Paediatr Croat. 2013; 57 (Supl 1): 1-9

Pregled
Review

ON THE ASSESSMENT OF PREGNANT WOMAN/FOETUS EXPOSURE TO ELECTROMAGNETIC FIELDS BY USING NUMERICAL METHODS

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Aim: The paper deals with pregnant woman and foetus exposure to electromagnetic fields at extremely low and high frequencies, respectively using numerical modeling approach.

Methods: The pregnant woman and foetus are represented by different computational models taking into account both the geometry and the electrical properties of organs. Different physical and geometrical properties of the relevant tissues are taken from medical data available in relevant literature. At Low Frequency (LF) realistic, anatomically based, model of pregnant woman/foetus is based on a quasistatic approximation, Laplace equation and related numerical solution by means of a three dimensional multi-domain Boundary Element Method (BEM). The model accounts for variations in geometry, body mass, fat and overall chemical composition in the female body. At High Frequency (HF) exposures, due to high mathematical complexity of the problem a simplified representation of pregnant woman/foetus is based on the corresponding Helmholtz equations formulation. (based on the Finite Element Method - FEM). Numerical simulation is carried out by means of FEKO software package.

Results: Some computational examples are presented throughout the paper. Certain results for the induced current density and specific absorption rate (SAR), respectively suggest the foetus to might get overexposed.

Conclusions: The paper reviews the exposure of a pregnant woman/foetus to LF electric fields generated by overhead power lines and to HF antenna/plane wave radiation.

Analyzing the calculated results for LF exposure the simulation results suggest that the foetus is exposed to higher values of current density than the mother brain. Regarding HF exposure it has been found that for foetus, the limit for whole-body average should be considered, as for this quantity the foetus might get overexposed.

Descriptors: THE PREGNANT WOMAN/FOETUS EXPOSURE, ELECTROMAGNETIC FIELDS, INDUCED CURRENT DENSITY, SPECIFIC ABSORPTION RATE (SAR), NUMERICAL METHODS

Abbreviations:
AF - amniotic fluid; BEM - Boundary Element Method; ELF - Extremely Low Frequency; FDTD - Finite Difference Time Domain; FEM - Finite Element Method; HF - High Frequency; HV - High Voltage; ICNIRP - International Commission on Non-Ionizing Radiation Protection; LF - Low Frequency; MRI - Magnetic Resonance Imaging; SAR - Specific Absorption Rate

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INTRODUCTION

The tremendous growth of modern power and communication systems has caused the increase of public concern regarding possible adverse health effects of electromagnetic fields generated by these systems. A comprehensive view to the subject could be found in a number of review papers (1, 2). As the human body is extremely complex structure from the bioelectromagnetics point of view it is usually analyzed by means of sophisticated numerical methods. Furthermore, as measurement of induced currents and fields in the body is not possible the phantoms having some electrical parameters corresponding to humans are often used (3-5).

In particular, the assessment of exposure levels in the pregnant woman/foetus is extremely difficult task due to; a lack of data on electrical properties at low frequency for the foetus and the surrounding tissues, a complex variation of geometrical and physical properties of the body throughout the pregnancy period. Also, it is not possible to collect in-vivo measurement in a real case scenario.

Generally, the numerical models existing in literature can be divided in two groups:

- The realistic models of the human body (or specific organs) with a high discretization density - mainly based on Magnetic Resonance Imaging (MRI) and require high computational cost (1, 6-11).

- Simplified models, computationally much less expensive fail to ensure accurate results in many scenarios (1-5, 12).

The present paper reviews a pregnant woman/foetus exposed to high voltage (HV) extremely low frequency (ELF) electric fields generated by overhead power lines and to HF antenna/plane wave radiation (13-15). The LF analysis is based on the calculation of induced currents and electric fields in the foetus for different conductivity scenarios at different stages of pregnancy, taking into account different position of the foetus inside the maternal matrix. The LF exposure assessment is carried out by means of a three dimensional multi-domain collocation Boundary Element Method (BEM), while the HF exposure analysis is performed via FEKO simulation tool (based on the Finite Element Method (FEM)) (13-15).

THEORETICAL DOSIMETRY

Depending on the frequency, the electromagnetic radiation is classified as non-ionizing or ionizing. Non-ionizing fields are split into two main categories:

- Low frequencies (up to about 30 kHz);
- High frequencies (from 30 kHz to 300 GHz).

As far as the interaction of humans with non-ionizing radiation is concerned the LF fields may cause excitation of sensory, nerve and muscle cells while at HF fields the body, due to the resonance effect (the body dimensions become comparable to the external field wavelength), absorbs the radiated energy, and the related heating effects become dominant. When human is exposed to LF fields the thermal effects seem to be negligible, and possible nonthermal effects are related to the cellular level. The knowledge of the internal current density is the key to understanding the interaction of the human body with LF fields. Note, that according to ICNIRP guidelines from 1998 the current density was a main parameter for the estimation of LF exposure effects, while the new ICNIRP guidelines from 2010 propose the induced electric field instead of the induced current density (16, 17). However, there is a substantial amount of results for the current density in the relevant literature, therefore, for the comparison purposes, this work also deals with the assessment of current density.

The key point in HF dosimetry is related to thermal effects, i.e. the question is how much EM energy is absorbed by a biological body and where it is deposited. The basic dosimetric quantity for HF fields is the specific absorption rate (SAR). Theoretical models are required to simulate various exposure scenarios, and thereby establish safety guidelines and exposure limits for humans (17). The mathematical complexity of the problem has led researchers to investigate simple models such as plane slab, cylinders, homogeneous and layered spheres and prolate spheroids (18).

Sophisticated numerical modeling is required for a successful prediction of the internal field distribution in realistic body models (13-14, 18-20). Contemporary anatomically based computational models comprising of cubical cells are mostly related to the application of the Finite Difference Time Domain (FDTD) methods, the Finite Element Method (FEM) and Boundary Element Method (BEM).

Low frequency exposures

The current density inside the biological body, a key-quantity to analyze the interaction of humans with LF fields, can be induced due to an external electric or magnetic field, respectively. Internal current density J due to electric fields is axial in nature and is defined by the constitutive equation:

$$J = \sigma E \tag{1}$$

where σ is tissue conductivity and E is the corresponding internal electrical field.

The current density induced due to magnetic field forms loop and is given by:

$$J = \sigma \pi r f B \tag{2}$$

where B is the corresponding magnetic induction normal to the human body, f is the operating frequency and r is the radius of the loop.

High frequency exposures

The fundamental quantity in HF dosimetry is the specific absorption rate (SAR) which is defined as the rate of energy W absorbed by, or dissipated in the unit body mass:

$$SAR = \frac{dP}{dm} = \frac{d}{dm}\frac{dW}{dt} = C\frac{dT}{dt} \tag{3}$$

where C is the specific heat capacity of tissue, T is the temperature and t denotes time.

In tissues, SAR is proportional to the square of the induced electric field:

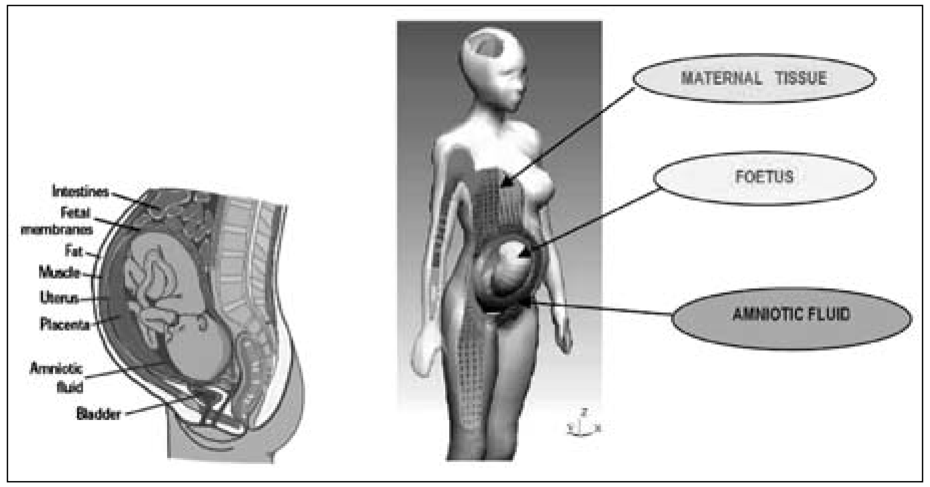
$$SAR = \frac{dP}{dm} = \frac{dP}{\rho dV} = \frac{\sigma}{\rho}|E|^2 \tag{4}$$

where E is the root-mean-square value of the electric field and ρ is the tissue density and s is the tissue conductivity.

The distribution of SAR generally depends on the incident field parameters, the characteristics of the exposed body, ground effects and reflector effects. In the cases when the electric field is oriented parallel to the long body axis the whole body SAR reaches maximal values.

EXPOSURE OF PREGNANT WOMAN/FOETUS TO LF FIELDS

At LF exposures human tissues and organs behave as good conductors. For most of the tissues, conductivity σ varies between 0.2 and 0.5 S/m, while the relative permittivity is around 100. Challenging aspects of the problem are related to variable geometrical and physical data of the relevant tissues for mother and foetus along gestation, varying exposure conditions and changes in material proper-



a) Different tissues b) Division of maternal abdomen into equivalent subdomains

Figure 1
A view to the calculation domain

ties and geometry pertaining to; volume, mass and geometry of the maternal body and foetus, same as electrical properties of the participating tissues.

During the fetal period (from 8th to 40th gestational week), the growth, development and maturation of the structures that have been already formed takes place. Pregnancy stages considered in this model are: 8th, 13th, 26th and 38th gestational weeks (13-14). The conductivity data for the foetus are scarce and scattered in the literature.

For the maternal abdomen, the division into sub-domains is based on the different properties of the tissues, as shown in Fig 1a. The amniotic fluid (AF) has the highest conductivity which varies depending on the period of gestation. Kidney, muscle bone cortical, bladder, spleen, skin have conductivity very close to 0.1 S/m, while the ovary and cartilage conductivity is around 0.2 S/m. Therefore, all these tissues can be grouped into one sub-domain - maternal tissue. Furthermore, the uterus conductivity is 0.23 S/m, which is very similar to the conductivity of the maternal tissue. On the other hand, the placenta is assumed to have the same conductivity as the blood and considered as part of the maternal-tissue sub-domain. Thus, the maternal abdomen is divided into 3 subdomains: maternal tissue, amniotic fluid, contained within the uterus and foetus, as depicted in Fig. 1b.

During the foetal period length and weight do not change in the same way, i.e. the foetal length change is greatest in the second trimester, while foetal weight change is greatest in the final weeks of development. Furthermore, the foetus is free to move inside the maternal abdomen, principally until the 24th week. Since then, the movement is more constrained. Figure 2 shows a general 3D view of 1.7 m tall at 26th week of pregnancy (foetus in the cephalic position).

Note that the model accounts for both cephalic and breech position of the foetus.

An outline of the mathematical model

At low frequencies the quasi-static approximation can be used as the body dimensions are electrically short, i.e. rather small compared to the wavelength of the external field. Upon this assumption, considering σ and ε to be constant within a sub-domain and the static approximation for the ELF exposure model can be formulated via the Laplace type equation (See Appendix). The electric field over flat ground plane is assumed to be vertical and uniform near the ground level and, the human body is located between the parallel plate electrodes, in the middle of the lower one. A calculation domain with the corresponding boundary conditions is shown in Fig 3.

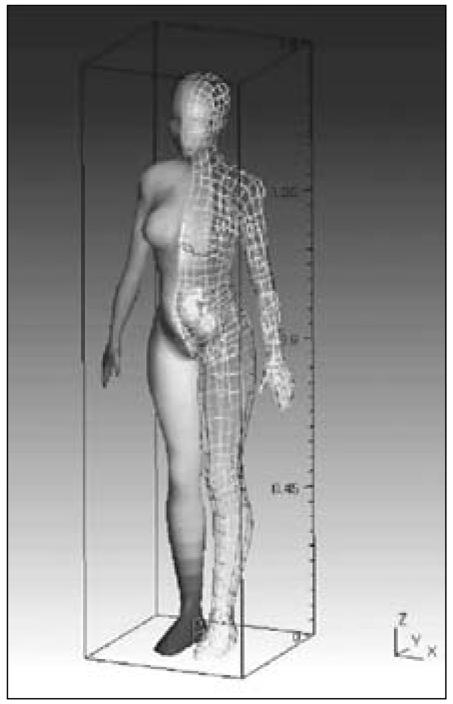


Figure 2
A 3D view of the model at 26th week of pregnancy (cephalic presentation)

The lower plate electrode represents the zero potential of the ground while the upper plate electrode is assumed to be at the potential of a high voltage power line. Three different conductivity scenarios, adopted from literature and shown in Table 1 are used in this study (13). The multidomain Boundary Element Method (BEM) has been applied to solve the Laplace equation and determine internal currents, potentials and electric fields (19, 20).

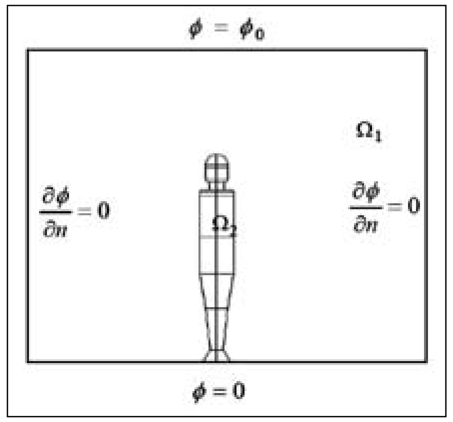


Figure 3
Calculation domain with the prescribed boundary conditions

Table 1
Conductivity scenarios

Scenario	[S/m]	Week 8	Week 13	Week 26	Week 38
	σf	0.23	0.23	0.23	0.23
1	σAF	1.28	1.28	1.27	1.10
	σm	0.20	0.20	0.20	0.20
	σf	0.996	0.996	0.574	0.574
2	σAF	1.70	1.70	1.64	1.64
	σm	0.52	0.52	0.52	0.52
	σf	0.732	0.732	0.396	0.396
3	σAF	1.70	1.70	1.64	1.64
	σm	0.17	0.17	0.17	0.17

Numerical results

Figure 4 shows a lateral view of the sliced pregnant woman model at 8th, 13th, 26th and 38th gestational week. Note that the direction of the electric field in the maternal tissues is represented with black arrows, while the iso-lines represent the corresponding scalar potential. A view to the sliced model of the pregnant woman with the electric field/scalar potential lines for the foetus in cephalic and breach presentation, respectively is shown in Fig. 5.

From the results presented in Figs 4 and 5 it is visible that the uterus, due to its higher conductivity comparing to the maternal tissue, tends to concentrate the field lines. Figure 6 shows a 3D view of the partially sliced model of the pregnant woman with clipping planes in order to visualize the interior results for the scalar potential and electric field respectively. There are seven colorbars on the left hand side of the Figure 6 representing the correspondence between the colormap and the numerical scale in each case. All results correspond to the case of exposure to 1/5 V/m (13).

The maximum current density occurs at the 8th gestational week and decreases progressively as the foetus develops. This decrease can be explained as a consequence of two factors: 1) Both the foetus and AF conductivity decrease with age; 2) As the foetus grows the extremities drawn in towards the center of the chest and head tucked down to the chest. Thus, the external surface of foetus is smoother and the cross sectional area becomes more regular.

In addition, in all conductivity scenarios the current density in breech presentation tends to be higher than in the cephalic. This effect is less pronounced in the last stage of pregnancy (38 week). For a given exposure, the maximum value of current density in the foetus occurs during the 8th week. The maximum current density obtained in the foetus for an incident external field E=10 kV/m is 7.4 mA/m2.

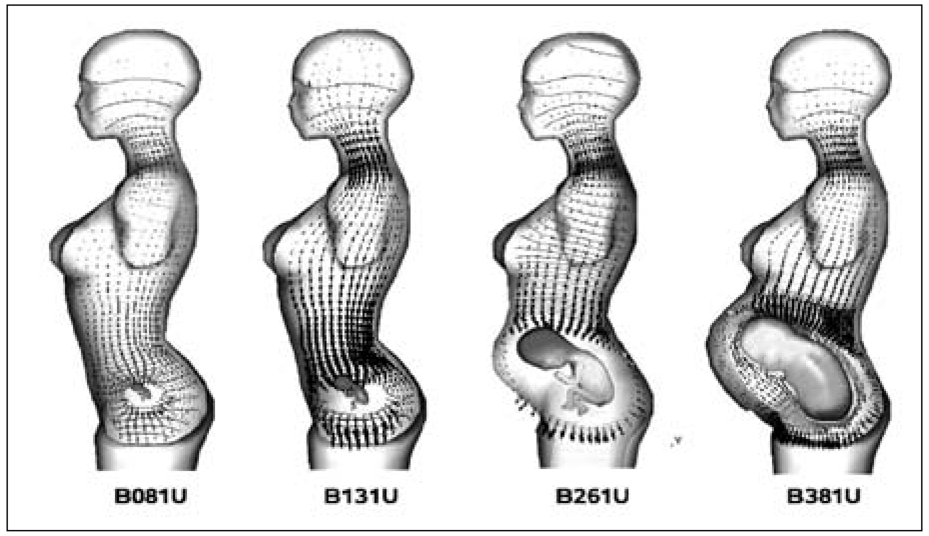
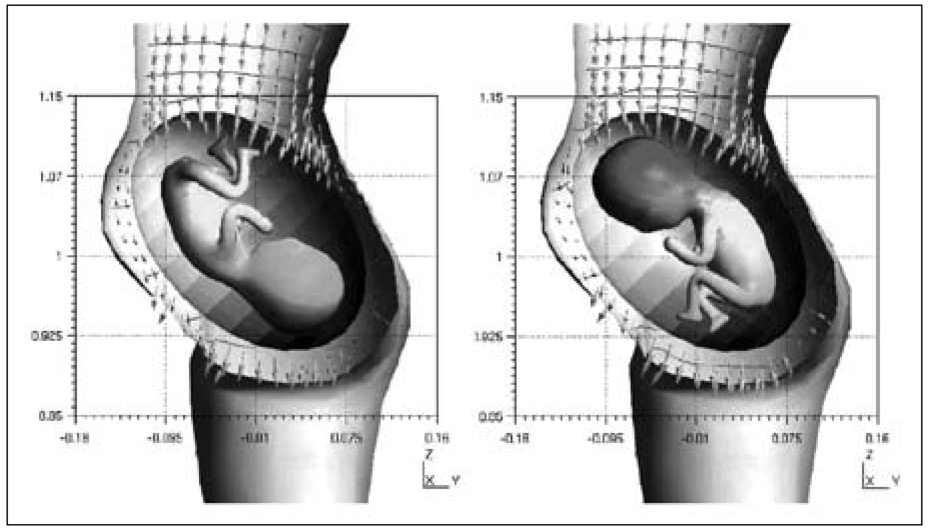
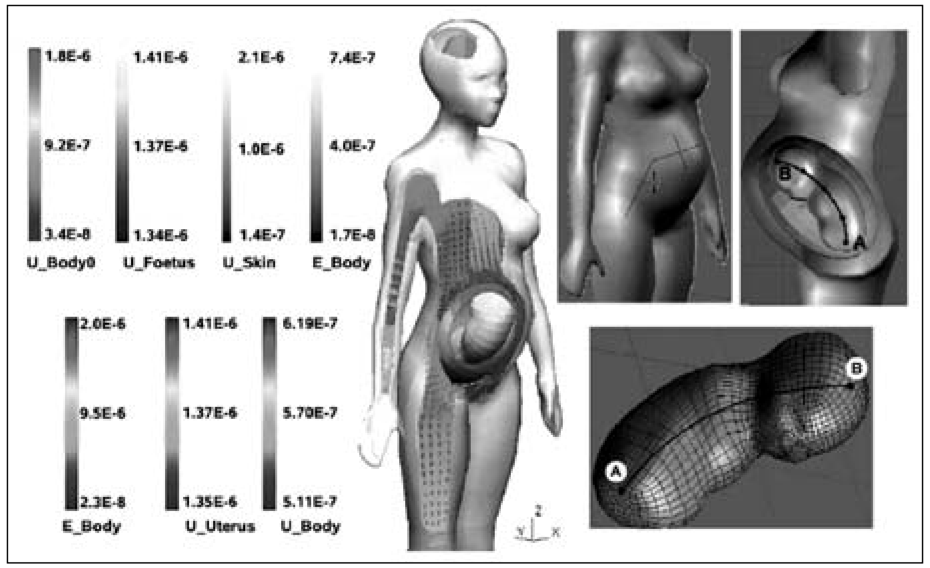


Figure 4
Lateral view of the pregnant woman at 8th, 13th, 26th and 38th gestational week (breech presentation)



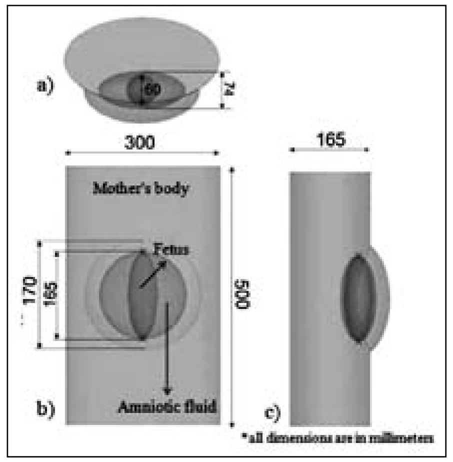
a) foetus in the cephalic presentation   b) foetus in the breach presentation

Figure 5
Lateral view of the pregnant woman at 26th gestational week



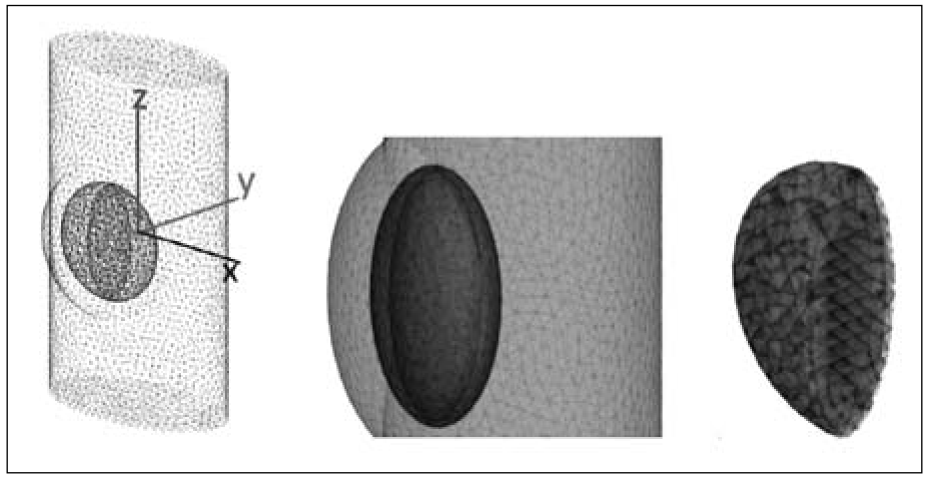
Ubody0 - the potential observed in the sagittal plane, excluding the limbs.
U_Foetus - the potential in the skin of the foetus, the values range from 1.41 μV to 1.34 μV.
U_Skin - the potential measured in the maternal skin, i.e. the interface between air and body.
E_body and E_body0 - the vector field plot related to E- field in the maternal body.
U_Uterus and U_Body - the potential in the uterus and body surfaces, respectively.

Figure 6
The slice model of the pregnant woman (left) and observational model along the spine (right) at 26th gestational week



a) top view, b) front view, c) side view

Figure 7
Numerical model of pregnant woman



a) entire model   b) more detailed preview of mother's torso   c) foetus in amniotic fluid

Figure 8
Meshed model (FEKO)

EXPOSURE OF PREGNANT WOMAN/FOETUS TO HF FIELDS

When the body size is half the wavelength, the resonant frequency is reached and a large amount of energy is absorbed from the field at frequencies between 30 MHz and 300 MHz Note that children have a higher resonant frequency than adults.

FEKO model of the pregnant woman

This work addresses the pregnant woman/foetus exposure to HF fields using FEKO software package (based on Finite Element Method - FEM). The computed SAR distribution, peak localized 10g-averaged SAR and volume-averaged SAR are compared to the results available from relevant literature. A simplified FEKO model of the pregnant woman body is shown in Fig 7 (15).

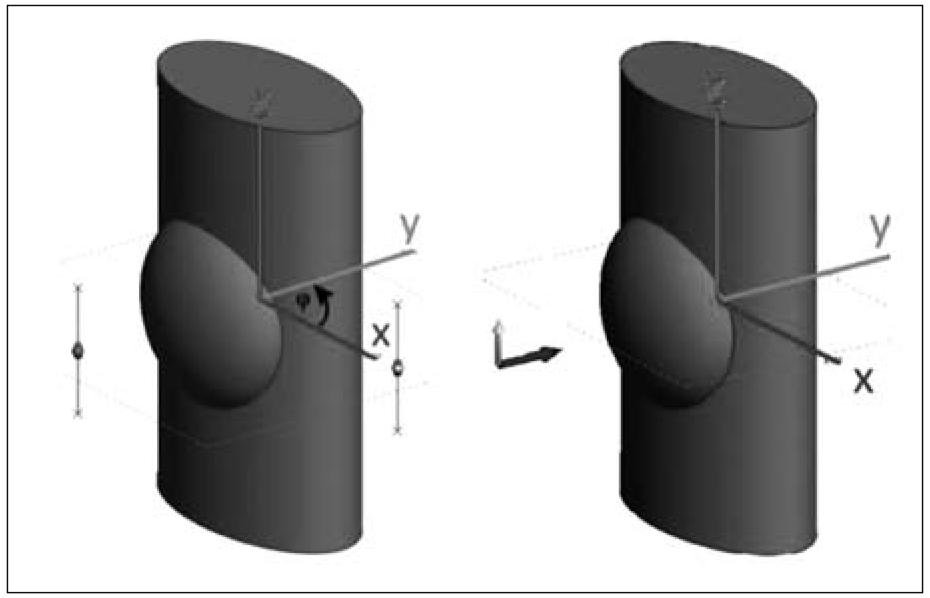
The presented model required discretization to more than 150000 tetrahedra. The discretization scheme is depicted in Fig 8.

The pregnant woman is exposed to dipole antenna (at 150, 900 and 1800 MHz) and incident plane wave (at 900 and 1800 MHz), as indicated in Figure 9. The vertical dipole with radiated power Prad =1 W is located at the distance d=6 cm in front of the torso.

The model is analyzed for two dipole positions: φ=0°, φ=-90°. Furthermore, an exposure to vertically polarized incident plane wave with power density S=1 mW/cm2 is considered. The actual parameters are chosen for the comparison purposes.

Numerical results

SAR simulation results at 900 and 1800 MHz, respectively, using FEKO are shown in Figure 10 and 11, respectively. The results are presented for two excitation types: dipole antenna positioned at φ=-90° and plane wave radiation. The results for peak localized 10g-averaged SAR in fetus and the peak value of SAR in mother's body at 150 MHz, for diffe-



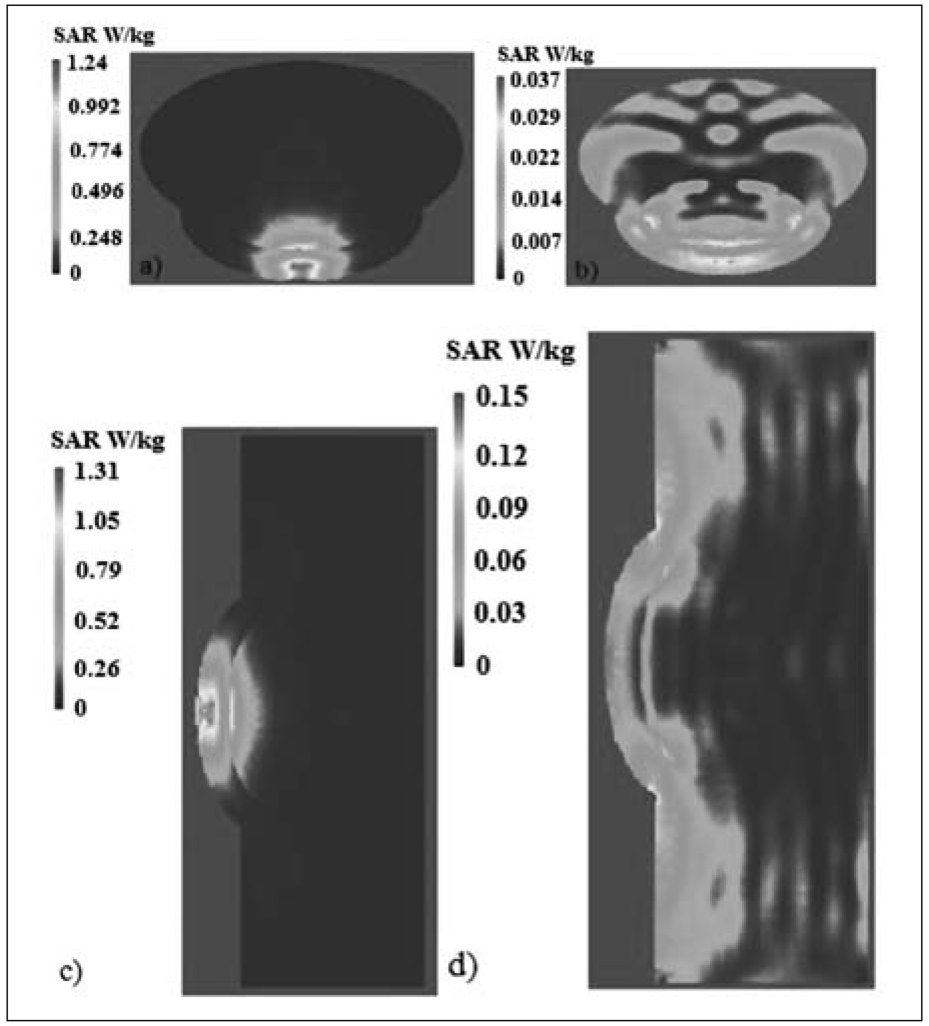
a) dipole antenna b) plane wave

Figure 9
Radiation sources

rent antenna positions (see Fig. 6a), are listed in Table 2. The results, obtained with FEKO are compared to the results reported in (6-8) and found to be in a satisfactory agreement.

A certain discrepancy exists for the foetus with the antenna in position φ=0°. However, our model had larger amniotic fluid volume having resulted in more progressive electric field attenuation which caused lower SAR values in the foetus. Table 3 presents the values of peak localized 10g-averaged SAR and volume-averaged SAR. The results, obtained with FEKO are compared to the results reported in literature. The volume-averaged SAR calculated for the foetus at 900 MHz (dipole source) is 0.11 W/kg which exceeds the limit of 0.08 W/kg given for whole-body average SAR by ICNIRP (16).

This raises the question regarding the limit applicable for the foetus exposure. As a matter of fact the limits for localized 10g-averaged SAR given by ICNIRP (2 W/kg for head and trunk, 4 W/kg for limbs) are meant for body parts. However, foetus essentially represents a whole body, possibly more sensitive to potential adverse effects than children or adults. Therefore, the limit foe whole-body average SAR should be reconsidered for the case of foetus as the obtained results suggest the foetus to might get overexposed.



a) xy plane, dipole source; b) xy plane, plane wave source
c) yz plane, dipole source; d) yz plane, plane wave source

Figure 10
SAR distribution at 900 MHz

CONCLUSION

The paper reviews the exposure of a pregnant woman/foetus to LF electric fields generated by overhead power lines and to HF antenna/plane wave radiation. Analyzing the calculated results for LF exposure the simulation results suggest that the foetus is exposed to higher values of current density than the mother brain. Namely, the contrast between foetus, amniotic fluid and maternal tissue conductivities plays a significant role in the assessment of the current densities induced in the foetus. The important factors are the foetus geometry and its relative posture inside the uterus, as well. It is worth noting that the amniotic fluid and foetus tissues are more conductive than the rest of the adult tissues.

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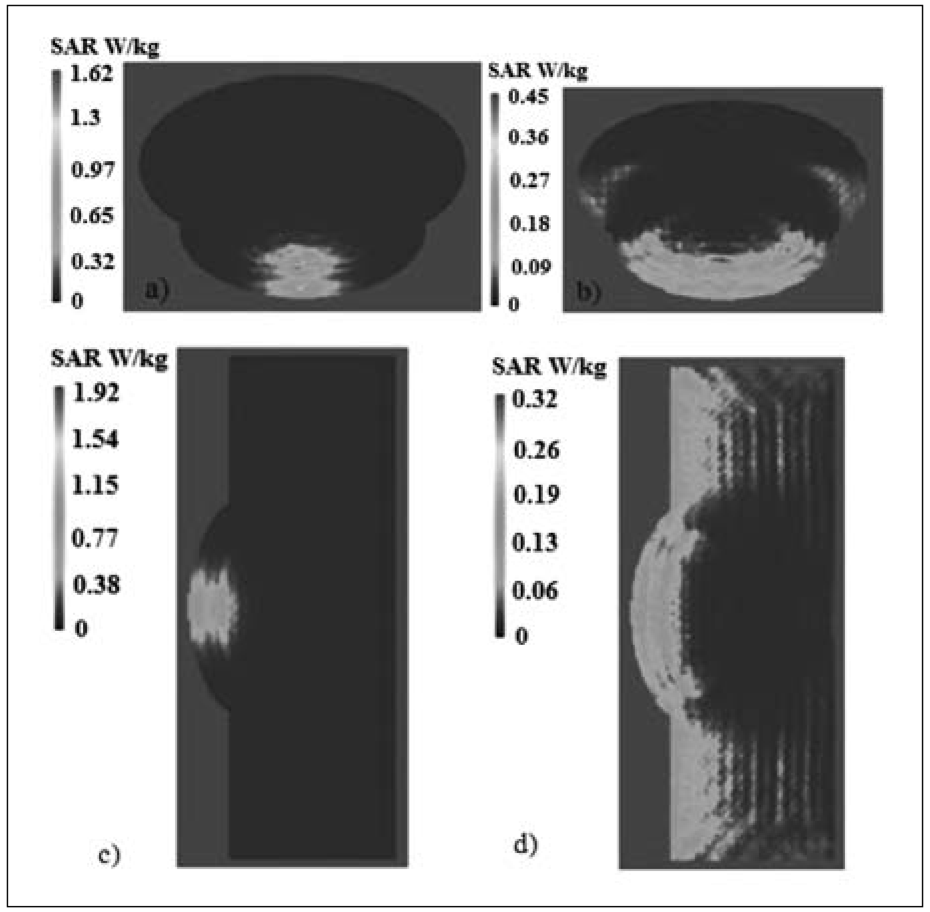

a) xy plane, dipole source; b) xy plane, plane wave source
c) yz plane, dipole source; d) yz plane, plane wave source

Figure 11
SAR distribution at 1800 MHz (FEKO)

Table 2
Peak SAR and peak localized 10g-averaged SAR at 150 MHz

SAR [W/kg]	φ=0°		φ=-90°	
	Fetus avg_10g	Mother's body Peak	Fetus avg_10g	Mother's body Peak
K. Ito (5) FDTD	-	-	0.36	1.15
H. Kawai (12) FDTD	0.1	1.3	-	-
FEKO FEM	0.03	1.6	0.34	1.4

Table 3
Peak localized 10g-averaged SAR and volume-averaged SAR

		Dipole source				Plane-wave source			
	SAR [W/kg]	900 MHz		1800 MHz		900 MHz		1800 MHz	
		10g	avg	10g	avg	10g	avg	10g	avg
FEKO	Mother's body	1.25	0.01	1.12	0.006	0.3	0.05	0.22	0.05
	Amniotic fluid	0.62	0.07	0.26	0.03	0.09	0.05	0.02	0.05
	Fetus	0.24	0.11	0.12	0.03	0.06	0.02	0.03	0.02

As far as the HF exposure is concerned it has been found that for foetus, the limit for whole-body average should be considered, and these results suggest the foetus might get overexposed. Regarding the future work, in a long term, more detailed tissues could be incorporated, particularly in the foetus, where little information pertaining to the electrical properties is currently available.

APPENDIX: THE LAPLACE EQUATION FORMULATION AND RELATED BEM SOLUTION

The problem of human exposure to LF fields can be formulated by Laplace type equation of the form:

$$\nabla\left[(\sigma + j\omega\varepsilon)\nabla\phi\right] = 0 \tag{A.1}$$

where φ is the scalar electric potential, ε and σ denotes the medium permittivity, respectively, and conductivity $\omega=2\pi f$ is the operating frequency.

The induced current density can be expressed in terms of the scalar electric potential using the constitutive equation:

$$\vec{J} = -\sigma\nabla\phi \tag{A.2}$$

To solve the Laplace equation (A.1) the corresponding air-body interface conditions have to be specified.

The continuity condition for the tangential component of the electric field near the two-media interface is given by:

$$\vec{n}\times\left(\vec{E}_b-\vec{E}_a\right)=0 \quad \text{and} \quad \vec{E}_{a,b}=-\nabla\phi_{a,b} \qquad (A.3)$$

where $\vec{n}$ is the unit normal to the interface and $\vec{E}_a$ and $\vec{E}_b$ represent the fields in the air and in the body, respectively.

The continuity condition for the normal component of the induced current density near the body-air interface is given by:

$$\vec{n}\cdot\vec{J}_b=-j\omega\rho_s \qquad (A.4)$$

where p_s denotes the surface charge density.

Finally, the continuity condition for the normal component of the electric flux density at the air-body interface is:

$$\vec{n}\cdot\vec{D}_a=\rho_s \quad \text{and} \quad \vec{D}_a=-\varepsilon_0\nabla\phi_a \qquad (A.5)$$

In addition to interface conditions certain boundary conditions have to be prescribed:

$$\phi=\bar{\varphi} \quad \text{on } \Gamma_1 \text{ and } \quad \frac{\partial\phi}{\partial x_j}n_j=\frac{\partial\bar{\varphi}}{\partial n_j} \quad \text{on } \Gamma_2 \qquad (A.6)$$

The calculation domain is considered to be piecewise homogeneous and is decomposed into an assembly of N homogeneous subdomains Ω_k (k=1, m), where Γ_1 and Γ_2 form the domain boundary.

Using the Green's theorem for scalar functions, the following integral representation for a subdomain can be written, as follows:

$$c(\xi)\phi(\xi)+\int_{\Gamma_k}\phi\frac{\partial\phi^*}{\partial n}d\Gamma=\int_{\Gamma_k}\frac{\partial\phi}{\partial n}\phi^* d\Gamma \qquad (A.7)$$

where φ^* is the 3D fundamental solution of Laplace equation, $\partial\varphi^*/\partial n$ is the derivative in normal direction to the boundary, and c(ξ) is the geometrically dependent free term accounting for the Cauchy type singularity of the integral on the left hand side of (B.3).

Discretization of eqn (14) with N_k elements leads to an integral relation:

$$c_i\phi_i+\sum_{j=1}^{N_k}\int_{\Gamma_{k,j}}\phi\frac{\partial\phi^*}{\partial n}d\Gamma=\sum_{j=1}^{N_k}\int_{\Gamma_{k,j}}\frac{\partial\phi}{\partial n}\phi^* d\Gamma \qquad (A.8)$$

where i stands for the source point and $\Gamma_{k,j}$, represents the *j*-th boundary element of Ω_k. The present implementation is based on the isoparametric approach with quadratic interpolation functions defined for triangular elements.

The method is presented in detail elsewhere, i.e. in (19).

One of the principal advantages of the domain decomposition technique, in addition to its capabilities in dealing with piecewise homogeneous material properties, is that the final system of equations is sparse and highly banded.

Autor izjavljuje da nije bio u sukobu interesa.
Author declare no conflict of interest.

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Sažetak

O ODREĐIVANJU IZLOŽENOSTI TRUDNICE/FETUSA ELEKTROMAGNETSKIM POLJIMA PRIMJENOM NUMERIČKIH METODA

D. Poljak

Svrha: U radu se razmatra izloženost trudnice i fetusa elektromagnetskim poljima na niskim, odnosno visokim frekvencijama, primjenom numeričkog modeliranja.

Metode: Trudnica i fetus predočeni su različitim računalnim modelima uzimajući u obzir geometriju i električna svojstva organa. Različita fizikalna i geometrijska svojstva relevantnih tkiva preuzeta su iz medicinskih podataka dostupnih u relevantnoj literaturi. Na niskim frekvencijama (NF) realistični, anatomski zasnovani, model trudnice/fetusa temelji se na kvazistatičkoj aproksimaciji, Laplace-ovoj jednadžbi i odgovarajućem numeričkom rješenju primjenom trodimenzionalne metode rubnih elemenata (MRE) s višestrukom diskretizacijom domene. U modelu se uzimaju u obzir varijacije u geometriji, masi tijela, salu te sveukupne kemijske karakteristike tijela trudnice. Na visokim frekvencijama (VF), uslijed matematičke složenosti problema pojednostavljnea reprezentatacija trudnice/fetusa zasnovana je na odgovarajućoj formulaciji koja se temelji na Helmholtzovoj jednadžbi (zasnovanoj na metodi konačnih elemenata - MKE). Numeričke simulacije provedene su programskim sustavom FEKO.

Rezultati: Neki računalni primjeri prezentirani su u radu. Određeni rezultati za gustoću inducirane struje, odnosno specifičnu gustoću apsorbirane snage (SAR), ukazuju na mogućnost da u fetusu može doći do prekoračenja graničnih vrijednosti.

Zaključci: U ovom preglednom radu radu razmatra se izloženost trudnice /fetusa NF električnim poljima koje generiraju nadzemni električni vodovi i VF zračenju antena/ravnih valova.

Analizirajući rezulate proračuna za NF izloženost rezultati simulacije ukazuju da je fetus izložen višim vrijednostima gustoće struje od mozga majke. Što se tiče VF izloženosti ustanovljeno je da bi se za fetus trebalo razmatrati usrednjeno ograničenje za čitavo tijelo, pošto za ovu mjeru može doći do prekoračenja graničnih vrijednosti.

Deskriptori: IZLOŽENOST TRUDNICE /FETUSA, ELEKTROMAGNETSKA POLJA, INDUCIRANA GUSTOĆA STRUJE, SPECIFIČNA GUSTOĆA APSORBIRANE SNAGE (SAR), NUMERIČKE METODE

Primljeno/Received: 15. 2. 2013.
Prihvaćeno/Accepted: 28. 3. 2013.