Numerical and Experimental Approaches to Millimeter-Wave Dosimetry for *in vitro* Experiments

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***Abstract*—The main purpose of this paper is to provide numerical and experimental dosimetry data for *in vitro* bioelectromagnetic experiments at millimeter waves. Numerical field-based and experimental temperature-based approaches were implemented in order to determine the average specific absorption rate (SAR) values in typical biological samples commonly used in bioelectromagnetic studies. It was shown that for frequencies ranging from 42 to 64 GHz and for an incident power density of 1 mW/cm^2 the average SAR within a cell monolayer located in a 24-well tissue culture plate is in the range of 13-15 W/kg.**

I. Introduction

INCREASING interest to the potential biological effects of millimeter-wave radiations mainly result from the emerging near-future applications of the 57-64 GHz frequencies in short-range wireless communication systems. In this framework, the aim of a number of ongoing studies is to assess potential biological modifications at the cellular and sub-cellular levels and to estimate potential biological effects and health risks related to the environmental exposure to low-power millimeter waves. The existence of bioeffects is strengthened by the fact that some frequencies within the millimeter-wave frequency band are clinically used in several countries for therapeutic purposes. Whereas it was shown that thermal action of millimeter waves upon biological systems is primarily mediated by free water molecules, it is still not clear if this or any other mechanisms could result in significant changes at the cellular or sub-cellular levels. To perform reliable and reproducible bioelectromagnetic experiments an accurate electromagnetic dosimetry in biological samples is necessary.

At millimeter waves, the major international standards and recommendations assign the limiting exposure values in terms of the incident power density because of the shallow penetration of millimeter waves in the biological tissues. However, for the accurate characterization of the exposure levels, particularly in case of *in vitro* experiments at the cellular level, data about the specific absorption rate (SAR) distribution within the biological sample are required. These data are critical for the reliable interpretation of the biological or biophysical results obtained experimentally.

In this study we utilized and compared both numerical field-based and experimental temperature-based methods to provide the data on the average SAR in the keratinocyte cell monolayers located in a 24-well tissue culture dish.

II. Methods

Model. We considered a standard 24-well tissue culture dish with the keratinocyte cell monolayer attached to the bottom of the well and covered by the culture medium. Fig. 1 shows the typical dimensions of a single well of a 24-well tissue culture plate. In the numerical modeling the well was irradiated from the bottom by a normally incident linearly-polarized plane wave. This model can be applied to experimental conditions where the tissue culture plate is located in the far-field region of the source (e.g. horn antennas, open-ended waveguides).

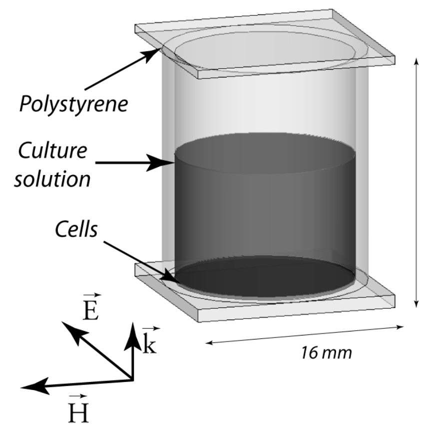

Fig. 1. Model of a single well of a 24-well tissue culture dish.

Dielectric characteristics. The dielectric characteristics of the structure must be defined carefully in order to determine an appropriate physical model for a reliable computation of the SAR. The dielectric properties of the model were determined for each material within the considered frequency range. Complex permittivity of the keratinocyte cells and culture medium were determined using Maxwell's mixture equation and free water permittivity data. The ionic conductivity of the culture medium was measured using a conductivity meter (WTW ProfiLine Cond 197i with a standard conductivity cell TetraCon® 325) and it was in a good agreement with literature data. The values of the dielectric permittivity, loss tangent, and ionic conductivity at 60 GHz for the materials and biological media considered in this study are summarized in Table I. All of the materials are assumed to be non-magnetic and isotropic.

Infrared thermometry. Infrared thermometry was used to determine the average SAR by passive measurements of the temperature rise dynamics of the sample exposed to millimeter waves. We used a gelatin gel with high viscosity as an

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Medium	Relative permittivity ϵ_r	Loss tangent $tan(\delta_l)$	Ionic conductivity σ_i (S/m)	Skin depth δ (mm)
Air	1	0	0	∞
Free water	16.11-24.17j	1.50	0	0.31
Polystyrene	2.56-0.003j	0.001	0	850
Culture medium	15.19-22.41j	1.48	1.5	0.33
Keratinocytes	10.94-14.53j	1.33	1.5	0.42

Table 1. Material properties used for computations at 60 GHz.

experimental model of cells and culture medium. The tissue culture plate containing the gelatin gel was exposed at 42.25 GHz under far-field conditions. The pyramidal horn antenna with aperture dimensions of 10.1 mm × 20.0 mm and maximal isotropic gain of 16.7 dB was located at a distance of 22 cm from the bottom side of the tissue culture plate. During the exposure the temperature distribution dynamics was monitored using an Amber 4256 infrared camera.

III. RESULTS

Two different approaches were applied and compared in order to obtain the average SAR within the cell monolayer. First, the average SAR was calculated based on the electric field value, conductivity, and mass density:

$$SAR = \frac{\sigma\left|\vec{E}\right|^2}{2\rho}$$

Electric field distribution was computed numerically. Then the results obtained using numerical field-based approach were compared with the SAR determined based on the initial temperature rise rate and specific heat capacity of the considered sample:

$$SAR = C\left.\frac{dT}{dt}\right|_{t=0}$$

Numerical field-based approach. Using finite element method we calculated the average SAR for a well exposed at several discrete frequencies selected according to their target applications for wireless communication and therapeutic purposes (Table 2). The incident power density was normalized to 1 mW/cm^2. Calculation of the SAR distribution within a given well of the 24-well tissue culture plate was accomplished by applying periodic boundary conditions. Our results show that for all considered frequencies the average SAR is in the 14±1 W/kg range. The power transmission coefficient as defined as the ratio of the average intensity of the internal EM field within the cell layer and the intensity of incident plane wave was found numerically and was equal to 0.55. The results obtained by the finite element method were in excellent agreement with the calculations performed using the finite integration technique considering the same model and exposure conditions.

Frequency range	Frequency, GHz	Average SAR, W/kg
Therapeutic frequencies	42.25	13.0
	53.57	14.8
	61.22	14.9
Wireless communications	57	14.9
	60	14.9
	61	14.8
	64	14.7

Table 2. Average SAR within a cell monolayer for the different exposure frequencies.

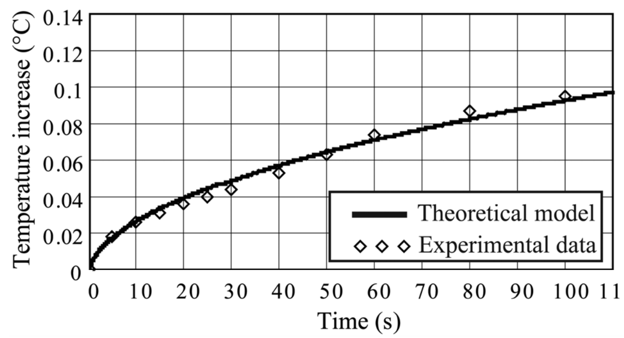

Fig.2 Temperature dynamics of one of the central wells of the exposed tissue culture plate.

Experimental temperature-based approach. To confirm the numerical results we compared the computed and measured values of the average SAR. The average near-surface SAR was determined indirectly by measuring the initial temperature rise rate in the exposed sample using infrared thermometry.

A 24-well tissue culture plate was exposed at 42.25 GHz for 100 seconds. The total radiated power was equal to 420 mW corresponding to a maximal power density of 3.2 mW/cm^2 at the level of the tissue culture plate. The temperature profiles were recorded every 5 seconds using an infrared camera. Then the average temperature for the central wells was calculated.

The initial rise rate of the near-surface temperature was determined by fitting the experimental heating dynamics to a theoretical thermal model based on the 1-D heat transfer equation (Fig. 2). The average SAR value normalized to the 1 mW/cm^2 of the incident power density was equal to 21.8 W/kg. The numerical calculation was performed for the well filled with the gelatin gel. The calculated average SAR was found to be 22.6 W/kg. The very good agreement with the measured SAR (relative deviation Δ=3.5%) confirmed the reliability of the numerical model and results.

IV. ACKNOWLEDGMENT

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