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Numerical Dosimetry to Estimate the Specific Absorption Rate in Some Insects Exposed to Radiofrequency Electromagnetic Fields up to 100 GHz

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Abstract Subject Area(s)

["Numerical dosimetry","RF/Microwave","MM Waves","Risk assessment"]

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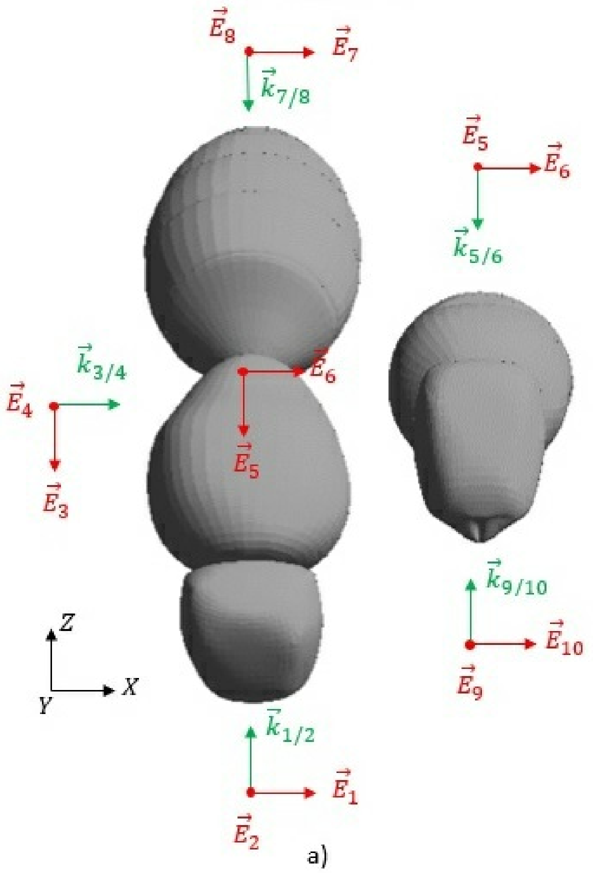
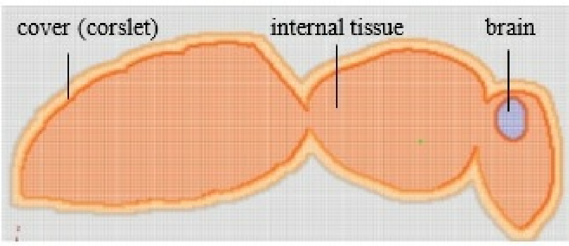


a)

Tissue Parameters	cover (corslet)		internal tissue		brain	
	ε	σ [S/m]	ε	σ [S/m]	ε	σ [S/m]
2.5 GHz	38.7	1.79	51.5	2.0	42.5	1.54
3.7 GHz	36.2	2.83	49.8	3.0	40.9	2.38
6 GHz	31.8	5.09	47.2	5.5	38.1	4.44
12 GHz	23.2	10.8	38.2	13.9	31.0	11.1
25 GHz	14.3	18.8	25.3	30.1	20.2	23.7
40 GHz	10.3	23.7	17.2	41.8	14.1	32.5
60 GHz	8.04	27.5	12.2	50.7	10.2	39.05
85 GHz	6.75	30.4	9.3	56.9	8.2	43.7
100 GHz	6.30	31.7	8.28	59.49	7.24	45.6
	density ρ [kg/m³]					
	1100		1061		1043	

b)



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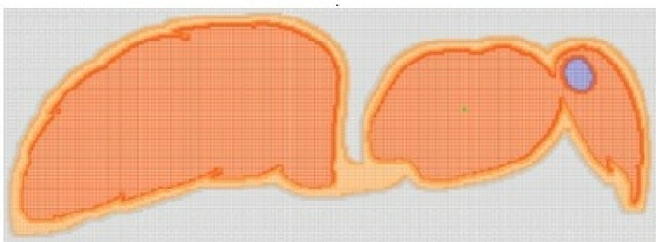

d)

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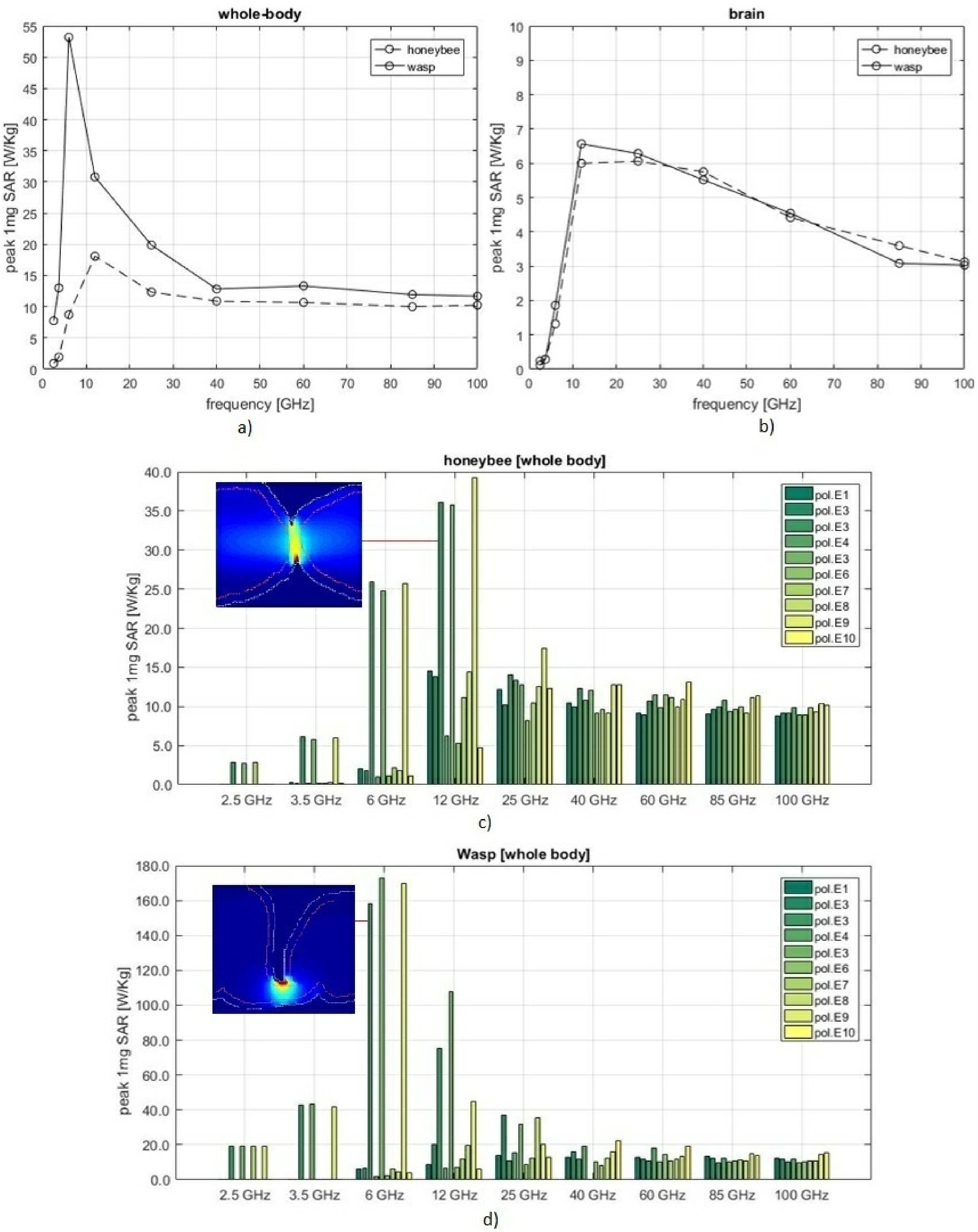

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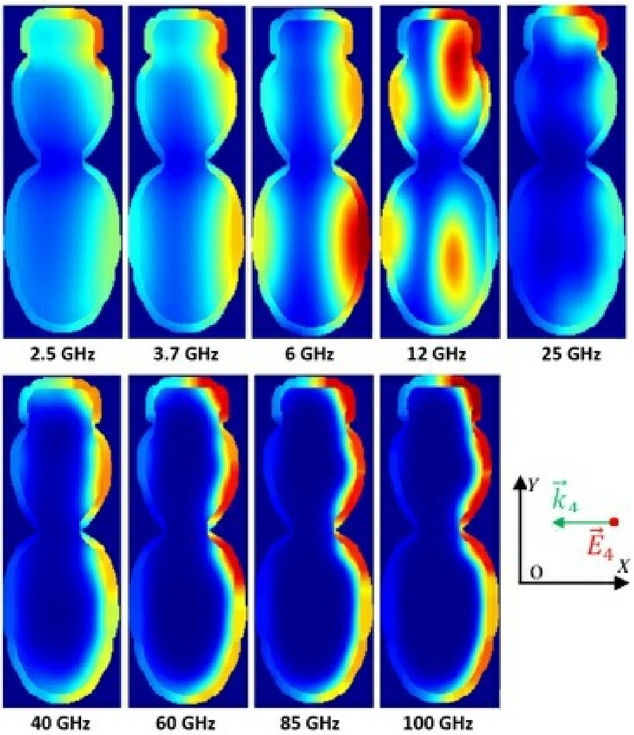
2.5 GHz
3.7 GHz
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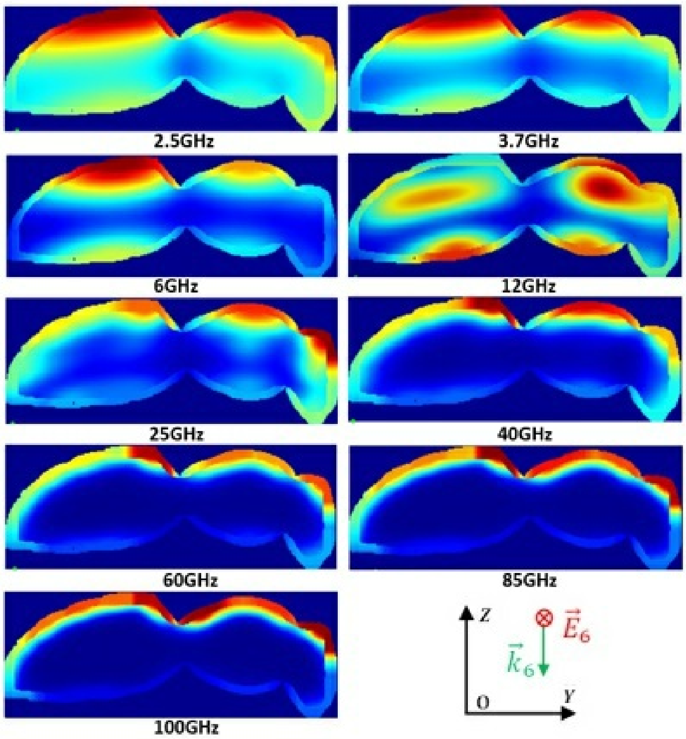
2.5GHz
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INTRODUCTION

Radiofrequency (RF) electromagnetic fields (EMFs) are emitted by telecommunication antennas. Presently, this mainly occurs at RF frequencies located between 100 MHz and 6 GHz [1]. Insects are exposed to these fields. A fraction of these fields is absorbed by their bodies. This absorption can have biological effects [2]. This absorption depends on the frequency [3, 4]. It is known that such RF absorption can be enhanced when a full-body or partial-body resonance occurs [5].

Investigating this insect exposure and its potential effects is important because insects, especially bees pollinate and thereby take part in the fertilization of 80% of all plant species, including vegetables, all kinds of fruits, and others [6]. Without pollination, these plants will disappear. This might break down important food chains. Other insects play an important role in the ecosystem as well in their role as pollinators, predators of other insects, and food for many birds, reptilians, and amphibians. Therefore, the investigation into the impact of RF-EMFs utilized in future telecommunication networks on insects is of great importance as the deployment of new networks in the environment could alter EMF exposure of insects.

RF absorption in insects has already been studied for particular insects at different individual frequencies: 2–300 GHz [3, 4]. These studies have shown that most insects show a maximal absorption of RF-EMF at frequencies above 6 GHz, where future telecommunication systems will also operate, due to a whole-body resonance. Future wavelengths of the EMFs used for wireless telecommunication systems will decrease and become comparable to the body size of insects and therefore, the absorption of RF-EMFs in these objects is expected to increase if the total incident power density remains unaltered. Up to now, only homogeneous insect models were used in such studies [3, 4], while it is known that insects are heterogeneous organisms consisting of tissues with different dielectric properties [2]. This research will validate whether these trends are still valid when considering heterogeneous dielectric insects.

The absorption of EMF energy in insects can cause dielectric heating [8] which can have biological effects [9]. RF heating of insects has been reviewed in [10-12]. Studies not necessarily aimed at investigating thermal effects of RF-EMF exposure exist as well [13-18].

[19] shows that EM radiation of mobile telecommunication antennas affects the abundance and composition of wild pollinators. The effect of EMF radiation emitted by mobile phones on insect’s population, using Drosophila melanogaster as a model organism is studied in [20]. Experimental research has shown that the exposure of mobile phone at 900/1800 and 2100 frequencies significantly affected the population generation time. The authors of [21] showed that RF-EMF exposure of the model organism Calliphora vomitoria below the ICNIRP reference levels at 5 GHz resulted in an altered development time of these insects.

Most of the prior studies focus on RF frequencies below 6 GHz. However, there have been some limited studies at higher frequencies, e.g. [22] investigated the influence of a radar's irradiation on insects above 10 GHz [22].

An alternative approach to study EMF exposure influence on bio-objects is the use of numerical simulations. This approach was previously used to determine the absorption of RF-EMFs in humans and requires numerical models or phantoms [23-25]. Thielens et al. [3, 4] investigated the exposure of four different insects (Australian stingless bee, Western honey bee, desert locust, and beetle) to RF-EMF from 2 to 120 GHz; and the exposure of Western honey bees (two workers, a drone, a larva, and a queen) at frequencies from 0.6 to 120 GHz using a combination of in-situ exposure measurements near beehives and numerical simulations. In [26], the far-field RF exposure on yellow fever mosquito was examined between 2 and 240 GHz using FDTD simulations, and the distribution of the electric field in and around the insect and the absorbed RF power were found for six different mosquito models (three male, three female). In [27], the far-field RF-EMF exposure of a series of insects (more than 20) was modeled as a function of frequency in the 2-120 GHz, showing that the whole-body absorption strongly depends on the insect volume. Finally, in [28], the exposure of a honey bee was studied in the near field of an emitting RF-EMF antenna. In these studies, all insects are modeled as homogeneous dielectric objects, while in reality, they have heterogeneous dielectric parameters. The absence of this makes it impossible to completely understand the biological effects of this exposure. Therefore, the goal of this study is to develop realistic heterogeneous insect 3D models and determine tissue-specific SARs. In a first step towards reaching this goal, this research focuses on honey bees as well as on wasps, as model organisms. The role of the honey bee as the most useful insect is known to all. The most important ecosystem service provided by wasps is pest control. Wasps hunt live prey (like flies, caterpillars, spiders, etc.).

METHODS

To investigate the exposure of RF-EMFs emitted from telecommunication networks, including 5th generation (5G) networks on insects from 2.5 to 100 GHz we have used computer simulations. For this purpose, we use the Finite-Difference Time-Domain (FDTD) technique [29] for EM simulations to evaluate the absorption of RF-EMFs energy quantified by the SAR (Specific Absorption Rate [W/Kg])) inside the insect tissues. In particular, we wanted to evaluate how this absorption is distributed in an insect's body. This required the development of realistic heterogeneous 3D discrete models of selected insects for EM simulations, which could potentially lead to more accurate results of whole-body and tissue- or organ-specific SAR. Because the body dimensions of most insects are in the millimeter and centimeter range, our hypothesis was that resonant effects can occur. We assumed that RF-EMFs can penetrate their body at certain frequencies and could potentially have a direct impact on their nervous system. Therefore, the focus was on evaluating SAR values inside the brain tissues of insects, as the brain is the major vital organ responsible for the functioning of this organism. It was previously shown that this absorption depends on insect size [27]. Therefore, in the first stage, 2 different size insects were selected for this research. These are a honey bee worker and a wasp. The selected frequencies for EM exposure simulations are 2.5 GHz, 3.7 GHz, 6 GHz, 12 GHz, 25 GHz, 40 GHz, 60 GHz, 85 GHz, and 100 GHz (9 frequencies).

To achieve the set goals of this research, it was needed to implement the following tasks, for each selected insect (honey bee worker and wasp): (1) Creation and discretization of the insect's 3D realistic heterogeneous model, (2) selecting and assigning dielectric properties to each tissue, and (3) conducting EM simulations using FDTD technique to evaluate the absorption of EMF energy (SAR) inside the insects' body tissues. The FDTD is the most suitable numerical technique for computational analysis of complex-shaped and inhomogeneous objects such as the bodies of insects. In the proposed research we use FDTD-based EM and Thermal solver FDTD Lab (Tbilisi State University, Tbilisi, Georgia) for EM simulations. In FDTD Lab, as in other FDTD-based programs, the EM solver is based on the numerical solution of Maxwell differential Equations by the FDTD method and Yee Algorithm [28, 29]; the thermal solver is based on penne's bio-heat equation[30]. FDTD Lab gives us the ability to determine E-field, SAR and evaluate temperature rise values in each body tissue of selected insects during EMF Exposure. FDTD Lab also has a SAR averager that allows SAR values to be averaged over a volume of any mass of tissue. SAR is usually averaged either over a small volume of tissue, typically 1g or 10g of tissue, because in vertebrates this averaging has been shown to closely approximate thermal effects of this exposure. Such an averaging is impossible for a honey bee and a wasp because of their small mass (close to 1g). Therefore, we chose to work with 1mg-averaged SAR values in selected insect tissues in order to visualize the SAR distribution within the insects. We also determined the maximal 1mg averaged SAR value in the whole insect and in each separate tissue, denoted peak 1mg SAR throughout this paper. In a second step, we averaged the SAR over each separate tissue of the insect models and over the whole body, by dividing the total absorbed power in those tissues or the whole body by the mass of these tissues or the whole body, respectively.

Insect Models and Dielectric Properties of Tissues

The creation of heterogeneous insect models was done as follows. At first, the bodies and body parts of selected insects (honey bee and wasp) were processed in STL format (Figure 1(a)) using graphics software: 3ds max (Autodesk, San Francisco, USA) and Netfabb premium (Autodesk, San Francisco, USA). STL files describe only the surface geometry of a three-dimensional object without any representation of color or texture. The FDTD technique needs to discretize the simulation domain (including 3D objects) using a 3-dimensional grid. So, created STL files of 3D body models have been imported and discredited into the FDTD-based solver FDTD Lab.

Once the model is imported into the simulation platform, we need to assign dielectric properties to the model. Insect-tissue-specific dielectric properties are rare and do not exist for the insects that we aimed to study [29]. Therefore, in this research, we planned to use the IT'IS Database of tissue properties [31], which provides EM parameters for many biological tissues. In this database, frequency-dependent EM parameters (permittivity and conductivity) are available from 10 Hz to 100 GHz frequency range.

The selected honey bee and wasp models were modeled using 3 different tissues: the cover (corslet), the internal tissue inside the corslet, and brain matter (Figure 1 (c, d)). The cover(corslet) of insects was modeled as cartilage tissue. This choice is based on the observation that the permittivity and conductivity of cartilage in the IT'IS database are very close to the permittivity and conductivity of the insects studied in [4, 5]. The values of internal tissue parameters were obtained by averaging the values of several main internal tissue parameters from the IT'IS database, taking into account the anatomical peculiarities of each insect. These tissues are muscle, heart muscle, stomach, stomach lumen, small and large intestines, nerve and gland. The values of brain parameters are the average values of brain grey and white matter parameters. The density values of these 3-tissues of honey bee and wasp were determined in the same way as permittivity and conductivity. The averaged values of tissue parameters are given in Figure 1(b). Such a selection of EM parameters of insects from the IT'IS database is an approximation but allows us to get a first estimation of SAR values in insect tissues, which can be refined in a later stage with insect-specific parameters. Such an approach in the future will also allow us to select the thermal parameters of insect tissues and evaluate temperature rise values since insect thermal parameters haven't been measured yet. Such creation of insect models and tissues with EM and thermal parameters represents a novel approach that has not been used for insects prior to this research.

The dimensions (length, width, height) of the 3D discrete model of the honey bee are 13.4 × 5.0 × 5.2 [mm], and the wasp model has the dimensions: 17.4 × 5.4 × 6.0 [mm]. The thickness of the honey bee and wasp cover(corslet) tissue is 0.2 mm. The brain tissue dimensions are 2 × 1 × 1.5 [mm].

EMF exposure Modeling

The EMF exposure was modeled using a sinusoidal (continuous) waveform of plane waves at a single frequency. We have selected sinusoidal plane waves at 9 harmonic frequencies: 2.5, 3.7, 6, 12, 25, 40, 60, 85, and 100 GHz. For each frequency, 10 incident plane waves fall on the insect model from five directions (front, back, top and bottom, left) defined by the Cartesian coordinate system. Two orthogonal, incident E-field polarizations are chosen for each direction. These incident E-fields are shown in Figure 1 (a). We did not consider the right-side direction of incidence because it gives the same result as the left incidence direction because the insect models have symmetry towards the ZOY plane.

Figure 1. a) Honey bee 3D model in STL format and the considered E-field polarizations with the directions of incident plane waves; b) the averaged values of tissue parameters; c) honey bee 3-tissue discrete model; d) wasp 3-tissue discrete model;

The next step was selecting the discretization size for FDTD modeling. According to the method, the calculation area is divided into cubes using a 3-dimensional grid. The discretization size depends on the wavelength, the sizes of the objects, and the desired spatial accuracy. The FDTD technique requires a predefined simulation time in order to reach a steady-state solution, which also depends on the wavelength, the spatial resolution, and the simulation domain size. The grid step should be less than one-tenth of the smallest wavelength for a stable solution [32]. The smallest wavelength in dielectric tissue is defined as $\lambda/\sqrt{\varepsilon_r}$. All these requirements of the FDTD algorithm are accepted in this research. The voxel size (grid discretization size) equals 0.1mm (100 μm) along the all-axis in each calculation.

The next stage of this study was to conduct numerical simulations using an FDTD-based EM solver of FDTD Lab to estimate SAR values in the body tissues of selected insects. The assessments of tissue-specific SAR values in insect tissues exposed to RF EMFs have not been done in existing studies up to now and therefore, the research we are proposing is novel.

RESULTS

Within this research, 3-tissue heterogeneous 3D models of a honeybee and a wasp were created with averaged EM parameters, which are presented in Figure 1.

For each insect, 90 EM simulations were conducted (10 directions of the incident plane wave for 9 frequencies). With these calculations, the peak values of 1mg-averaged SAR in the whole body of the honey bee and wasp and the peak value of the 1mg-averaged SAR in the brain tissues were determined at frequencies from 2.5 to 100 GHz. The obtained results are presented in Figure 2. 1mg SAR values are given in units [W/Kg] and are normalized to the incident power density of 1 mW/cm^2.

Figure 2. a) The peak value of the 1mg-averaged SAR values over the whole body for honey bee and wasp, averaged according to 10 polarizations for each frequency; b) peak 1mg-averaged SAR values in brain tissue of honey bee and wasp, averaged according to 10 polarizations for each frequency; c) honey bee's peak 1mg SAR for all considered incident wave directions and polarizations when considering the whole insect body; d) wasp's whole-body peak 1mg SAR values for all considered incident wave directions and polarizations. All peak 1mg SAR values are normalized to 1 mW/cm^2.

Figure 2 (a) shows the dependence between peak 1mg SAR values (averaged for 10 polarizations of incident E-field) and frequency for each insect. Peak 1mg SAR values at 6 GHz and 12 GHz frequencies are significantly higher than for other frequencies, especially for the wasp. The difference between the peak 1mg SAR value in the whole-body of the honey bee and wasp is highly noticeable up to 40 GHz. Such a difference is not observed between the peak 1mg SAR values in honey bee and wasp brain tissues (Figure 1(b)).

Figures 2 (c) and (d) show the peak 1mg SAR values over the whole body of insects for each E-field polarization at all considered frequencies. It can be seen that the peak 1mg SAR values are significantly variable according to polarizations up to 40 GHz. In particular, a sharp increase of SAR will be observed in the cases, when the incidence of the plane waves to the insect bodies occurs from the left, top, and bottom directions and the E-fields are directed along the insects' length (pol. E3, E5, E9).

For a honey bee, peak 1mg SAR peak values in the cases of E3, E5, and E9 polarizations are being between 25 - 40 W/Kg at 6 GHz and 12 GHz frequencies for an incident power density of 1 mW/cm^2. While for the rest polarizations, peak 1mg SAR values do not exceed 4 W/Kg at 6 GHz and 20 W/Kg at 12 GHz. From 12 GHz to 100 GHz, peak 1mg SAR values generally do not exceed 15 W/Kg and up to 12 GHz are between 0.05 - 6.3 W/Kg, except for a few cases mentioned above (Figure 2 (c)). All for an incident power density of 1 mW/cm^2.

For a honey bee, peak 1mg SAR values occur in the cases of E3, E5, and E9 polarizations are between 40 - 175 W/Kg at 6 GHz and 12 GHz frequencies, for 1mW/cm² incident power density. While for the rest polarizations, peak 1mg SAR values do not exceed 7 W/Kg at 6 GHz and 20 W/Kg at 12 GHz. From 12 GHz to 100 GHz, peak 1mg SAR values generally do not exceed 20 W/Kg up to 12 GHz as they are between 0.06 - 6.7 W/Kg, except for a few cases mentioned above (Figure 2 (d)). All for an incident power density of 1 mW/cm².

Figure 3. a) 1mg SAR distribution inside the honeybee at the parallel section of the YOX plane. E-field vector is directed along the Z-Axis (Pol. E4); b) 1mg SAR distribution inside the honeybee model at the parallel section of the ZOY plane. The E-field vector is directed along the X-Axis (Pol. E6).

Figure 3 shows 1mg SAR distributions for the honey bee models in some sections in the case of different E-field polarizations (pol. E4, E6). As can be seen from the pictures, EMF penetrates deeper into the honey bee tissues at 6 GHz and 12 GHz frequencies, and therefore, 1mg SAR peak values are localized deeply inside the honey bee body, while at other frequencies, the absorption of EM field energy mainly occurs in the superficial tissues of the honey bee body, and therefore, the SAR peak values are localized in the same areas.

DISCUSSIONS

The dimensions of the created honey bee and wasp models are less than the wavelengths for frequencies up to 25 GHz. At the same time, the dimensions of the wasp model are slightly larger than the honey bee model, and also wasp has a longer petiole and more curly surface. Based on the obtained results, from figure 2, a sharp variation of the SAR values depending on the polarization up to 25 GHz frequencies and high SAR values for a wasp compared to the honey bee and their localizations can be caused by the insects' body peculiarities and also by the difference in body sizes. The dependence of the absorbed power on the size of insects is also shown in the paper [27]. The obtained results have shown, that SAR values for considered insect models significantly depend on the incident E-field polarization at frequencies up to 40 GHz.

In this study, we used insect models processed using graphics software. The validation of the obtained results in the future could be approved by conducting EM simulations using insect models, created by Micro CT Imaging, as the insect models obtained in this way are closer to reality.

In the presented research, we have averaged SAR values over a volume of 1 milligram of tissue. Such an averaging of SAR values for small-sized insects with a mass close to 1 gram (honeybee and wasp) was introduced for the first time. It was not possible to average SAR in accordance with international standards over a volume of 1 g and 10 g of tissues. 1mg SAR values will be more informative and could be considered as a standard in the future for small-sized biological organisms, like insects if it could be demonstrated that this quantity can be seen as a proxy for biological effects associated with RF-EMF exposure in a certain frequency range. Future studies should be aimed at determining such a relationship.

Finally, we aim to study the influence of the choice of simulation parameters and settings on the obtained results.

CONCULSIONS

The paper presented a study of RF- EMFs dosimetry of a honey bee worker and a wasp from 2.5 to 100 GHz, including frequencies that will be utilized in future 5G technologies.

A discrete, 3-tissue heterogenous honey bee and wasp 3D models were created and used for FDTD modeling, and a new approach for the selection of tissues' EM parameters was introduced.

The whole-body SAR values and SAR values in brain tissues were estimated for 9 considered frequencies and 10 polarizations of incident plane wave. For the first time, 1mg SAR values were determined in insect tissues.

The obtained results showed high SAR values in honey bee and wasp body tissues, that are depending on the direction of the incident plane wave and polarization, frequency and also, and the insect's body size and peculiarities. The highest values of SAR were observed in the case when E-field polarization is directed along the honey bees' length (pol. E5, E5, E9). SAR peak values were mostly observed in the range from 0.05 to 15 W/Kg for a honeybee, and from 0.06 to 20 W/Kg for a wasp. The exception was several cases when the SAR values increased extremely for above mentioned (pol. E5, E5, E9) polarizations at 6 GHz and 12 GHz frequencies for both insects.

Future studies consider introducing insect models that will be obtained using Micro CT scanning, examining the effects of high-frequency electromagnetic fields on other insects of different forms and sizes; also conducting thermal simulations along with EM simulations and evaluating temperature rise in insect tissues.

Based on the obtained and future results, we expect this research to have an impact on (environmental) policymaking and standardization and regulation regarding RF-EMF emissions. We expect to contribute to the harmonization of 5G EMFs safety and compliance doses and to the development of future recommendations about safe frequencies and doses of 5G-EMFs concerning the above-mentioned organisms.

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