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DETERMINATION OF EMF INFLUENCE ON A HUMAN EXPOSED TO EMF – MODELING AND METHODOLOGY

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A b s t r a c t: The wide use of electric energy in every segment of everyday living demands specific attention be paid to investigations connected with biological effects from the influence of electromagnetic fields on humans and the environment. Investigations connected with electromagnetic influence assessment on human health emphasize the influences of electromagnetic fields in a wide frequency range. Here, the interest in knowing the mechanisms of these interactions and ways of determining them is obvious. The parameters and quantities that describe such influence depend on the frequency of the electromagnetic field source that underlines the importance of their appropriate definition. Induced currents and charges as well as electric field distribution, or SAR, are quantities that represent this influence. Their determination is important for the formulation of norms and standards for human protection from exposure to electromagnetic fields.

In this paper, a developed procedure for the determination of electric field distribution in the human body when exposed to EMF influence is presented. Several issues emerge in the course of this, such as finding representative parameters for problem description, modeling of the incident field source, which is obvious in various forms and in a wide frequency range, modeling of the human body, which is complex in geometric aspect and has a wide range of electric characteristics in its parts, developing an appropriate calculation methodology and a suitable presentation of the results. Modeling the incident field form and the human body are in direct correlation with the calculation method developed for determining the electric field distribution. Developed methodology enables the electric field in the humans to be determined, and other parameters such as SAR to be calculated. Having those values, we can discuss the biological effects on humans from such exposure.

Key words: Electromagnetic field, electromagnetic influence, human model, induced electric field, SAR.

I. Introduction

In the present day, the increase of new technologies and the demands put upon them are becoming more and more obvious. The use of an enormous number of electrical devices in human living and working environments are the result of high technology development. In this, there is a need to understand more about electromagnetic field (EMF) influences on the environment, equipment and complex systems. The electromagnetic energy used has a wide frequency range. On the one hand there are devices and equipment that work on low frequencies, such as the units in industrial installations, transmission power lines, devices for welding and melting. On the other hand, there is the communications technology that has experienced a huge growth in recent times, so studies concerning mobile phones, wireless communication systems, base station antennas and their electromagnetic impact are important in understanding and providing protection from their electromagnetic influence and its reduction.

Thus it is obvious why the concern for human health when exposed to electromagnetic field influences is receiving more and more attention. At the same time, the investigations made are connected with the biological effects of electromagnetic field exposure on humans. The growing concern, correlated with possible health risks because of public and professional exposure to EMF from electrical devices and from the use of electric energy in everyday living, is causing significant debate among relevant individuals and institutions. A series of investigations related to human EMF exposure has been made with the goal of understanding more about the interaction of EMF influence and humans and the possible consequences of such exposure [1, 2]. The goal of many studies is the discussion and evaluation of possible effects on humans. But, taking into account the fact that knowledge of the mechanisms by which EMF could cause negative health effects are still insufficient, it is still not quite clear what parameters need to be measured so that the relation between EMF and the effects caused can be explained and be tested.

On the assumption that the current and induced field explain the negative effects of EMF exposure [1, 2], the average value of the electric field is a quantity that has been determined in a lot of studies. Some other quantities, such as the level of exposure to anelectric field, certain other characteristics of magnetic fields (such as harmonics, transient processes, changes in time and space) have occupied less attention. The most frequently used parameter for describing the effect of EMF on humans is the generalized specific absorption rate (SAR) [1, 2]. However, there are other relevant parameters, such as the distribution of EMF and induced charges and currents in a human body exposed to EMF.

On the one hand there is concern about the possible negative effects of EMF exposure; on the other hand there is a need to find ways of using such an influence with positive aims as in diagnostic and therapeutic procedures. EMF influences investigations are important from another point of view, also, to determine the parameters for their description and to define recommendations and standards for human protection.

In this paper, a developed procedure for electric field distribution determination or, if it is requested, for SAR distribution in the human body exposed to EMF influence and represented by a model, is presented. These parameters are determined for typical values of the electrical field from the sources taken as examples. Having the values for the electric field distribution or for SAR, we can discuss the biological effects of EMF exposure on humans.

This paper is an attempt to observe the main points during the determination of EMF influence when a human is exposed to frequency-dependent EMF. The main questions to be solved are the modeling of the human field exposed, a suitable presentation of the environment, finding an appropriate human model for the presentation of its structure, taking account its geometrical and electrical characteristics, and finding a suitable method for solving the field determination and an appropriate presentation of the results [3]. Special attention is paid to modeling EMF sources which have a wide frequency range, and finding an appropriate human model. During such analysis several problems appear, connected with the fact that the human body has a very complex geometric structure. Therefore it is very difficult to obtain a precise theoretical or experimental description of the human body. At the same time, when the influences of EMF exposure are determined, one must consider the fact that human tissues have electrical characteristics which depend on the frequency of the exposed EMF.

In the procedure developed for analysis, the human model is formed describing its boundary surfaces. Triangles are used as a basic shape for representation of the surface. The influence of a body with different characteristics from those of the free space is replaced with equivalent surface currents during the computing. In this way, a field inside the human body is determined. The presented method for EMF influence determination does not depend on an incident field's form or its frequency.

II. Aspects of interaction and quantities

EMF frequency has a direct influence on effects from human exposure to EMF influence [1, 2]. These can be manifested as neuromuscular stimulation, tissue heating or surface heating. This influence is characterized by quantities:

– contact current (I_c) between subject and object given in (A). The contact current is the result of the conducting object and charged by field influence,

– specific absorption energy (SA), defined as energy per unit mass (J/kg), used for description of the non-thermal effect during pulsed microwave radiation,

– rate or norm of specific energy of absorption (SAR specific absorption rate) as an average value for a whole body or for some part of it. SAR definition is the ratio of energy absorbed from the mass tissue unit

$$SAR = \frac{\sigma}{2\rho}\left|E_i\right|^2 \tag{1}$$

where σ is tissue specific conductivity, ρ tissue mass density, and E_i is maximum value of an electric field at a given point. SAR can be expressed in (W/kg), or (mW/g). Whole body SAR is a quantity widely used as a measure for relatively harmful effects from EMF exposure in the radio frequency (RF) spectrum. The value of local SAR is related to a specific human part and is based on mean SAR value; it is necessary for limit estimation of excessive energy imported into a specific part, as a consequence of a specific condition of exposure.

Biomechanisms of acting and dosimetric quantities depend on incident field frequency and they are:

– for 3 kHz – 100 kHz range the biomechanism is characterized by neuromuscular stimulation, then current density is defined as a dosimetric quantity,

– for middle RF (100 kHz – 3 GHz), such as characteristic tissue heating and SAR quantity are defined,

– for microwaves 3 GHz – 300GHz, biomechanism is defined as surface heating given as a power density (W/m^2).

III. Effects of EMF exposure

The effects of EMF exposure depend on the frequency of the incident field.

When we talk about the interaction of extremely low frequency (ELF) and low frequency (LF) fields with a biological system, the electric signals in it have to be considered. The electric signals are important in the control of biological processes and information flow in the body. These field effects can be described as:

– electric field effects on cell membranes,

– nonlinear effects from AC fields on cells,

– thermal effects,

– electric field effects on the biological system.

When a biological system is positioned in ELF EMF induced internal electric currents and fields and surface charges on the connection of different electric medium appear. This can be described with Maxwell's equations. When we deal with ELF fields significant simplifications for solutions can be made because they are quasi-static. Because of the object size and tissue electric characteristics, the depth penetration into it can be neglected.

The interaction between an ELF magnetic field and a biological system can be described through two well-known and established mechanisms:

– the appearance of an induced electric field defined in Faraday's law of electromagnetic induction and

– the direct effects of a magnetic field on magnetic particles as magnet crystals detected in some organisms.

The interaction of EMF in RF range and biological tissues is a complex function with many parameters. These fields are characterized by their frequency, field intensity, direction and polarization. When a body is exposed to known EMF, Maxwells equations taking account of specific boundary conditions can be used todetermine the field inside it. In this case, a biological body represents a non-homogenous medium with characteristics of an imperfect dielectric, so complex permittivity has to be defined. Even a whole problem formulation is a complex task, knowing the complexity of shapes and dielectric inhomogeneity. Accordingly, only quite simplified models can be analysed. On the other hand, an experimental approach is a subject with significant limitations and simplifications. The intensity of internal fields during EMF exposure depends on external field parameters such as its frequency, intensity, polarization, shape, position of the human and source. Thus the complexity of interaction and its determination is obvious.

A series of investigations is made to find relevant parameters for EMF exposure description and define basic restrictions. The quantities that define basic restrictions depend in the EMF source frequency and they can be current density, magnetic flux density, power density or SAR. Part of basic restriction of SAR is given in Table 1 [4].

Table 1 – Табела 1

Basic restriction for SAR
Базични рестрикции за SAR

SAR[W/kg]	Occupational exposure	General public exposure
Whole body average	0.4	0.08
Localized (head)	10	2
Localized (limbs)	20	4

It should be mentioned that basic restrictions are related to one universal human model, and do not take into consideration specific individual characteristics such as human sensitivity, age, or environmental conditions.

In cases of EMF influence, when there is a probability of exceeding basic restrictions, referent levels are defined. They refer to public or professional exposure to EMF influences. The quantities that define referent levels depend on frequency, so that the electric or magnetic field as well as magnetic flux density and equivalent power density of plane wave describe them [5].

IV. Modeling

During the determination of the influence on humans exposed to EMF, modeling of incident field and human body are issues to be solved. Modeling determination is important from the point of view of the credibility of the results obtained.

The modeling problem is not simple, on one hand there is a complex and wide range of sources of EMF influences, on the other hand it is not easy to form an appropriate human model taking account its geometric and electric characteristics.

The excitation (incident field) source has obviously various forms and frequency. The modeling of an incident field depends on its frequency.

The most common sources of low frequency EMF are industrial power systems, power lines and electrical devices, devices for melting and welding. Currents with great intensity appear in these devices. Such an incident field can be modelled as a field from a power line, or a field from a current frame representing a field in industrial power systems. That field can be obtained by knowing the power line incident field and its frequency, and the relative position of the human and the line. If a conducting frame is positioned as a model, it is necessary for current intensity, frequency, shape and the dimensions of the frame and also the position of the human to be defined [6].

The most common type of high frequency EMF source are the units in cellular telecommunications, various types of antennas, mobile base stations, etc., which are widely used and present in the human environment. Here, the incident field can be described as an antenna field, or as a plane wave field. If an incident field is modelled with antenna field, the parameters that have to be defined are the power with which the antenna is fed, its geometry, working frequency, and the relative positions of the antenna and the human. If we model using a plane wave field, the electric field of the plane wave, its frequency, polarization, direction of propagation, the position of the human and the electric field vector are parameters to be defined [7].

The other problem that needs to be solved during modeling is forming an appropriate human model.

Determination of an appropriate human model during EMF influence calculation is directly connected with the accuracy of the results obtained. Human body modeling can be various, due its complexity and the proposed calculation method. The task that arises is how to find an appropriate and suitable representation, taking into account the human body's complex geometric structure. Some geometric bodies such as a parallelepiped, cylinder, sphere, spheroid or ellipsoid or their combination can be used as a human model, where the approximation is rather rough. Another possibility for modeling is using cubes or parallelepipeds, where the dimensions have a direct influence on the results gained.

Our system offers a semiautomatic procedure for the development of individual human models. The human model is presented with a description of its external surface and the surface between different tissues inside the human body using triangles [8, 9]. The choice of the triangles as a basic shape for surface description is because of their characteristics such as flexibility and the possibility of simple representation of any surface shape with their suitable selection. Figure 1 represents a human model described using triangles. The choice of describing the surface structure with triangles is linked to the calculation methodology developed for field determination.

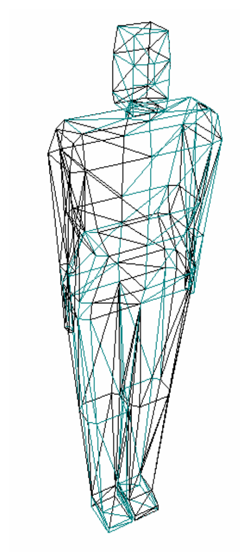

Figure 1 – A human model
Слика 1 – Модел на човечкото тело

V. Methodology

The human body has a complex geometric structure and consists of different tissues such as skin, fat, muscles, bones, etc., each with different frequency-dependent electrical characteristics. From the aspect of EMF influence determination, the electrical characteristics of interest are tissue permittivity and specific conductivity. These characteristics are frequency dependent and different for each body tissue. Table 2 gives the relative permittivity values for some tissues for specific frequencies. In Table 3, specific conductivity values for the same tissues and for the same frequencies are given [10].

Table 2 – Табела 2

Relative permittivity for different tissues
Релативна пермитивност за различни ткива

f	Muscle	Brain	Bone	Fat
100 Hz	$3.2\ 10^5$			1.510^5
100 kHz	$3\ 10^4$	3800	280	$2\ 10^4$
1 MHz	2460–2530	1250	87	
100 MHz	67–72	237–289	23	4.5–7.5
1 GHz	57–59	45	8	4.3–7.5
10 GHz	40–42	40	50–52	4–7

Table 3 – Табела 3

Specific conductivity [S/m] for different tissues
Специфична проводност [S/m] за различни ткива

f	Muscle	Brain	Bone	Fat
100 Hz	0.076		0.0126	0.02-0.07
100 kHz	0.40	0.17	0.02–0.07	
1 MHz	0.83–0.85	0.21	0.0144	
100 MHz	0.95–9.99	0.45–0.63		0.02–0.07
1 GHz	1.38–1.45	0.89–1.17	0.0173	0.03–0.09
10 GHz	8.3	10		0.3–0.4

In fact, we are dealing with a complex structure in regard to electric characteristics. Therefore, it is clear that the problem to be solved is to determine the electric field in non-homogenous media. One procedure is well known in the literature [11 ,12], based on the equivalency of body influence with characteristics different from those of free space with an equivalent current

$$\vec{J} = j\omega(\underline{\varepsilon} - \varepsilon_0)\vec{E} \tag{2}$$

where $\vec{J}$ is the current density, $\underline{\varepsilon}$ complex permittivity and $\vec{E}$ is the electric field vector. The use of this procedure is to determine the field in a homogenous medium with a known current distribution in space. But when dealing with a complex geometric system, although we determine the field in a homogenous medium, the problem leads to solving systems of a high order. Therefore, a procedure requires that a human body, as a non-homogenous medium, be divided into regions with the same electrical characteristics. The influence of the field within separated body regions is calculated from electric and magnetic currents on the boundary surfaces. Posted mathematical models determine equivalent electric and magnetic current densities on boundary surfaces, obtained from boundary surface conditions [12], leading to

$$\vec{J}_s = \vec{n} \times \vec{H} \quad \text{and} \quad \vec{J}_{sm} = -\vec{n} \times \vec{E} \tag{3}$$

where $\vec{J}_s$ and $\vec{J}_{sm}$ are surface electric and magnetic currents densities, $\vec{n}$ is normal surface vector directed to the boundary surface and $\vec{E}$ and $\vec{H}$ are electric and magnetic field vectors, in the same place. Electric and magnetic fields can be expressed with electric and magnetic vector potential, with the relations

$$\vec{E} = -j\frac{1}{\omega\underline{\varepsilon}\mu} graddiv\vec{A} - j\omega\vec{A} - \frac{1}{\underline{\varepsilon}} rot\vec{F} \tag{4}$$

$$\vec{H} = \frac{1}{\mu} rot\vec{A} - j\frac{1}{\omega\underline{\varepsilon}\mu} grad\vec{F} - -j\omega\vec{F} \tag{5}$$

where $\vec{A}$ is magnetic vector potential, $\vec{F}$ electric vector potential, $\underline{\varepsilon}$ complex permittivity, μ permeability of the medium and ω is frequency. The following relations are valid for electric and magnetic vector potential

$$\vec{A} = \frac{\mu}{4\pi}\int_s \vec{J}_s \frac{e^{-\gamma r}}{r} dS \qquad \vec{F} = \frac{\varepsilon ?}{4\pi}\int_s \vec{J}_{sm} \frac{e^{-\gamma r}}{r} dS \tag{6}$$

where $\vec{J}_s$ and $\vec{J}_{sm}$ are surface electric and magnetic current densities, and γ is the propagation constant in the region with defined characteristics.

Replacing the relation (6) in field equations (4) and (5), we obtain the equations for electric and magnetic fields as functions of electric and magnetic vector potentials. Using the boundary conditions for tangential components for electric and magnetic fields for both sides of the boundary surface, the equations for equivalent surface currents are obtained. This approach leads to the determination of surface distributed currents and it requires fewer calculations.

During these calculations, we request that the developed procedure is not limited by the geometry structure analysed. Here, the determination of surface current distributions is a problem that has no exact analytical solution. For an approximate solution, some approximations are made, taking constant values for currents over each part of the surface, ect., triangle, or using special approximations for currents and charges. For current determination, a point-matching method is used, where matching points are the centres of gravity of the triangles.

During the calculation, the human body is considered as a homogeneous medium with relative permittivity ε_r and conductivity σ, taken as average values for tissue characteristics of specific frequencies, according to [10]. The electric field determined in the human is from equivalent electric and magnetic currents on its surface and a field given through electric scalar potential and magnetic vector potential

$$\vec{E} = j\omega\vec{A} - grad\,\varphi \tag{7}$$

where $\vec{E}$ is electric field, $\vec{A}$ is magnetic vector potential, and φ is electric scalar potential. Knowing the electric field distribution in the body, other parameters valid for the assessment of EMF influence such as SAR can be obtained.

In many cases, the object of interest is a specific part of human body, and the determination of EMF influence on it. The proposed method enables solving the problem in steps. First, the calculations are made using a rough human model. The next step uses a precise model of the part selected for calculation. For example, if an implant is positioned in a human leg, that part can be described with much finer presentation. Figure 2 represents a human body model in such a case. This method of human model presentation slightly decreases the accuracy of the results, but in this way we reduce the scope of the calculations.

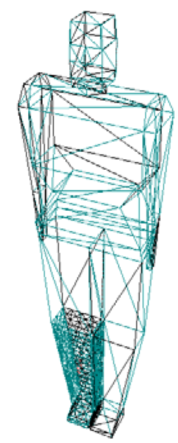

Figure 2 – Human model with in parts different precision
Слика 2 – Модел на човечкото тело со вариpачка прецизност

As an illustration of the proposed procedure for EMF influence determination, several examples are given. According to the fact that EMF sources have wide frequency range, the examples illustrate the procedure for sources on low and high frequencies.

The first is related to electric field in human determination when exposed to a normalized value of the incident field (1 kV/m), from a power line at 50 Hz. The power line is defined with its geometry, and the human is positioned under it, on perfect ground. That means that during calculations, the ground is considered as a perfect surface in taking account of its influence. The human body is considered as a homogenous medium with relative permeability ε_r and conductivity σ, as average values of those quantities for tissues of a specific frequency, accordingly [10]. The results for the electric field in a human being can be given in a longitudinal or a cross section of the human body. Some of the obtained results are presented in Figure 3. Figure 3 represents the electric field distribution in longitudinal section on the same surface as the power line. In the Figure the brighter shadows represent a stronger field. It should be mentioned that the bright zones which appear especially on the edges are the result of a rather rough model representation. The results show that electric field values in such a case are within recommended limits.

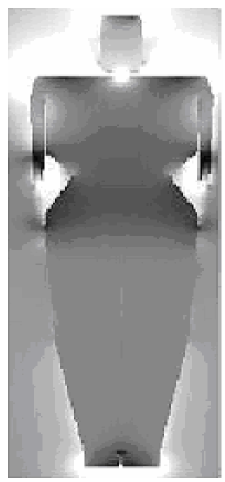

Figure 3 – A longitudinal section
Слика 3 – Лонгитудинален пресек

The second example illustrates electric field determination in the human head when a mobile device antenna is near it. The antenna geometry is given as a dipole antenna, and it is positioned vertically and parallel with the human head at a distance of 2 cm. The antenna is fed with 0.6 W power, and it works on 900

MHz. The human body is considered as a homogenous medium with relative permeability ε_r and conductivity σ, as average values of those quantities for tissues of that frequency [10]. The obtained electric field is usedto calculate the values for SAR. In such a case SAR value are around 1.25 mW/g, when the distance between the human head and the antenna is 1.5-2.5 cm, and they are below protection value of 1.6 mW/g according to ANSI/IEEE standards.

The developed procedure is applied for electric field determination in a human body that contains an implant with electrical characteristics quite different from those of tissues. The implants can be different, from metal implants to various electrical devices such as pacemakers, for example. In that case, the structure geometry, source value, characteristics of implant and the human body are defined parameters. Obtained values for the electric field show it slightly increasing by several percentage points compared with the case where there is no implant in the body, but far below permitted limits. Some stronger field appears on the edges of the implant, but this is also below the recommended values for such a case.

VI. Summary

Investigating the ways EMF influences the human body enables us to understand more about the effects of human exposure, and with that to find ways for protection. The proposed methodology for determining EMF influence on humans exposed to EMF fields is an effort in that direction. During this, modeling of human body and forms of incident fields arise as problems that should be solved with consideration. The proposed human model is correlated with techniques developed for determining the electric field in the human body. The determined field in the human enables other relevant parameters for EMF influence on humans, such as SAR, to be obtained. The advantages of the method presented are that it has no specific restrictions due to methods of EMF source modeling, the forms of the incident field or its frequency, as well as the geometric or electric characteristics of the described structure. The last one enables EMF influence determination in a case where there is an implant in a human body with characteristics quite different from those of tissue. The proposed methodology enables calculations to be made in steps due to possibility of modeling different parts of the human body with varying precision.

The obtained results for the electric field in humans are a basis for a discussion of the possible biological effects on humans exposed to EMF influence.

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Резиме

ОДРЕДУВАЊЕ НА ЕЛЕКТРОМАГНЕТНИ ВЛИЈАНИЈА НА ЧОВЕК ИЗЛОЖЕН НА ЕЛЕКТРОМАГНЕТНИ ПОЛИЊА – МОДЕЛИРАЊЕ И МЕТОДОЛОГИЈА

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Проучувањата на начините на електромагнетните влијанија врз луѓето, овозможуваат да се разберат ефектите од ваквата изложеност, а со тоа да се пронајдат начини за заштита. Предложената методологија за одредување на електромагнетните влијанија на човек изложен на електромагнетни полиња, е обид во тој правец. При тоа, моделирањето на човекот и облиците на инцидентните полиња, се појавуваат како проблеми што треба посебно да се решат. Предложениот модел на човек е во корелација со развиената техника за одредување на електричното поле во човекот. Вака одреденото поле овозможува да се добијат и други релевантни параметри за отсликување на електромагнетните влијанија, како на пример величината SAR. Предностите на презентираниот метод се тие што истиот нема посебни ограничувања во однос на начините на моделирањето на изворите на електромагнетните полиња, облиците на инцидентното поле или неговата фреквенција, како и геометриските или електричните карактеристики на опишаната структура. Последното овозможува одредување на влијанијата кога постои имплант во телото на човекот со сосема различни карактеристики од неговите. Предложената методологија овозможува пресметките да се вршат во чекори, како резултат на можноста на моделирање различни делови од телото со различна прецизност.

Добиените резултати за електричното поле во човекот се основа за дискусија за можните биолошки ефекти врз човекот изложен на електромагнетно влијание.

Клучни зборови: електромагнетно поле, електромагнетно влијание, човечки модел, индуцирано електрично поле, САР.

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