The Study of Biological Effects of Electromagnetic Mobile Phone Radiation on Experimental Animals by Combining Numerical Modelling and Experimental Research

Dejan Krstić[1] , Darko Zigar[1], Dušan Sokolović[2], Boris Đinđić[2], Branka Đorđević[2], Momir Dunjić[3], Goran Ristić[4]

Abstract – In order to study biological effects of electromagnetic radiation, it is essential to know the real values of field components that penetrated the tissue. The study of biological effects is usually performed on experimental animals. The biological effects observed on experimental animals should be linked with penetrating field in the tissue. The penetrating electromagnetic field is almost impossible to measure; therefore, modeling process must be carried out and the field components in models of experimental animals could be calculated. This paper presents an approach to modeling of field penetration and gives contribution to understanding the real effects of the fields and the sensitivity of tissues to electromagnetic radiation generated by mobile phone.

Keywords –Numerical bioelectromagnetic simulation, Calculations of Specific Absorption Rate, Biological effects of mobile phone radiation, Experimental animals - rats

I. INTRODUCTION

The electromagnetic radiation, which can be divided into thermal and non-thermal, produces undesirable effects on living things. Investigation of those effects is based on previously known distribution of electromagnetic fields in tissues.

Numerical simulation methods of penetrating electromagnetic fields allow the calculation of the field components in biological subjects. The components of electromagnetic field inside the biological subject determine the energy absorbed in that element space.

Calculating the energy absorbed from the mobile phones in the complete biological subject, is a prerequisite for studying the biological influence of electromagnetic field. For this calculation, it is extremely important to generate the electromagnetic models of real biological subjects.

[1]University of Niš, Faculty of Occupational Safety in Niš, Čarnojevića 10a, Niš, Serbia, e-mail: dejank@znrfak.ni.ac.rs

[2]University of Niš, Medical Faculty in Niš, Bulevar Zorana Đinđića 81, Niš

[3] University of Niš, Faculty of Electronic Engeenering Nis, Aleksandra Medvedeva 14, Niš

[4] Medical Faculty, University of Pristina in Kosovska Mitrovica

Application of numerical methods in electromagnetics is becoming necessary and, together with sophisticated software packages, it solves the problems of propagation of electromagnetic (EM) field in much shorter time than traditional methods of electromagnetics.

Biological effects of the absorbed energy calculated by numerical simulation have been tested in a real experiment with animals. The animals used in the study were under controlled conditions of exposure to electromagnetic mobile phone radiation. The authors believe that this is the right approach because it allows us to connect the calculated values of absorbed energy and its effects on certain tissues of living organisms. This approach to the study of biological effects of mobile phone radiation is a basis for a multidisciplinary approach that binds the knowledge in technical and medical science, with the aim to define the complete idea about biological effects of radiation.

II. APPLICATION OF NUMERICAL METHODS

There are numerous books with mathematical details about different numerical methods for calculating electromagnetic field. The numerical calculations in electromagnetics are a combination of mathematical methods and a field theory.

Computational electromagnetics involves evaluating the fundamental field quantities from the Maxwell's curl equations using numerical methods with a given set of initial or boundary values [1]. These solutions describe propagation of electromagnetic waves and their interactions with a material. There are many different methods which can be used to solve 3-dimensional electromagnetic problems. These methods can be classified into:

- integral equation and differential equation methods or
- time domain and frequency domain methods.

Before solving the problem, it is important to establish a correct mathematical model of the problem or its parts. Maxwell's equations and appropriate boundary conditions are necessary practical basis for the modelling of electromagnetic problems. Green's theorem and the method of equivalent sources are essential tools for numerical techniques [2].

Integral equation method based on an appropriate Green's function incorporates the boundary conditions after which the solution can be sought. Differential equation methods start at Maxwell's equations in differential form and require a minimum of analytical manipulation.

Generally, methods for numerical modelling of continuous real environment can be divided into: the integral method, differential and variation method.

Time domain methods typically obtain the impulse response (which contains information at all frequencies) and frequency domain methods obtain the transfer function at a specific frequency.

Differential methods are: Finite Difference Method (FDM), Finite Difference Time Domain Method (FDTD) and Finite Element Method (FEM).

Integral methods are: Charge Simulation Method (CSM), Surface Charge Simulation Method (SCSM), Boundary Integral Equation Method (BIEM), Method of Moments (MoM), Finite Integration Technique (FIT), Multiple Multipole Method (MMP) and Generalized Multiple Technique (GMT).

The methods can be further classified into: Transmission Line Method (TLM), Boundary Elements Method (BEM), Scalar Potential Finite Difference (SPFD), Three-Dimensional Impedance Method (3-D IM), etc.

In this paper Finite Difference Time Domain Method (FDTD) has been used to calculate distributions of electromagnetic field in the body of an experimental animal i.e. a rat.

III. FINITE DIFFERENCE TIME DOMAIN METHOD

Numerical methods that have been developed use millimetre resolution of anatomically based models of the human body to determine SAR or the induced electric fields and current densities for real-life EM exposure conditions. A popular method used at RF and microwave frequencies is the finite-difference time-domain method (FDTD).

FDTD is the most widely used method for bio-electromagnetic applications in the range of a few MHz to several GHz [3]. FDTD solves Maxwell's equations in the time domain. This means that the calculation of the electromagnetic field values progresses at discrete steps in time.

FDTD method is one of the best methods for computation EMF and it becomes quickly more efficient in terms of computer time and memory than other methods since there is no matrix to fill and solve [5, 7, 8]. FDTD can provide results for a wide spectrum of frequencies from just one calculation using transient pulse excitation and FFT (Fast Fourier Transformation). This method is based on a solution grid. Main reason for using the FDTD approach is the excellent scaling performance of the method as the problem size grows. The grid is fundamentally different than those used by other methods. The FDTD grid is composed of rectangular boxes.

In the FDTD approach, both space and time are divided into discrete segments. Space is segmented into box-shaped "cells", which are small compared to the wavelength. The electric fields are located on the edges of the box and the magnetic fields are positioned on the faces as shown in Fig. 1. This orientation of the fields is known as the Yee cell [5, 6] and is the basis for FDTD.

Time is quantized into small steps where each step represents the time required for the field to travel from one cell to the next. Given the offset in space of the magnetic fields from the electric fields, the values of the field with respect to time are also offset. The electric and magnetic fields are updated using a leapfrog scheme where first the electric fields, then the magnetic are computed at each step in time.

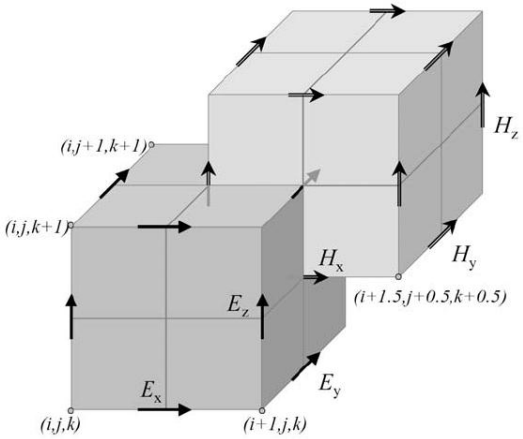

Fig. 1. Electrical and magnetic field components in FDTD grid

Within the mesh, materials such as conductors or dielectrics can be added by changing the equations for computing the fields at given locations. Introducing other materials or other configurations is handled in a similar manner and each may be applied to either the electric or magnetic fields depending on the characteristics of the material.

The FDTD strategy is to use many very small mesh elements that can be computed quickly and with very little computer memory. A general rule of thumb sets the minimum resolution, and thus the upper frequency limit, at ten cells per wavelength. In practice the cell size will often be set by dimensions and features of the structure to be simulated.

FDTD grid can be uniform or expanded. Uniform FDTD grid has mostly been used for the bioelectromagnetic problems. An expanding-grid formulation has also been proposed by Gao& Gandhi [9] and has been used for near-field sources. This offers the advantage of modeling the tightly coupled regions such as the ear and the proximal side of the head with a fine resolution (small cell size) while allowing cell sizes to increase gradually as one moves further away from the regions of primary interest. The expanding-grid algorithm allows different cell-to-cell expansion factors along the three coordinate axes, and can reduce by a factor of 4 to 10 the total number of cells needed to model a given volume as compared to a uniform grid formulation wherein the cells with the finest resolution are used throughout the volume [10].

An excitation may be applied to an FDTD simulation by applying a sampled waveform to the field update equation at one or several locations. At each step in time, the value of the waveform over that time period is added into the field value. The surrounding fields will propagate the introduced waveform throughout the FDTD grid appropriately, depending on the characteristics of each cell. A calculation must continue until a state of convergence has been reached. This typically means that all field values have decayed to essentially zero (at least 60dB down from the peak) or a steady-state condition has been reached.

There are a number of software packages for simulation based on FDTD, such as for example: XFDTD – Remcom, EMPIRE- IMST, SEMCAD X and FIDELITY.

REMCOM XFDTD simulation program was chosen. In most cases, an XFDTD project will begin with the creation of the simulation spaces physical geometry. Input excitations and output storage values will then be defined and saved and the calculation will be performed. The geometry can be entered in a variety of ways, which may include importing a CAD file, creating objects using the internal XFDTD editing features, or some combination. Whatever the approach chosen, the geometry should be a good representation of the actual device in terms of the dimensions of the structure and the materials it contains. The geometry will typically be composed of numerous objects, each of which is independent and editable. After all objects describing the geometry have been entered, the FDTD mesh can be created. The calculations will be performed on the FDTD mesh, so it is important that the mesh is a good approximation of the objects and in turn the actual device. In XFDTD the display can quickly be switched between the object view and the mesh view to allow easy comparison of the two. The mesh creation process can be fully automatic, but many controls are included to allow fine-tuning of the geometry as needed. With the geometry step finished, the desired inputs to the calculation may be defined.

The excitation can be at discrete locations such as voltage or current sources, from an incident plane wave for scattering calculations, or in the case of optical frequency calculations, in the form of a Gaussian beam. The input signal may be a pulse for broadband calculations, a sinusoidal source, or a user-defined waveform. A wide range of output data may be saved by XFDTD, including both time-domain and frequency-domain values. Both near-zone and far-zone results can be saved for most calculations and numerous methods are included for storing field distributions. Depending on the application, the outputs can vary, but all time-domain field values may always be saved and should always be reviewed to ensure proper convergence of the time response before viewing any other output quantity. Without proper convergence in the time-domain, all other results will be inaccurate. The calculation engine may be run from within the XFDTD interface, externally from a command line, or as a batch job. The engine performs the actual FDTD calculations of the fields over the geometry mesh and saves the outputs specified. Following the calculation the output data can be viewed in the interface. Some data, such as far-zone results, may need post-processing. Most results are immediately available for display within the interface. All output file formats are explained in this manual as well for cases where further processing of the data is desired [6].

IV. INVESTIGATION OF BIOLOGICAL EFFECTS IN EXPERIMENTAL ANIMALS

EMF effects in a wide frequency range from ELF to MW have been considered in the frames of the same physical models [11-14]. It has been known for long time that weak ELF fields and NT MW result to similar effects with significant overplaying of molecular biological pathways for their appearance [15-17]. Series of studies demonstrated the change in oxidative stress intensity and in antioxidative enzyme activities in various organs after MW exposure [18-24]. Lipid peroxidation and oxidative modification of protein molecules are the most important mechanisms of oxidative damage in tissues. Chemical reaction between biomoleculs (proteins, DNA and phospholipids) and peroxidation secondary products (malondialdechyde, MDA) causes covalent modification of those biomolecules and leads to consequent cell membrane injury and intracellular macromolecules alteration [25].

In order to determine the biological effects of electromagnetic radiation, it is necessary to study the effects on experimental animals. It is also significant to combine theoretical research on animal models with calculation absorbed electromagnetic energy and experimental studies on test animals under the same exposited condition.

However, the analysis of the biological effects requires the knowledge of the field strength, absorbed energy and the SAR in rats' bodies. Therefore, the electromagnetic simulation of field components in the body of test animals has been necessary [26].

To obtain the numerical results of calculation of absorption of EM mobile phone radiation in experimental animals, it is necessary to define: model of the source (mobile phone) with the antenna pattern characteristic, the animal model with the actual characteristics of tissues and under the conditions of the actual use [28,29], the model of wave propagation in half-conductive environment, i.e. the choice of numerical simulation methods (FDM, MoM, FDTD, FIT, etc.).

All the elements of experimental studies on test animals, including a radiation source (mobile phone with antenna) and radiation object (experimental animals - rat) have been formed in the simulation area in order to be used in the XFDTD software, with the aim to get the proper numerical results.

A. Experimental design

Experiments were performed on 84 adult male Wistar Albino rats (6–8 weeks old, 150 g), bred at the Vivarium of the Institute of Biomedical Research, Medical faculty, Nis, under conventional laboratory conditions [23]. All animals were suited in the same room without near sources of EMF, from the cages (Fig.2.). All animals were housed collectively (7 animals in each cages 30 × 40 × 40cm – W × L × H). The rats were kept in a pure (i.e. lacking any metallic fittings) polycarbonate cage and given ad libitum access to standard laboratory food and water. The housing room was maintained at 24°C with 42 ± 5% relative humidity and had a 12–12-h light–dark cycle (light on 06:00–18:00 h).

The animals were allocated into four experimental groups. Each group consisted of 21 animals, situated in 3 cages, 7 animals in each. Group 1 (control)-animals treated by saline, intraperitoneally (i.p.) applied every day during the follow up, Group 2 (Mel)-everyday treated rats with melatonin (2 mg kg–1 body weight i.p.), Group 3 (MWs)-MWs exposed rats, Group 4 (MWs + Mel)-MWs exposed rats treated with melatonin (2 mg kg–1 body weight i.p.)

The animals were exposed to microwave radiation for 20, 40 and 60 days (4 h/day during light period). The microwave radiation was produced by a mobile test phone (model NOKIA 3110; Nokia Mobile Phones Ltd.) connected to a Communication Test Set PCDK with PC and appropriate software module. MW exposure was performed in the same room where all animals were housed. The two mobile test phones and PC module were situated at the wooden desk with rubber surface.[23]

Fig. 2- Experimental animals with a mobile test phone [7,23]

B. Electromagnetic design

As a source of electromagnetic radiation, a mono-block mobile phone with a dipole antenna has been used (half-wave dipole).

These complimentary animal meshes are provided by The Radio Frequency Branch of the Human Effectiveness Division of the Air Force Research Lab at Brooks Air Force Base [31]. It is significant to know the real position of all tissues in animal body and their electromagnetic characteristics (Fig.3 and Fig.4.).

Exposition model included two cases: when the antenna of the mobile phone is near the rat's head (case 1, Fig. 5) and when it is in the vicinity of the rat's stomach (case 2, Fig. 6).

Fig. 3 - High-fidelity model of a rat

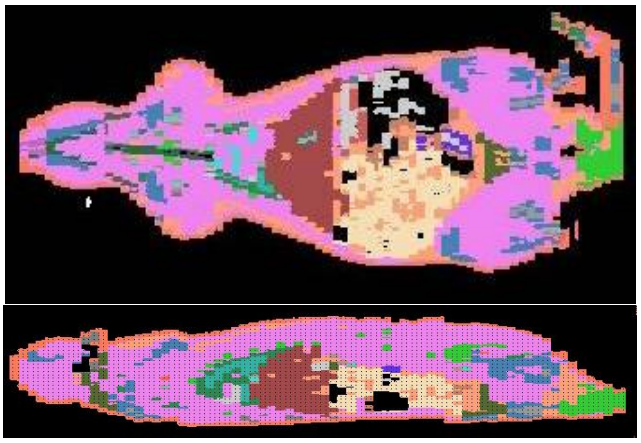

Fig. 4 - Vertical and horizontal cross section with inner structrure

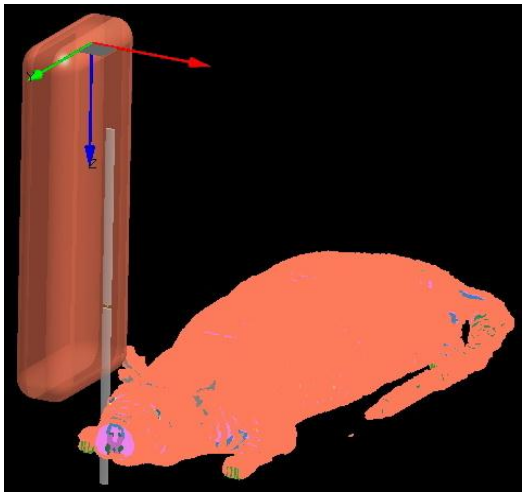

Fig. 5 – Exposition case 1 - antenna of the mobile phone is near the rat's head

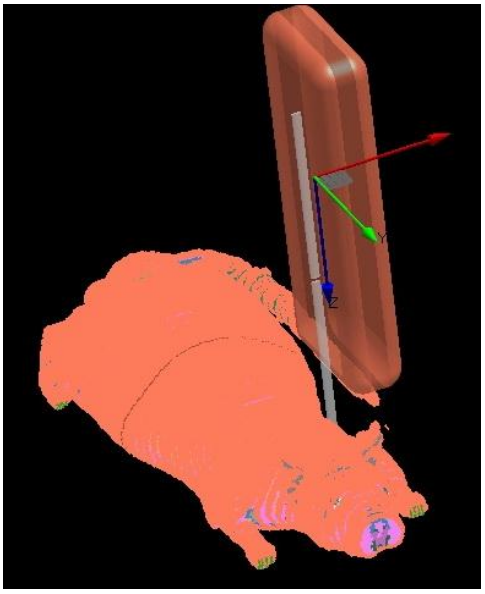

Fig. 6 - Exposition case 2 - antenna of the mobile phone is in the vicinity of the rat's stomach

V. RESULTS OF INVESTIGATION

The results obtained by simulation for the component fields in free space have been compared with the values measured by Field meter AARONIA HF6080. In the simulation program used is a source of power 1W. The results matched have been satisfactory.

The results of the calculated field components showed the distribution of components inside the body in two margined cases 1 and 2. The values of electric and magnetic field and the SAR values for specific organs such as liver, brain and eyes (Table 1, Table 2, Fig. 8 to Fig. 17) have also been calculated.

The specific energy absorption (SAR) rate in irradiated animals was estimated to 0.043-0.135 W/kg using data for a rotating ellipsoidal rat model [23]. Average $SAR_{[1g]}$ value for three organs is 0.09083 W/kg.

Lipid peroxidation is a well-established mechanism of cellular injury in both plants and animals, and is used as an indicator of oxidative stress in cells and tissues. Lipid peroxides, derived from polyunsaturated fatty acids, are unstable and they decompose to form a complex series of compounds. These include reactive carbonyl compounds which are the most abundant malondialdehyde (MDA). Therefore, measurement of malondialdehyde is widely used as an indicator of lipid peroxidation.

Experimental investigation of exposed animal in general increase in MDA (malondialdehyde, lipid peroxidation end product) level in organs such as brain (5,16±0,31 vs. 3,55±0,64 nmol/mg of proteins, $p<0,001$) and liver (6,13±0,36 vs. 5,44±0,27 nmol/mg of proteins, $p<0,01$) after 40 days of exposure to MW [23].

Thus obtained results allow us to obtain the real and adequate data about the biological effects of electromagnetic radiation in experimental animals and their influence on certain organs.

By numerical simulation distribution of EM field and absorbed energy is precisely determined. In this way, the areas with maximum SAR are determined and tissues and organs with highest absorption potential are defined. This also enables defining of the most probable organs and tissues with biological effect of electromagnetic radiation. Combining numerical modelling and experimental research gives opportunities for specific biological and medical research on the level of tissue, cell or organelle.

TABLE 1

CALCULATION OF ELECTRICAL FIELD IN CERTAIN BODY PARTS IN A RAT MODEL

Organ	Electrical field E(V/m)		
	Position of the antenna		Average
	Next to the head (Case 1)	Next to the trunk of the body (Case 2)	
liver	5.61	10.8	8.205
brain	16.9	7.65	12.275
eye	13.8	4.31	9.05

TABLE 2

CALCULATION OF SAR IN CERTAIN BODY PARTS IN A RAT MODEL

Organ	SAR(W/kg)		
	Position of the antenna		Average
	Next to the head (Case 1)	Next to the trunk of the body (Case 2)	
liver	0.0132	0.166	0.089
brain	0.148	0.046	0.097
eye	0.147	0.026	0.0865

There was significant positive correlation between SAR and MDA concentration in brain tissue ($C=0.56$, $p<0.05$), which was not seen for liver ($C=0.37$, NS) tissue.

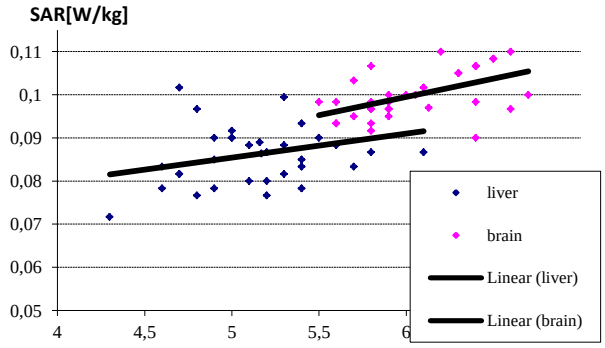

Fig. 7- Liver MDA according to SAR values in liver and brain

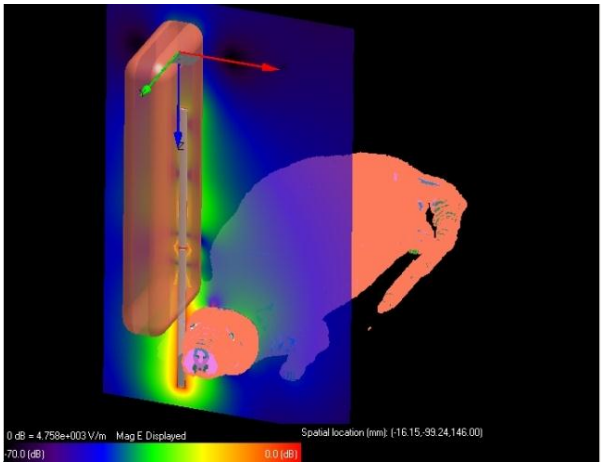

Fig. 8 - Electric field in model of a rat - case 1

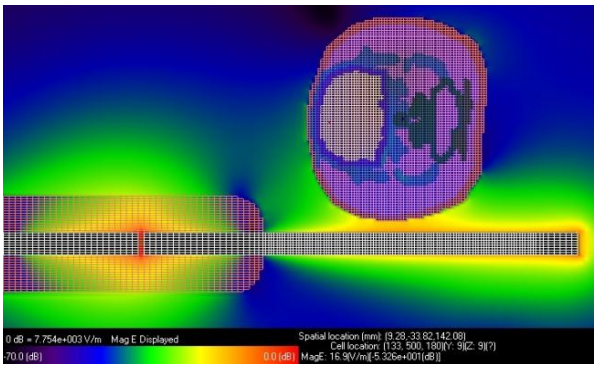

Fig. 9 – Distribution of electric field in head of a rat - case 1

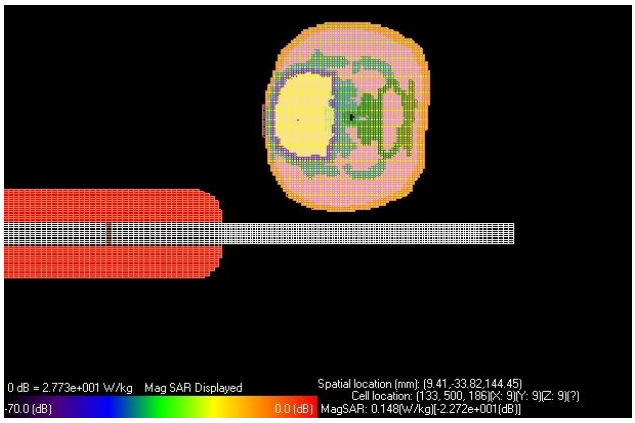

Fig. 10 - Distribution of SAR in head, cross section of brain - case 1

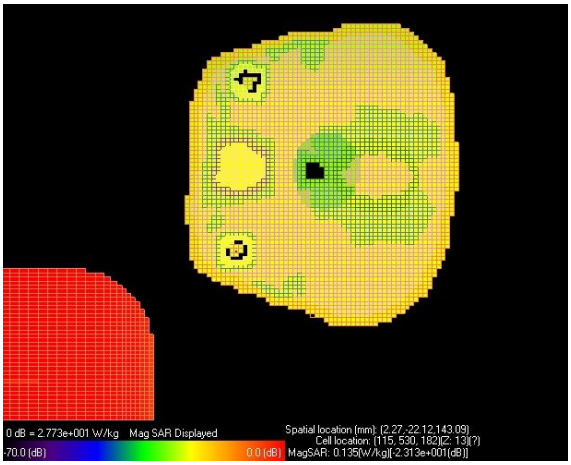

Fig. 11 - Distribution of SAR in eye tissue - case 1

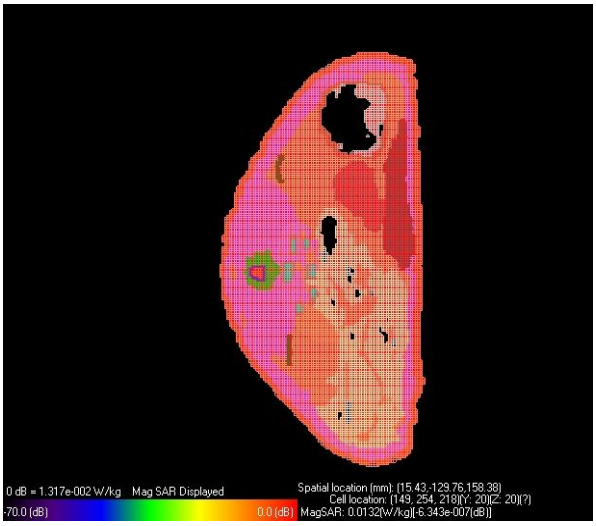

Fig. 12 - Distribution of SAR in trunk of model cross section liver – case1

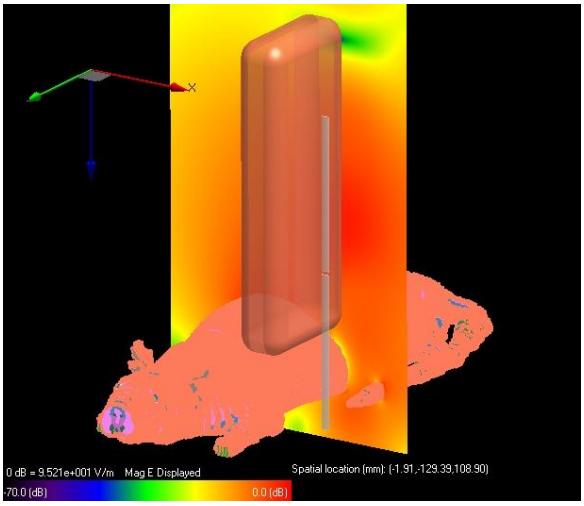

Fig. 13 - Electric field in model of rat- case 2

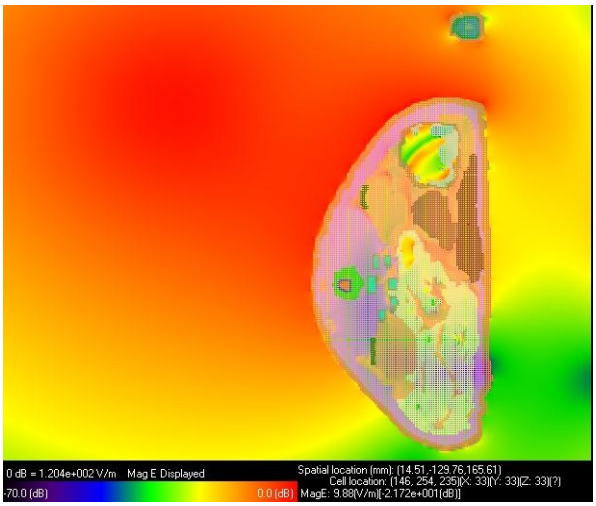

Fig. 14 - Distribution of electric field in trunk, cross section liver- case 2

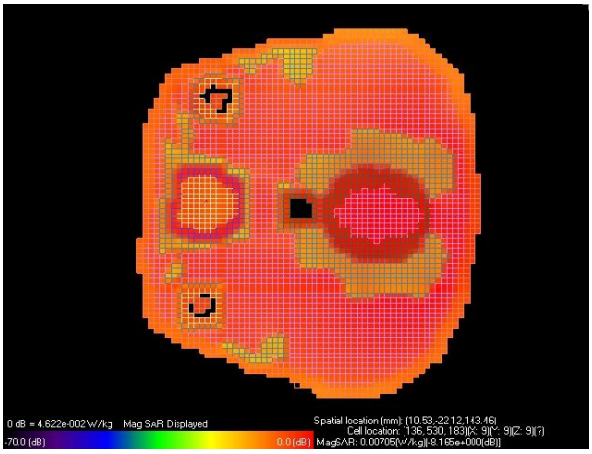

Fig. 15 - Distribution of SAR in head, cross section of brain- case 2

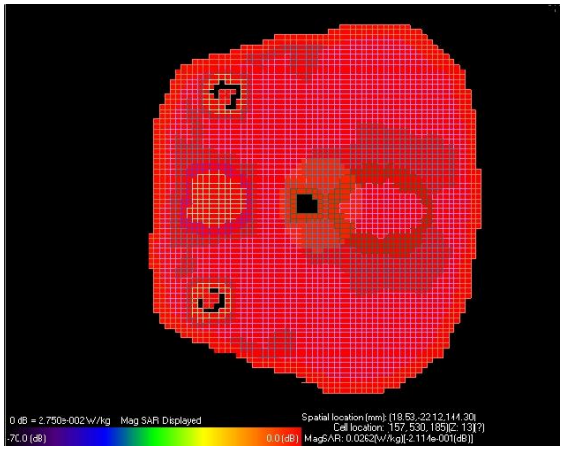

Fig. 16 - Distribution of SAR in eye tissue- case 2

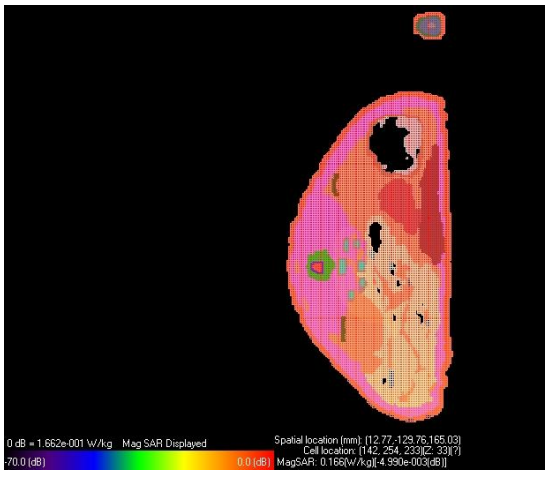

Fig. 17 - Distribution of SAR in trunk, cross section liver- case 2

VI. CONCLUSION

The results of the field components in a free space show a satisfactory match with the values measured by the field meter. The results of electric field distribution in the rat bodies suggest that there is an unequal distribution of the fields, which depends on the position of the sources and characteristics of each tissue.

Numerical methods as FDTD and appropriate software tools like XFDTD enables precise determination distribution electromagnetically fields. In this way, absorbed energy and SAR in any part of the body exposed to EM radiation is calculated. Thus tissue and organs with highest absorption potential can be defined (electromagnetic wave absorption potential) which determines the most probable biological effects.

The increased level of oxidative stress in different tissues could be patogenetic mechanism of tissue damage. Significant positive correlation between SAR and oxidative damage in brain tissue indicates preventive approach in reducing duration of using mobile phones. Multidisciplinary approach enables the integration of numerical simulation and experimental research which deepen knowledge about biological effects of electromagnetic radiation on biological tissues and living things in the whole.

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