

Computation of SAR in Human Eye and Pregnant Woman Using Different Simulation Tools

Zlatko Živković, Duje Despalatović, Dragan Poljak, Antonio Šarolić, and Khalil El Khamlichi Drissi

Abstract: Electromagnetic modeling of large scale problems arising from complex geometries, such as the human body or the specific organ, is generally undertaken by numerical methods implemented in simulation software packages. The structures involving high discretization density (mainly based on Magnetic Resonance Imaging and handled by Finite Difference Time Domain method) consume tremendously high computational cost. On the other hand, oversimplified numerical models may result in significantly less accuracy. The aim of this work was to investigate how detailed numerical model could be created using standard personal computer. Two rather complex cases of exposure were analyzed: human eye and pregnant woman exposed to radiofrequency electromagnetic radiation. The SAR distribution, peak localized 10g-averaged SAR and volume-averaged SAR in these models were determined using two software packages based on different numerical methods: FEKO software based on Finite Element Method and SEMCAD X software based on Finite Difference Time Domain method. The obtained results were compared to the results arising from other scientific studies which included the models of different complexity solved by different numerical methods.

Index terms: the human eye model, the pregnant woman model, SAR, FEKO, SEMCAD X, FEM, FDTD

I. INTRODUCTION

The rapid growth of modern communication systems has caused the increase of public concern about possible adverse effects of EM radiation to human health. Therefore, the influence of EM radiation on human health has become very interesting research topic. The detailed description of the research that has been done so far is presented in [1]. As the human body presents electromagnetically complex structure, it is generally analyzed using numerical methods. Furthermore, as measurements of absorbed EM energy inside the human body are not possible, the phantoms with equivalent electrical parameters are often used [2-4].

The numerical models existing in literature can be divided in two groups regarding discretization density and tissues involved in the analysis. The realistic models of the human

body (or organs) with a high discretization density are mainly based on Magnetic Resonance Imaging (MRI) [1], [5-10] and require enormous memory capacity same as high processor speed. On the contrary, more simplified models, with lower discretization density and lower demands on computer resources, [1-4] and [11], fail to ensure accurate results. Discretization density becomes particularly important at high frequencies so the simplified models can only be used to a certain extent.

In this paper 3D models of the human eye and pregnant woman were developed in order to estimate how a detailed numerical model can be analyzed using PC with a common nowadays configuration (4-6 GB RAM, 2 GHz processor). The simulations were carried out at standard GSM frequencies (900 and 1800 MHz), and additionally at 150 MHz for the pregnant woman model. Regarding the fact that the basic restriction according to ICNIRP [12], at these frequencies, is defined by Specific Absorption Rate (SAR), its distribution, peak localized 10g-averaged value and volume-averaged value in the examined models were calculated.

The human eye and pregnant woman model, respectively available in literature [1-11] and [13], are based on different numerical methods and include geometries of different complexity (realistic and simplified models) exposed to different radiation sources. The comparison of the results among these studies can be problematic and certain discrepancies could be expected. Therefore, in this study, the identical models of the human eye and the pregnant woman were developed using two software packages based on different numerical methods: FEKO [14] - based on Finite Element Method (FEM) and SEMCAD X [15] - based on Finite Difference Time Domain (FDTD) method. The computer requirements for each model and both numerical methods were estimated and the results for SAR distribution, peak localized 10g-averaged SAR and volume-averaged SAR (obtained using FEM and FDTD methods) were compared. The results were also compared with those available in relevant literature.

II. SIMULATION MODELS

A. The human eye model

The considered model of the human eye (without the head) is presented in Fig. 1a. The model consists of seven tissues: anterior chamber, cornea, ciliary muscle, lens, retina, sclera and vitreous humour. The electrical properties of the eye tissues at the specific frequency are available in [16] and [17] and are listed in Table 1 together with tissue density.

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The dimensions of the eye and its tissues are also available in literature [18]. The eye has been modelled using geometric bodies (cylinder, sphere, cone etc.) which then have been combined in unique model using standard Boolean operations.

For the purpose of FEKO/FEM analysis, the model has been meshed with about 60000 tetrahedra. Hence, the edge length of each tetrahedron has been set to 1 mm. This was found to be the upper mesh limit which could be solved with the dual core 32-bit PC equipped with 4 GB RAM. The detailed view of discretized structure is shown in Fig. 1b.

The same model for SEMCAD X/FDTD analysis has been voxelized with nearly 3 Mcells for the plane wave exposure and with nearly 4 Mcells for the dipole antennas exposure (which yielded the average voxel size in the eye of approximately $0.2 \times 0.2 \times 0.2 \text{ mm}^3$ for both types of radiation sources). Although even higher resolution could be run on such a computer (dual core 32-bit PC, 4 GB RAM), the computational cost would increase rapidly, without any significant improvement in the results accuracy. The voxelized representation of the model is shown in Fig. 1c.

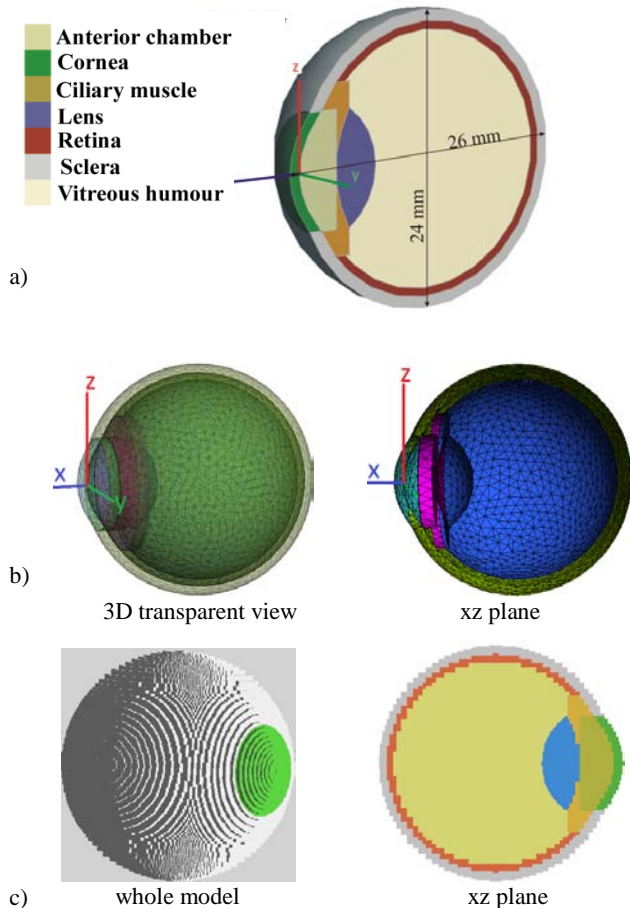


Fig. 1. a) Numerical model of the human eye, b) Meshed model (FEKO/FEM), c) Voxelized model (SEMCAD X/FDTD):

The eye model was exposed to two different sources of radiation – vertical short dipole (0.1λ long, divided in 20 wire segments for FEKO analysis) with radiated power $P_{rad}=1 \text{ W}$

which was placed at the distance $d=10 \text{ cm}$ in front of the eye (Fig. 2a) and vertically polarized incident plane wave with the power density $S=5 \text{ mW/cm}^2$ (Fig. 2b). All simulations were performed at frequencies $f=900$ and $f=1800 \text{ MHz}$, respectively.

TABLE I THE EYE TISSUE PROPERTIES

Tissue	f [MHz]	ϵ_r	σ [S/m]	ρ [kg/m ³]
Sclera	900	55	1.2	1170
	1800	53.9	1.5	
Retina	900	55.3	1.2	1039
	1800	53.5	1.6	
Cornea	900	55.2	1.4	1076
	1800	52.8	1.8	
Lens	900	46.6	0.8	1100
	1800	45.3	1.1	
Ciliary muscle	900	54.8	0.97	1040
	1800	53.8	1.22	
Anterior chamber	900	68.9	1.6	1010
	1800	68.6	2	
Vitreous humour	900	68.9	1.6	1000
	1800	68.6	2	

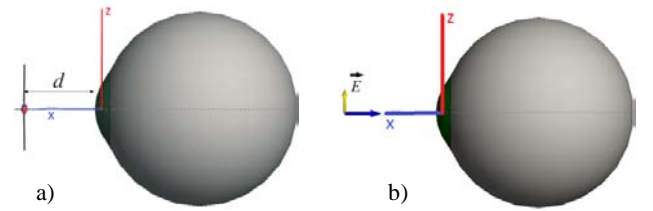


Fig. 2. Radiation sources: a) short dipole, b) plane wave

B. The pregnant woman model

The realistic model of the pregnant woman with all organs taken into account is too complex structure for analysis with standard PC equipment. Such a composite structure is therefore often replaced by a simplified model consisting of three parts: mother's torso, fetus and amniotic fluid [2-4] and [11]. The mother's torso was approximated with an elliptical cylinder while the fetus was replaced with an ellipsoid which was assumed to be immersed in the amniotic fluid. The electrical tissue properties of the fetus and the amniotic fluid were taken from [5], [11] and [17] and are listed in Table 2. The conductivity and permittivity of the mother's torso were calculated as 2/3 of the respective values for muscles given in [17], as suggested in [2], [3] and [19].

The detailed description of the analyzed model is shown in Fig. 3. The dimensions and geometrical properties of the model were taken from [4] for the comparison purposes.

The presented model required discretization to more than 150000 tetrahedra for FEM analysis with FEKO, which yielded the edge length of each tetrahedron of 1 cm. In spite of the mentioned geometric simplification, such a meshing

density was too dense to be carried out with PC equipped with 4 GB RAM. Hence, more powerful 64-bit PC with 6 GB RAM was used. The discretized structure is shown in Fig. 4, together with detailed preview of fetus and amniotic fluid discretization.

The pregnant woman model for SEMCAD X/FDTD analysis was voxelized in 4 Mcells for the plane wave exposure and in 4.5 Mcells for the dipole antennas exposure (which yielded the average voxel size in the pregnant woman model of approximately $3 \times 3 \times 3 \text{ mm}^3$ for both types of radiation sources). The calculation was carried out using the dual core 32-bit PC equipped with 4 GB RAM. The voxelized representation of the complete model and fetus immersed in the amniotic fluid is shown in Fig. 5.

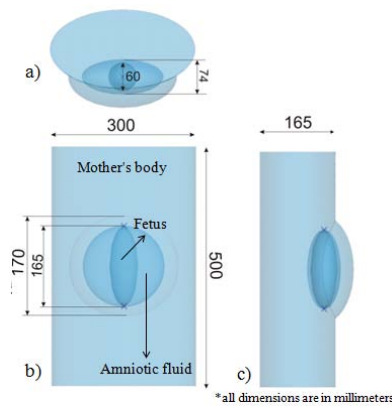


Fig. 3. Numerical model of pregnant woman: a) top view, b) front view, c) side view

TABLE II ELECTRICAL PARAMETERS OF A MOTHER'S TORSO, AMNIOTIC FLUID AND FETUS

Tissue	f [MHz]	ϵ_r	σ [S/m]	ρ [kg/m ³]
Mother's torso	150	42.1	0.50	907
	900	36.7	0.62	
	1800	35.7	0.90	
Amniotic fluid	150	78.3	1.23	986
	900	60.4	1.89	
	1800	76.0	2.15	
Fetus	150	76.9	0.91	967
	900	62.9	1.17	
	1800	60.4	1.89	

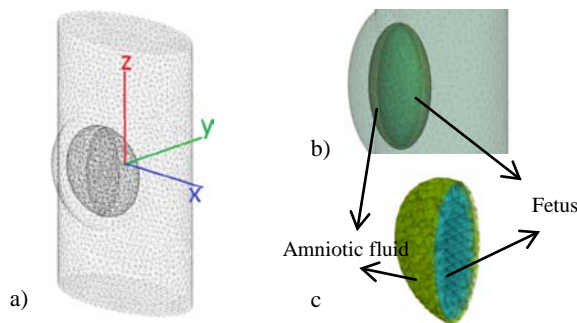


Fig. 4. Meshed model (FEKO): a) whole model, b) more detailed preview of mother's torso, c) fetus in amniotic fluid

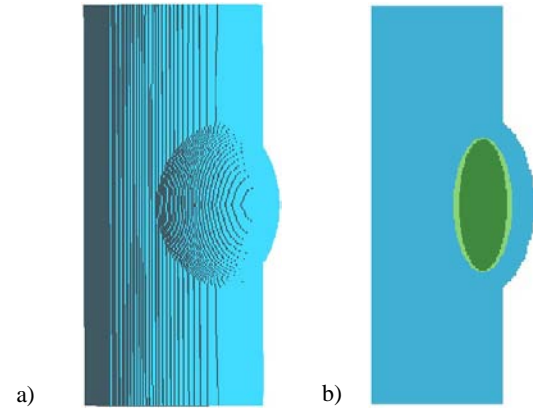


Fig. 5. Voxelized model (SEMCAD X): a) whole model, b) yz plane

The analyzed pregnant woman model was exposed to two different sources of radiation: dipole antenna (at 150, 900 and 1800 MHz), and the incident plane wave (at 900 and 1800 MHz). First, the vertical dipole (half-wave at 900 and 1800 MHz, 0.18λ long at 150 MHz, divided in 20 wire segments for FEKO analysis) with radiated power $P_{rad}=1 \text{ W}$ was placed at the distance $d=6 \text{ cm}$ in front of the torso (Fig. 6a). The model was analyzed for two different dipole positions: $\varphi=0^\circ$ and $\varphi=-90^\circ$ (Fig. 6a). Next, a vertically polarized incident plane wave with power density $S=1 \text{ mW/cm}^2$ was used as the source (Fig. 6b). All parameters were chosen so the model could be compared with other scientific studies ([4-6] and [11]).

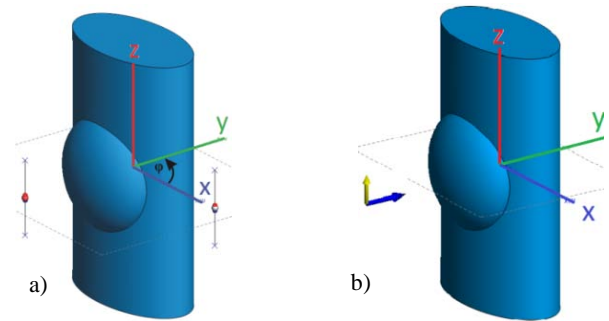


Fig. 6. – Radiation sources: a) dipole antenna, b) plane wave

III. SIMULATION RESULTS

A. SAR inside the human eye

SAR distribution simulation results for the human eye model are presented in Fig. 7 and 8 for FEKO/FEM analysis and in Fig. 9 and 10 for SEMCAD X/FDTD analysis. The results were obtained for xy and xz planes at frequencies $f=900 \text{ MHz}$ and $f=1800 \text{ MHz}$ for dipole antenna and plane wave radiation.

The obtained results clearly demonstrate that the position of the maximum induced SAR strongly depends on the frequency. At $f=900 \text{ MHz}$ the maximum SAR is induced in part of the eye closest to the radiation source (anterior chamber), while at $f=1800 \text{ MHz}$ the maximum SAR is induced in a deeper part of the eye (vitreous humour, right behind the lens).

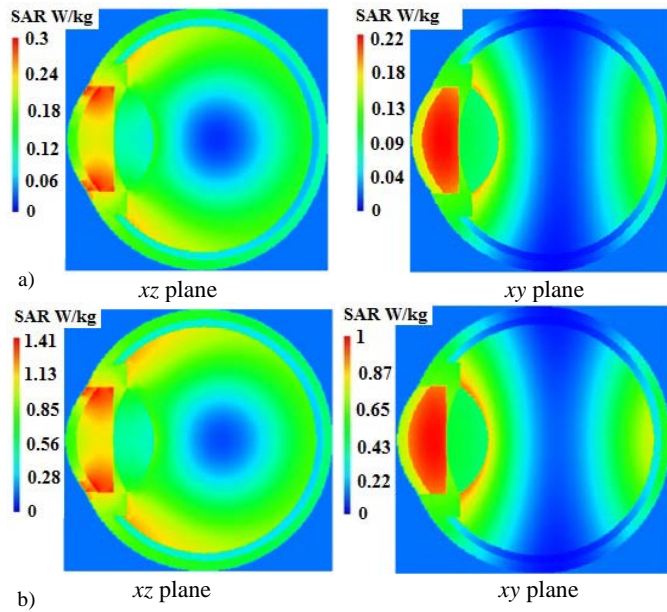


Fig. 7. SAR distribution at 900 MHz (FEKO):
a) dipole antenna exposure, b) plane wave exposure

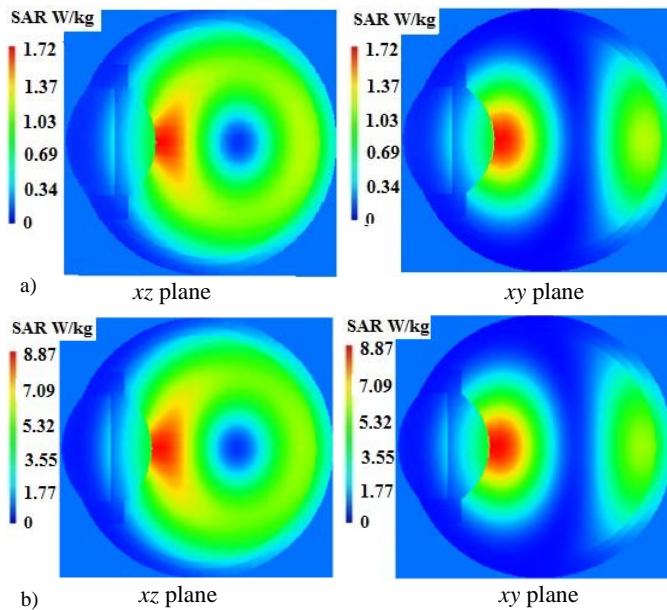


Fig. 8. SAR distribution at 1800 MHz (FEKO):
a) dipole antenna exposure, b) plane wave exposure

The similar results were obtained for the vertically polarized plane wave exposure at $f=900$ MHz in [16] and $f=1800$ MHz in [9], respectively. However, the maximum SAR in [16] is mainly induced in anterior chamber, while in [9] is mainly induced in vitreous humour, regardless the operating frequency. This difference could be explained by significant differences in developed eye models. In [16] 2D numerical model of human eye surrounded by head tissues was developed, based on MRI images. The SAR distribution in the eye was obtained by hybrid BEM/FEM method. In [9] an anatomically based 3D eye FDTD model involving the whole human head was developed. Although the realistic model of the human head was built, the simplified eye structure with only four tissues was modelled.

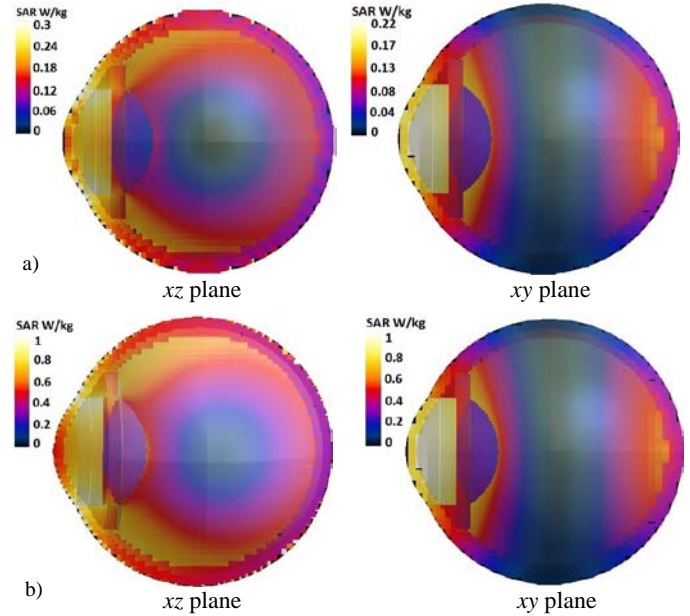


Fig. 9. SAR distribution at 900 MHz (SEMCAD X):
a) dipole antenna exposure, b) plane wave exposure

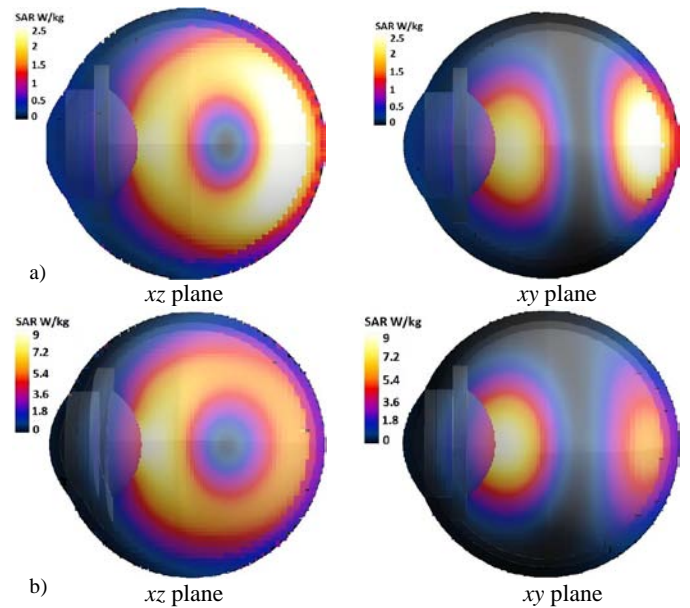


Fig. 10. SAR distribution at 1800 MHz (SEMCAD X):
a) dipole antenna exposure, b) plane wave exposure

The values of SAR averaged to whole eye are listed in Table 3. These values correspond also to 10g-averaged SAR, regarding the fact that the human eye weighs about 10 g [9]. The results were compared to ones available in [9] and [16] for plane wave exposure and to ones [8] for a dipole antenna exposure. The same dipole antenna model was used in this work for the purpose of comparison with [8]. Eye model in [8] is the same as in [9]. A very good agreement for $f=1800$ MHz could be noticed, while the results for $f=900$ MHz show more discrepancies. However, this is still in acceptable limits, when taking into account the model differences.

A rather satisfactory agreement of SAR distributions in the human eye, calculated using FEKO (Fig. 7 and 8) and

SEMCAD X (Fig. 9 and 10), can be observed. This is also the case for the whole eye averaged SAR results listed in Table 3.

TABLE III WHOLE EYE AVERAGED SAR – COMPARISON WITH LITERATURE

SAR [W/kg]	Antenna		Plane wave	
	900 MHz	1800 MHz	900 MHz	1800 MHz
FEKO/FEM	0.1	0.4	0.5	1.8
SEMCAD X/FDTD	0.1	0.4	0.4	2.1
H. Dodig [16] BEM-FEM	-	-	1.6	1.8
A. Hirata [9] FDTD	-	-	1.6	1.2
A. Hirata [8] FDTD	0.4	0.4	-	-

B. SAR in pregnant woman

SAR distribution simulation results at 900 and 1800 MHz for the pregnant woman model are presented in Fig. 11 and Fig. 12 for FEKO analysis and in Fig. 13 and Fig. 14 for SEMCAD X analysis. The results are presented for two different sources: dipole antenna positioned at $\varphi=-90^\circ$ (see Fig. 6a) and plane wave radiation. The maximum SAR values are induced in the part of mother's torso which is closest to the radiation source and in the amniotic fluid. However, in deeper parts of mother's body, SAR is progressively attenuated, ensuring negligible SAR values in fetus.

The values of peak localized 10g-averaged SAR and volume-averaged SAR are listed in Table 4.

The models given in [5-7] represent anatomically rather realistic model of the pregnant woman. The models were based on MRI images and analyzed with FDTD method. The vertically polarized plane wave with $S=1\text{mW/cm}^2$ at 900 MHz was used in [6]. The peak localized 10g-averaged SAR for the fetus was 0.01 W/kg, and for the mother's body 0.04 W/kg which represents a good agreement with values in Table 4, regarding significant model differences. The same plane-wave characteristics were used in [5]. The peak localized 10g-averaged SAR in fetus was 0.03 W/kg at 900 MHz and 0.02 W/kg at $f=1800$ MHz, which is still good accordance with our results.

TABLE IV PEAK LOCALIZED 10G-AVERAGED SAR AND VOLUME-AVERAGED SAR

	SAR [W/kg]	Dipole source				Plane-wave source			
		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
SEMCAD X	Mother's body	1.25	0.01	1.09	0.007	0.3	0.06	0.23	0.04
	Amniotic fluid	0.62	0.10	0.27	0.03	0.16	0.05	0.08	0.04
	Fetus	0.25	0.10	0.12	0.03	0.08	0.02	0.04	0.01

The results for peak localized 10g-averaged SAR in fetus and the peak value of SAR in mother's body at 150 MHz, for different antenna positions (see Fig. 6a), are listed in Table 5. It is evident that the results, obtained with FEKO and SEMCAD X, are in a very good agreement with those reported in [4] and [11]. The more significant discrepancy only exists for the fetus with the antenna in position $\varphi=0^\circ$. However, our model had larger amniotic fluid volume having resulted in more progressive electric field attenuation which caused lower SAR values in the fetus.

By comparing the simulation results obtained by FEKO/FEM and SEMCAD X/FDTD (Table 4 and 5, and Figures 11 to 14), a very good agreement can be observed for all frequencies and all radiation sources. However, the error was noticed in the results reported in [13], for the case of pregnant woman model exposed to the plane wave radiation. These results were obtained by specifying the effective value of the electric field instead of the electric field magnitude for the power density specification in FEKO simulation software (as indicated in FEKO manual [14]). Therefore, all erroneous results were corrected by scaling with factor 2.

TABLE V PEAK SAR AND PEAK LOCALIZED 10G-AVERAGED SAR AT 150 MHz

SAR [W/kg]	$\varphi=0^\circ$		$\varphi=-90^\circ$	
	Fetus avg_10g	Mother's body Peak	Fetus avg_10g	Mother's body Peak
K. Ito [4] FDTD	-	-	0.36	1.15
H. Kawai [11] FDTD	0.1	1.3	-	-
FEKO FEM	0.03	1.6	0.34	1.4
SEMCAD X FDTD	0.03	1.5	0.36	1.3

It should be noted (from Table 4) that the volume-averaged SAR calculated for the fetus at 900 MHz (dipole source) is 0.11 W/kg (FEKO) and 0.10 W/kg (SEMCAD X). Both values exceed the limit of 0.08 W/kg given for whole-body average SAR by ICNIRP [12]. This raises the question regarding the limit applicable for the fetus exposure. 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, fetus represents a whole body, possibly more sensitive to stress than the born human of any age. Fetus exposure, although considering as localized from mother's body, represents a whole-body thermal stress. Thus, the limit for whole-body average should be considered, and these results suggest the fetus might get overexposed.

IV. CONCLUSION

The SAR distribution, peak localized SAR and volume-averaged SAR inside the two anatomically complex geometries (human eye and pregnant woman) were analyzed with common nowadays office PC computer configurations, using FEKO software based on FEM method and SEMCAD X software based on FDTD method.

The human eye (without the head) with seven different tissues, discretized with about 60000 tetrahedra for

FEKO/FEM analysis, and with more than 3 Mcells for SEMCAD X/FDTD analysis, was successfully modelled and analyzed with a 32-bit 4 GB RAM personal computer. The realistic pregnant woman model was found to be too complex for analysis with such PC configuration, so the simplified geometrical model consisting just of mother's torso, amniotic fluid and fetus was developed. Even so, the model required discretization to more than 150000 tetrahedra for FEKO/FEM analysis. This model was too large to be solved with PC equipped with 4 GB RAM. Hence, more powerful 64-bit PC with 6 GB RAM had to be used.

The same model was discretized with more than 4 Mcells for the SEMCAD X/FDTD simulations and was successfully solved using a 32-bit 4 GB RAM personal computer.

All results obtained with SEMCAD X and FEKO were in a very good agreement. Moreover, the satisfactory agreement between these results and the results obtained with anatomically realistic FDTD models (based on MRI and available in relevant literature) was noticed.

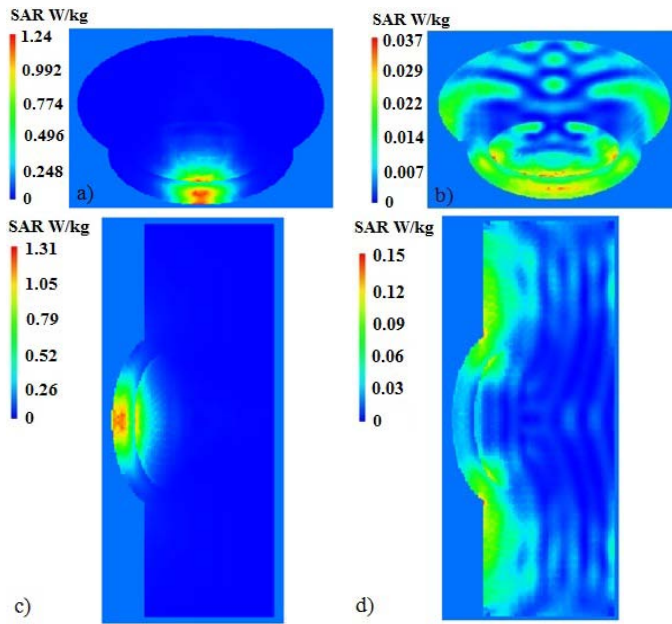


Fig. 11. SAR distribution at 900 MHz (FEKO):
a) xy plane, dipole source; b) xy plane, plane wave source;
c) yz plane, dipole source; d) yz plane, plane wave source

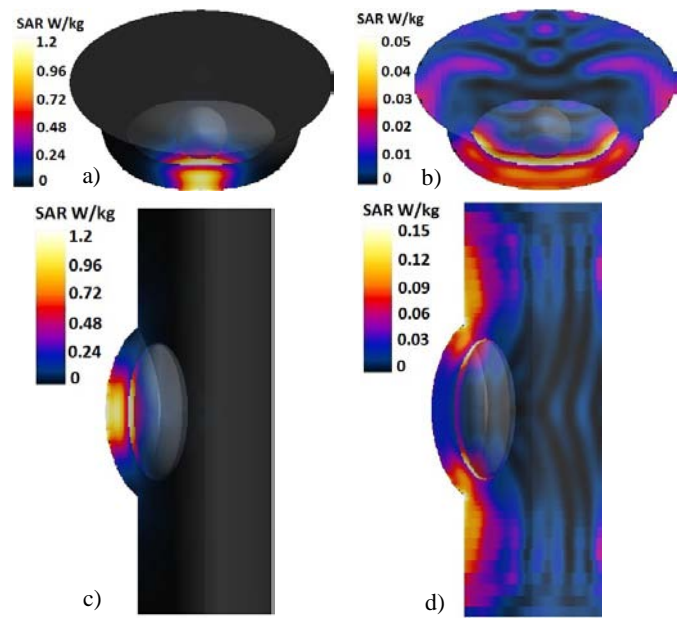


Fig. 13. SAR distribution at 900 MHz (SEMCAD X):
a) xy plane, dipole source; b) xy plane, plane wave source;
c) yz plane, dipole source; d) yz plane, plane wave source

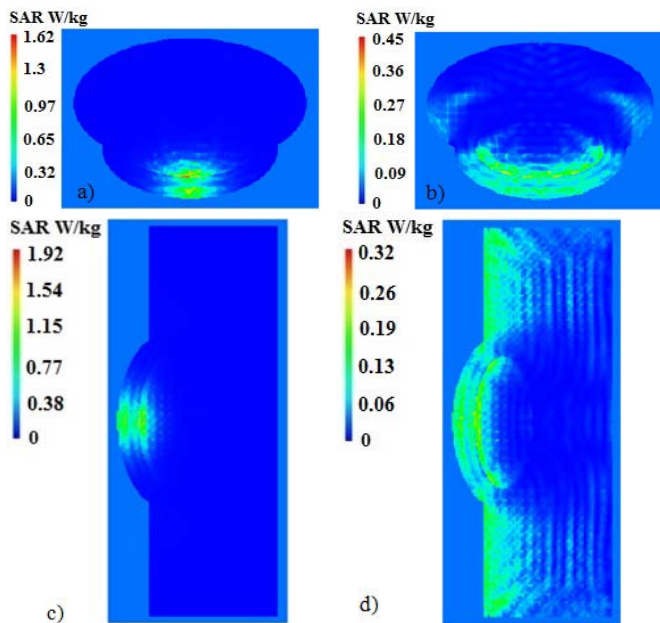


Fig. 12. SAR distribution at 1800 MHz (FEKO):
a) xy plane, dipole source; b) xy plane, plane wave source;
c) yz plane, dipole source; d) yz plane, plane wave source

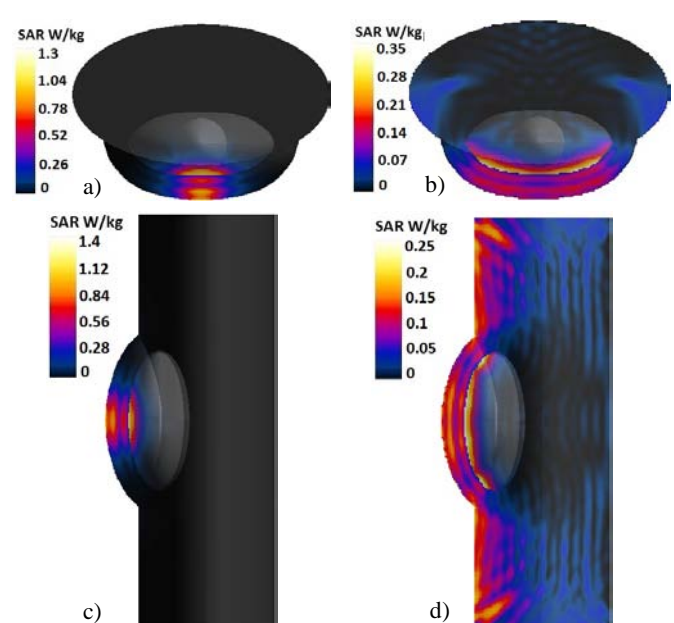


Fig. 14. SAR distribution at 1800 MHz (SEMCAD X):
a) xy plane, dipole source; b) xy plane, plane wave source;
c) yz plane, dipole source; d) yz plane, plane wave source

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