be used for biological experiments evaluating effects on peripheral blood lymphocytes due to the exposure at the typical frequencies of mobile communication systems and wireless devices. The TEM mode propagating inside the GTEM cell produces uniform, free-space, plane-wave irradiation in the exposed sample area. This exposure set-up allows the investigation of biological effects over a wide frequency range.

Prior to RF electromagnetic irradiation, it is important to carry out a numerical dosimetry study of the experimental procedure, which will enable the detailed characterization of the exposure conditions. This paper describes a numerical dosimetric analysis for the assessment of the amount of the electromagnetic power absorbed by the biological samples and the induced temperature elevation due to RF exposure. The cell-filled test tube is positioned parallel to the E, H and K directions of the propagating electromagnetic field, respectively, at 900 MHz, 1800 MHz and 2450 MHz, in order to evaluate average specific absorption rate (SAR), SAR uniformity and exposure efficiency. For a selected arrangement, the SAR distribution and the temperature increase induced inside the cell medium are estimated for a single-tube and a 12-tube exposure set-up.

II. NUMERICAL DOSIMETRY

A. Electromagnetic Simulations

At mobile frequencies, the dosimetry is expressed through the measurement of the SAR. SAR is quantified as the absorbed electromagnetic power divided by the biological tissue mass. In cell
solutions cultured as a suspension, the SAR distribution is estimated over the entire volume of cell medium, and should be as uniform as possible [3]. Notably, the SAR distribution is expressed through its mean value and its standard deviation (SD), computation of which provides a good insight into SAR heterogeneity. SAR heterogeneity is defined as the ratio of SAR SD to average SAR and should be less than 30% [4], [5].

The SAR distribution inside the blood sample is numerically estimated based on the finite-difference time domain (FDTD) calculation method, using the software package SEMCAD X [6]. Local SAR values are assessed by electric field calculations in the cell medium under exposure.

In our work, a continuous, plane-wave source is used as an electromagnetic field source to reproduce the uniform, planar electromagnetic field generated at the far-field region inside the GTEM cell. A 15 ml dielectric test tube filled with 5 ml blood cell solution is employed and placed inside the uniform electromagnetic field generated by the plane wave source. The physical and dielectric properties of the test tube and the blood sample, considered as a dielectric material, are listed in Table 1.

Fig. 1(a) illustrates the geometrical model of the test tube and the blood cell solution. The thickness of the polypropylene tube is 0.7 mm and its internal diameter is 15 mm. The height of the cell medium is 35 mm. The FDTD mesh model of the cell medium varies from 0.2 mm to 0.5 mm.

The long axis of the test tube is oriented to E, H and K directions of the incident electromagnetic field, respectively, for three different frequencies of the electromagnetic wave centered at 900 MHz, 1800 MHz and 2450 MHz respectively. The average value of SAR, its standard deviation, SAR heterogeneity and exposure efficiency for the different exposure arrangements are shown in Table 2, where the electric field power density is normalized to 10 W/m². Exposure efficiency is defined as the ratio of average SAR to the input power of the GTEM cell.

The results demonstrate the dosimetry differences for the various exposure arrangements. It is clear that for each frequency, the arrangement with the highest exposure efficiency and the lowest heterogeneity in the cell suspension differs. For example, at 900 MHz frequency, the above requirements are achieved when the long axis of the test tube is oriented parallel to the direction of the electric field. The estimated average SAR is 0.176 W/kg and a satisfactory heterogeneity of 46% is performed. Calculated SAR distribution patterns evaluated within the biological sample through the E-K, E-H and H-K planes are depicted in Fig. 1(b). The maximum SAR is 0.417 W/kg and appears at the periphery of the cell medium, as shown in the E-K and H-K planes.

Moreover, Fig. 1(c) shows the SAR distribution of 12 test tubes distributed in a 3*4 matrix. The distance between the centers of neighbouring tubes is 30 mm and the respective lids are separated by 12 mm. It is obvious, that there is a slight variation in the average SAR of each tube. The test tubes of series C present the highest average SAR and SAR uniformity of 46%. The total average SAR is 0.12 W/kg and the heterogeneity is 56%. The difference in the average SAR distribution between the single-tube and 12-tube exposure set-up may be attributed to the interaction of the scattered electromagnetic waves from one tube with the scattered waves from a neighbouring one.

B. Thermal Simulations

One of electromagnetic waves induced effects is a temperature elevation over the whole volume of the cell medium; consequently modeling and simulating the resulting thermal distribution is important. Temperature distributions are evaluated by numerical calculations of the bioheat conduction equation. The formula is shown below and assigns the local temperature increase of the biological sample to the deposited electromagnetic power:

\[ \rho c \frac{\partial T}{\partial t} = \nabla (k \nabla T) + \rho SAR \]  

(Eq. 1)

where \( T \) is the temperature (°C), \( k \) is the thermal conductivity (W/m°C), \( c \) is the specific heat capacity (J/kg °C), \( \rho \) is the density of the biological medium and SAR is the specific absorption rate, obtained by the electromagnetic simulations.
Convective boundary conditions are defined at the interface between the cell solution and the air and, at the interface between the test tube and the air expressed by the following equation:

\[-k \frac{\partial T}{\partial t} = h(T - T_{\text{air}}) \tag{Eq.2}\]

where \(h\) is the heat transfer coefficient (W/m\(^2\)°C) on the boundary and \(T_{\text{air}}\) is the air temperature. The temperature distribution inside the cell medium is evaluated by using these equations with an explicit finite-differential method. Thermal parameters of materials are listed in Table 1 and the initial temperature is fixed at room temperature [7].

The selected arrangement for temperature assessment simulations is the following: the cell-filled test tube is parallel to the direction of electric field, for power density of 53 W/m\(^2\) at 900 MHz. Absorbed electromagnetic waves of such power density leads to a local maximum temperature rise of 0.1 °C inside the cell medium. This is a critical value of temperature rise in RF-exposed cell mediums in order to avoid thermal effects due to electromagnetic exposure.

Fig. 2(a) shows the temperature distributions in the cell suspension, through the E-K, E-H and H-K planes, for 1 hour exposure time. The calculated average temperature over mass is 25.066 °C. Fig. 2(b) depicts the time-varying local maximum temperature rise in the cell medium. Furthermore, Fig. 2(c) shows the temperature distribution for the simultaneous exposure of the array of the test tubes, maintaining the same exposure arrangement. The calculated total average temperature is 25.045 °C. The test tubes of series C presents a higher temperature rise than the other test tubes, which is consistent with their respective higher average SAR value.

ACKNOWLEDGEMENT

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REFERENCES


Figure 1. SAR distribution patterns in the cell-filled tube model. (a) Geometry of the cell-filled test tube. (b) SAR distributions in the tube center through E-K, E-H and H-K planes for an incident E-field of 10 W/m². (c) SAR distributions in the 12-tube matrix.

Figure 2. Temperature distribution patterns in the cell-filled tube model. (a) Temperature distribution in the tube center through E-K, E-H and H-K planes for an incident E-field of 53 W/m². (b) Time-varying local maximum temperature rise in the cell medium. (c) Temperature distribution in the 12-tube matrix.

Table 1. Dielectric, physical and thermal properties of materials used at 900 MHz in room temperature.
Figure 2. Temperature distribution patterns in the cell-filled tube model. (a) Temperature distribution in the tube center through E-K, E-H and H-K planes for an incident E-field of 53 W/m$^2$. (b) Time-varying local maximum temperature rise in the cell medium. (c) Temperature distribution in the 12-tube matrix.

Table 1. Dielectric, physical and thermal properties of materials used at 900 MHz in room temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Permittivity $\varepsilon_r$</th>
<th>Conductivity $\sigma$ [S/m]</th>
<th>Density $\rho$ [kg/m$^3$]</th>
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<tr>
<td>Cell suspension</td>
<td>61</td>
<td>1.5</td>
<td>1.050</td>
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<td>Test tube</td>
<td>2.25</td>
<td>-</td>
<td>1.100</td>
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<th>Material</th>
<th>Specific heat capacity $c$ [W/kg °C]</th>
<th>Thermal conductivity $k$ [W/m °C]</th>
<th>Convection coefficient $h$ [W/m$^2$ °C]</th>
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<td>3.600</td>
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<td>Test tube</td>
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<td>0.12</td>
<td>41</td>
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Table 2. Electromagnetic dosimetry results at 900 MHz, 1800 MHz and 2450 MHz with electric field density power of 10 W/m².

<table>
<thead>
<tr>
<th>Tube orientation</th>
<th>E</th>
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<th>K</th>
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<tbody>
<tr>
<td>Average SAR (W/kg)</td>
<td>0.176</td>
<td>0.024</td>
<td>0.038</td>
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<td>SAR SD (W/kg)</td>
<td>0.081</td>
<td>0.012</td>
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<tr>
<td>SAR heterogeneity (%)</td>
<td>46</td>
<td>49</td>
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<td>Exposure efficiency (%)</td>
<td>0.103</td>
<td>0.014</td>
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<tr>
<td>Average SAR (W/kg)</td>
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<td>0.334</td>
<td>0.745</td>
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<td>Exposure efficiency (%)</td>
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<td>0.44</td>
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<th>Tube orientation</th>
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