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Exposure of High Resolution Fetuses in Advanced Pregnant Woman Models at Different Stages of Pregnancy to Uniform Magnetic Fields at the Frequency of 50 Hz*

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Abstract— **Extremely low frequency magnetic fields (ELF-MF) have been considered as a possible risk factor for childhood leukemia by several epidemiological studies. In this work the exposure assessment of fetuses at 3, 7 and 9 months of Gestational Age (GA) to differently polarized uniform magnetic fields at the frequency of 50 Hz by means of high resolution numerical models of pregnant women is carried out. This set of models is used to analyze the fetal tissue-specific induced electric fields and current densities as a function of both the incident magnetic field polarization and the GA.**

I. Introduction

There has been increasing concern about the safety of extremely low-frequency magnetic fields (ELF-MF) and their possible effects on children's health from prenatal life to adolescence. Several meta-analyses consistently found statistically significant increased relative risk estimates for childhood leukemia for ELF-MF exposure above 0.4 µT [1]. On the base of these results in 2002 the IARC classified these ELF-MF fields as "possibly carcinogenic to humans" [2]. In the intent to better understand the possible biological mechanisms linked to the association between ELF-MF exposure and childhood leukemia, in 2007 WHO Research Agenda for ELF-MF [3] indicated as urgent priority, among other measures, the estimation of the induced fields within human tissues, including fetal life, due to ELF-MF exposure. Until now dosimetric studies have been performed mainly with human models of adults [4-7], and some studies considered the ELF-MF exposure of children [8-9], but little is known about the induced EM field levels in the fetuses. Indeed, few dosimetrical studies [9],[12-14] evaluated the exposure of fetuses at ELF magnetic fields, checking the compliance to ICNIRP Guidelines [10-11]. The characterization of the exposure requires highly accurate anatomical models of the fetus and the mother at different gestational phases.

In this work recently developed high resolution pregnant woman models belonging to the "Virtual Population" developed by the IT'IS Foundation [14] have been used. These models consist of a model of non-pregnant "Ella" [15], that was augmented to account for changes in the mother due to pregnancy (the presence of the fetus and enlargement of the breasts). The objective of this study is to assess the tissue-specific induced electric fields and current densities within high resolution fetal models at 3, 7 and 9 months of Gestational Age (GA), due to the exposure of pregnant women to differently polarized uniform magnetic fields. In particular the fetal tissue-specific fields induced by a uniform magnetic field of amplitude equal to 1 µT at the frequency of 50 Hz have been analyzed, and the results have been compared in terms of the variation of both the magnetic field polarization and the GA.

II. Material and Methods

A. *Numerical Exposure Modeling*

Simulations were conducted using the Magneto Quasi-Static low frequency solver of the simulation platform SEMCAD X v.14.8 (by SPEAG, www.speag.com), which uses a Biot–Savart solver and is based on the scalar potential finite element (SPFE) method. Rectilinear grids were applied to easily discretize the complex anatomical models.

B. *Numerical Models of Pregnant Women*

Three anatomical whole-body models of pregnant women based on the "Ella" model of the Virtual Family [15] were used for the dosimetric analysis. All models are based on the computer-aided design representation of the organ surfaces and up to 80 different tissue types are represented (up to 26 in the fetus models). A detailed description of the construction of the models is given in [14]. Due to the formation of the organs at different stages of pregnancy not all three fetus models distinguish the same tissues. Details on the fetal tissues at each GA can be found in the following Table I. Furthermore, the position of the fetus changes at the three stages of pregnancy. Fig. 1 shows the three models of pregnant women used in the study.

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Figure 1. Pregnant women at the 3, 7 and 9 months of GA. The masses of the fetus models at the three GA are 15, 1700 and 2700 g, respectively.

C. Grid Resolution

Pregnant woman's tissues (both mother and fetus) at 7 and 9 months of GA were discretized with a grid resolution of 1 mm. Due to the small thickness of skin tissue at 3 month of GA, the fetal skin tissue was discretized with a grid resolution of 0.3 mm.

D. Conductivities of Tissues

The conductivities of most of the mother's tissues were assigned according to the commonly used database [16-18]. The skin conductivity was set to 0.1 S/m to take into account the higher conductivity of deeper granular tissue, i.e. dermis, [4]. Furthermore, an average value between grey matter and white matter conductivities were assigned to medulla oblongata, pons and midbrain tissues. The conductivity of the amniotic fluid was set equal to 1.28 S/m, 1.27 S/m and 1.10 S/m at 3, 7 and 9 months of GA, respectively, whereas the conductivity of the placenta was the same as that of the blood (0.7 S/m) [12],[19-20]. The fetal conductivity values are the same as the adult ones except for brain, bone and fat tissues. In particular, a lowest conductivity (0.185 S/m) has been assigned to brain tissue from a conservative point of view, while the bone tissue conductivity has been taken as a weighted average of bone and blood, due to the infiltration of bone marrow at a very young age, and fat conductivity was considered as a blend between fat and muscle conductivity values due to higher water content and blood presence at very young age [21]. Table I shows the fetal tissue conductivities used in this study.

E. Exposure Configurations

Three orthogonal polarizations of 1 μT incident magnetic field vector at the frequency of 50 Hz have been studied, resulting on Ella's body in a front-to-back, lateral and top-to-bottom exposure (B_{front}, B_{lat}, B_{top}), respectively. For all the polarizations, the magnetic field homogeneity was equal to 100% in a rectangular volume of 0.50 m x 0.26 m x 1.62 m, corresponding to Ella's dimension.

TABLE I. FETAL TISSUE CONDUCTIVITIES

Fetal Tissue	σ (S/m)	Gestational Age (month)
Brain	0.185	3,7,9
Bone	0.350	3,7,9
Eye-lens	0.200	3,7,9
Eye humour vitreus	1.500	9
Fat	0.120	3,7,9
Kidney	0.089	3,7,9
Liver	0.092	3,7,9
Heart muscle	0.292	3,7,9
Lung	0.158	3,7,9
Muscle	0.286	3,7,9
Bladder	0.205	3,7,9
Skin	0.100	3,7,9
Small intestine	0.522	3,7,9
Spinal cord	0.027	3,7,9
Spleen	0.086	3,7,9
Stomach	0.521	3,7,9
Gallbladder	0.900	7,9
SAT	0.120	7,9
Adrenal gland	0.521	9
CSF	1.790	9
Ovary	0.321	9
Pancreas	0.521	9
Thymus	0.521	9
Thyroidal gland	0.521	9
Esophagus	0.521	9
Uterus	0.229	9

F. Exposure assessment of fetus

The dosimetric results were assessed in terms of induced electric field and current density in fetal tissues. The electric field averaged (E_{av}) on a cube of 2 x 2 x 2 mm^3 [11] and current density averaged on a cross-section of 1 cm^2 (J_{av}) perpendicular to the direction of the current [10] induced in each fetal tissue were analyzed, and according to [22-23] for both metrics the peak value was calculated ($E_{av,peak}$, $J_{av,peak}$). Although the metrics suggested by ICNIRP have been used, the goal of this study was not assessing the compliance to ICNIRP Guidelines but only evaluating the induced fields within fetal tissues.

III. RESULTS

Fig. 2(a) and (b) represent, as an example, the tissue-specific $E_{av,peak}$ and the $J_{av,peak}$ induced by each polarized B-field in the 9 month fetus. This is the fetal model with the highest number of tissues among the ones used in this study. Data in Fig. 2(a) show that a common worst-case polarization for all the 9 month fetal tissues cannot be predicted. It can be observed that $E_{av,peak}$ value due to B_{lat} is 4 times higher than the one induced by B_{front} in fetal ovary, while the minimum variation across the same polarizations is equal to 3.25% in subcutaneous adipose tissue (SAT). Furthermore, high variations up to 240% are observed in $E_{av,peak}$ induced by B_{front} respect to B_{top} (e.g. in the small intestine, pancreas, uterus and gallbladder), while lower differences are observed comparing the B_{lat} and B_{top} exposure (up to 84% in gallbladder). In order to compare the induced fields tissue-by-tissue also the mean $E_{av,peak}$ across the polarizations in each tissue has been calculated (indicated by a yellow dot in Fig. 2(a)).

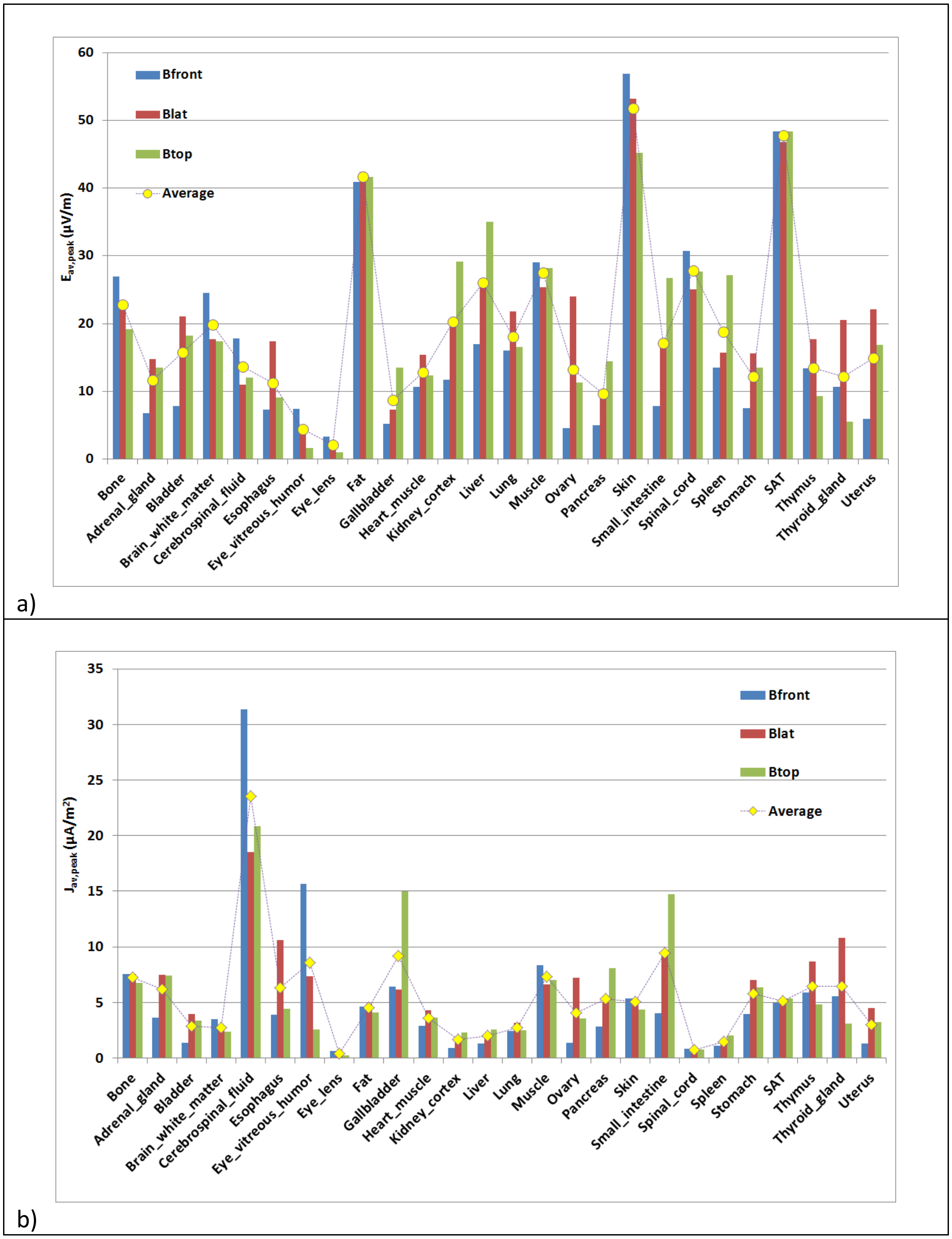

Figure 2. a) $E_{av,peak}$ in each 9 month of GA fetal tissue for the three polarizations of the incident B- field. The yellow dot indicates the mean across the polarization of $E_{av,peak}$ in each tissue, b) $J_{av,peak}$ in each 9 month of GA fetal tissue. The yellow diamond indicates the mean across the polarization of $J_{av,peak}$ in each tissue

The highest mean $E_{av,peak}$ is in the skin and SAT and it is equal to 51.77 µV/m and 47.85 µV/m, respectively. Also bone, fat, spinal cord, muscle and liver present higher mean $E_{av,peak}$ than the other tissues (equal to 22.81 µV/m, 41.66 µV/m, 27.82 µV/m, 27.54 µV/m and 26 µV/m, respectively). The highest mean $J_{av,peak}$, represented by a yellow diamond in Fig. 2(b), is equal to 23.57 µA/m^2 in cerebrospinal fluid, due to the high conductivity of this tissue. A comparison across the different gestational ages has also been performed. For example, in Fig. 3 the $E_{av,peak}$ induced by a front-to-back exposure in the three fetuses are represented. Only the tissues that are present in all fetal models have been considered. In some tissues (e.g. bone, brain, lung, muscle, skin and spinal cord) there are variations of the $E_{av,peak}$ up to 472% comparing the 3 and 9 months of GA fetuses. These differences are lower comparing the 7 and 9 months of GA fetuses, in which the highest variation is observed in skin and muscle. It is also possible to observe that some tissues have lower $E_{av,peak}$ in the 9 month of GA fetus respect the other two (i.e. bladder, eye-lens, kidney-cortex and small intestine).

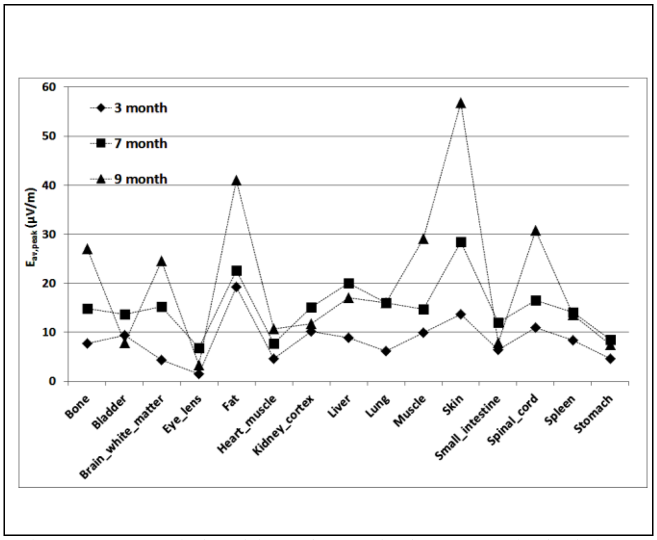

Figure 3. $E_{av,peak}$ induced by a front-to-back exposure in fetal tissues at different GA

IV. DISCUSSION

In this paper the preliminary results of the study of the exposure of advanced fetal models at 3, 7 and 9 months of GA to differently polarized uniform magnetic fields of amplitude equal to 1 µT at the frequency of 50 Hz to generate a front-to-back, lateral and top-to-bottom exposure on pregnant woman body have been presented. In particular the peak value of both induced electric field averaged on a cube of 2 mm x 2 mm x 2 mm ($E_{av,peak}$), and induced current density averaged on a cross-section of 1 cm^2 perpendicular to the direction of the current ($J_{av,peak}$) have been calculated. In each fetus, the worst case exposure scenario was found different as a function of the tissues investigated. The differences across the polarizations in the same fetal tissue are significant, reaching values up to 400%. Also, comparing fetal tissues at different GA, the same worst-case polarization of the B-field cannot be found; however there is generally an increment of the induced fields with the increasing of the stage of pregnancy. Future works could be done to evaluate the influence of grid resolution on the variation of fetal tissue-specific induced fields. Furthermore, an analysis of the uncertainty relative to the fetal posture in mother's womb will be done.

V.ACKNOWLEDGMENT

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