Radiation Protection Dosimetry Advance Access published November 30, 2015

Radiation Protection Dosimetry (2015), pp. 1–11 doi:10.1093/rpd/ncv488

COMPUTATIONAL ASSESSMENT OF PREGNANT WOMAN MODELS EXPOSED TO UNIFORM ELF-MAGNETIC FIELDS: COMPLIANCE WITH THE EUROPEAN CURRENT EXPOSURE REGULATIONS FOR THE GENERAL PUBLIC AND OCCUPATIONAL EXPOSURES AT 50 Hz

Ilaria Liorni[1,2,*], Marta Parazzini[1], Serena Fiocchi[1], Mark Douglas[3], Myles Capstick[3], Niels Kuster[3,4] and Paolo Ravazzani[1]

[1]CNR Consiglio Nazionale delle Ricerche, Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni IEIIT (CNR National Research Council of Italy, Institute of Electronics, Computer and Telecommunication Engineering), Piazza Leonardo da Vinci, Milano, Italy

[2]Dipartimento di Elettronica, Informazione e Bioingegneria DEIB (Department of Electronics, Information and Bioengineering), Politecnico di Milano, Piazza Leonardo da Vinci, Milano, Italy

[3]Foundation for Research on Information Technologies in Society (IT'IS Foundation), Zurich, Switzerland

[4]Swiss Federal Institute of Technology (ETHZ), Zurich, Switzerland

*Corresponding author: ilaria.liorni@ieiit.cnr.it

Received 27 May 2015; accepted 16 October 2015

The Recommendation 1999/529/EU and the Directive 2013/35/EU suggest limits for both general public and occupational exposures to extremely low-frequency magnetic fields, but without special limits for pregnant women. This study aimed to assess the compliance of pregnant women to the current regulations, when exposed to uniform MF at 50 Hz (100 μT for EU Recommendation and 1 and 6 mT for EU Directive). For general public, exposure of pregnant women and fetus always resulted in compliance with EU Recommendation. For occupational exposures, (1) Electric fields in pregnant women were in compliance with the Directive, with exposure variations due to fetal posture of <10 %, (2) electric fields in fetuses are lower than the occupational limits, with exposure variations due to fetal posture of >40 % in head tissues, (3) Electric fields in fetal CNS tissues of head are above the ICNIRP 2010 limits for general public at 1 mT (in 7 and 9 months gestational age) and at 6 mT (in all gestational ages).

INTRODUCTION

In the low-frequency range, external magnetic fields (MFs) induce intracorporal electric current densities, which can cause adverse health effects when they exceed specific reference levels and guidelines, such as those identified by the International Commission on Non-Ionising Radiation Protection ICNIRP 2010[1]. In detail, the exposure to low-frequency MFs can induce stimulation of the central (CNS) and peripheral (PNS) nervous system tissues and the induction of phosphenes in the retina. At the level of the European Union affairs, there are currently two legislative acts, which address exposure to electromagnetic fields (EMF). These are the EU Council Recommendation 1999/529/EU[2] on the limitation of exposure of the general public to EMFs from 0 to 300 GHz, and the European Parliament and EU Directive 2013/35/EU[3] on the minimum health and safety requirements regarding exposure of workers to the risks arising from EMFs. In this respect, accurate assessment of the human exposure to ELF-MF is necessary to be able to evaluate the compliance of both the general public and workers to the current regulations.

The demographics of the workforce have changed in recent years, with an increase in the number of female workers: ∼65 % of females in the 27 European Union countries are employed[4], many of them during their reproductive years. Several studies have addressed the evaluation of safe employment for pregnant workers[5–7]. However, as to the EMF exposure risk, in the new EU Directive 2013/35/EU[3], the exposure limits allowed for pregnant workers are the same as those for all the other workers; the only difference is a statement that pregnant workers are considered to be 'at a particular risk' and that it is mandatory for the employer to adopt special measures of safety for them, although no specifications are defined regarding what these measures should be. Already in Gobba *et al.*[8], the need for a systematic study to collect available scientific data about the evaluation of the safety of pregnant workers exposed to EMFs was stressed, and the lack of knowledge regarding which safety measures to adopt in the case of workers 'at a particular risk' under EMF exposure was highlighted.

Until now, compliance with ELF exposure guidelines and reference levels in both adults and children has been assessed in many dosimetry studies[9–14], whereas the analysis of the exposure of a pregnant woman to ELF-MF has been investigated in other studies[15–17]. Only a few studies have been devoted to the investigation of the compliance in pregnant women[17–20]. In Xue *et al.*[18], the exposure of pregnant women at the workplace was assessed to check compliance with the ICNIRP Guidelines 1998[21] by means of a cylinder model of the pregnant torso, in which the fetus is represented as an ellipsoid: exposure to a uniform electric field of 10 kV m^{-1} and to a transmission line, in which only the magnetic field is considered, was performed at a frequency of 50 Hz. Cech *et al.*[19] assessed the compliance to the ICNIRP 1998[21] basic restrictions for incident electric and magnetic fields at 50 Hz by means of the pregnant model Silvy at 30 weeks of gestational age (GA), as well as for simultaneous exposures to electric and magnetic fields at 50 Hz. Exposure of pregnant woman at 3, 7, and 9 months of GA to induction cookers at 20 kHz was addressed in Christ *et al.*[20], wherein compliance with the basic restrictions of the ICNIRP 1998[21] at that frequency was also analysed. Finally, in Liorni *et al.*[17], induced fields in fetal tissues were estimated by means of the pregnant models used in Christ *et al.*[20] for an exposure to uniform 1 μT MF at 50 Hz, and then those results were also analysed with respect to the ICNIRP 1998[21] and 2010[1] guidelines for general public exposure, but no assessment of the woman exposure was carried out.

Therefore, until now, there have been no studies in literature that assess the compliance of pregnant women exposed to MF at 50 Hz with both the European Recommendation 1999[2] and the Directive 2013[3].

This study aims to close this gap of knowledge through the assessment of the compliance of pregnant woman exposure to these legislative acts for the general public[2] and the occupational[3], respectively, analysing the induced fields in the pregnant woman and fetus for an exposure to uniform MF at 50 Hz. In order to draw knowledge that may be generalisable, several pregnant models have been analysed in different exposure scenarios. These models are the pregnant women at 3, 7 and 9 months of gestational age (mGA) introduced in Christ *et al.*[20] and used here as reference models and four additional models obtained by modification of the reference. Among these additional ones, two are pregnant woman models at 3 mGA with two different fetal postures with respect to the reference position, chosen among the ones most statistically significant at this stage of pregnancy[17], whereas the other two are new models of pregnant woman at 7 and 9 mGA with the fetus in breech position.

MATERIALS AND METHODS

European Recommendation 1999/519/EC for general public exposure

The European Recommendation 1999/519/EC[2] refers to the limits defined by the ICNIRP Guidelines 1998[21] with the aim to protect the general population from exposure to EMFs. In detail, at a frequency of 50 Hz, the basic restriction on the induced current density is intended to protect individuals from acute exposure effects on the CNS tissues of the head and trunk. The limits are expressed in terms of the peak value (J_{peak}) of the root-mean-square (RMS) of induced current density with a maximum value of 2 mA m^{-2}, averaged over a tissue of surface area 1 cm^2 positioned perpendicular to the direction of the current. The reference level for the magnetic flux density (**B**) at 50 Hz refers to the maximum allowed non-perturbated RMS-field level, equal to 100 μT. Furthermore, as stressed in the Recommendation itself, since the basic restriction refers to adverse CNS effects, current densities in other body tissues may be higher than this limit under the same exposure conditions.

European Directive 2013/35/EU for the occupational exposure

The new European Directive 2013[3] outlines the minimum health and safety requirements regarding the exposure of workers to the risks arising from EMFs. In contrast to the previously discussed basic restriction of the EU Recommendation 1999[2], the maximum permitted quantities in the body and in the tissues are expressed in terms of induced electric fields. These are called exposure limit values (ELVs), which are comprised of 'Health Effects ELVs' and 'Sensory Effects ELVs.' The former are the ELVs above which workers' adverse health effects are possible, whereas the latter are the ELVs above which workers might experience transient disturbed sensory perceptions and minor changes in brain function. The maximum permitted levels for external fields, referred to for the purpose of this paper in terms of magnetic flux density, are called action levels (ALs), which are divided in two sub-categories, 'low ALs' and 'high ALs'. These are the external field levels that correspond to Sensory Effects ELVs and Health Effects ELVs, respectively. Table 1 shows the ELVs and ALs for a magnetic field exposure at the frequency of 50 Hz according to the EU Directive 2013[3].

Computational modelling

Numerical simulations were conducted with the Magneto Quasi-Static low-frequency solver, based on the scalar potential finite element method and implemented in the simulation platform SEMCAD X v. 14.8 (SPEAG Schmid & Partner Engineering AG, Zürich, Switzerland)[22].

Different numerical models of pregnant woman at 3, 7 and 9 mGA were used to assess the exposure to ELF-MF at 50 Hz. In detail, three numerical models of pregnant women at 3, 7 and 9 months of GA, based on the model 'Ella' of the Virtual Family[23] and described in detail in Christ *et al.*[20], were used for the dosimetric analyses and referred below as reference models. In these models, the fetuses have masses of 15 g, 1.7 and 2.7 kg, respectively, and distinguish different tissues, due to the development of the organs at different stages of pregnancy. Details regarding the fetal tissues at each GA are found in Table 2. Additionally, other pregnant woman models, in which the fetus position was changed with respect to the reference models, have been used to assess the exposure to ELF-MF. In detail, at 3 months of GA, two additional pregnant models, each one based on the corresponding reference model at 3 months of GA, have been obtained by rotating the fetus and placenta with respect to their position in the reference model and adjusted to fit into the uterus. Further details about these models are reported in Liorni *et al.*[17] Furthermore, two new pregnant woman models at 7 and 9 mGA were provided for this study by the Foundation for Research on Information Technologies in Society (IT'IS Foundation). In both cases, the fetus has been moved from the cephalic position of the reference models to the breech position (Figure 1).

Table 1. Exposure limit values (ELV) and action levels (AL) according to the EU Directive 2013[3], at the frequency of 50 Hz.

	ELVs		ALs	
	'Sensory Effects' [V m^{-1}] (peak)	'Health Effects' [V m^{-1}] (peak)	'low' [mT] (RMS)	'high' [mT] (RMS)
$f = 50$ Hz	0.14	1.1	1	6

ALs are referring to the case of the magnetic field, of interest for this study.

Table 2. Fetal tissues evaluated at each GA.

Fetal tissue	GA [months]	Fetal tissue	GA [months]
Brain	3, 7, 9	Spinal cord	3, 7, 9
Bone	3, 7, 9	Spleen	3, 7, 9
Eye lens	3, 7, 9	Stomach	3, 7, 9
Eye-humour vitreus	9	Gallbladder	7, 9
Fat	3, 7, 9	SAT	7, 9
Kidney	3, 7, 9	Adrenal gland	9
Liver	3,7, 9	CSF	9
Heart muscle	3, 7, 9	Ovary	9
Lung	3, 7, 9	Pancreas	9
Muscle	3, 7, 9	Thymus	9
Bladder	3, 7, 9	Thyroidal gland	9
Skin	3, 7, 9	Oesophagus	9
Intestine	3, 7, 9	Uterus	9

In the numerical simulations, all the pregnant woman tissues were discretised with a grid resolution of 1 mm. A refinement of the grid resolution, set at 0.3 mm, was necessary at the level of the fetus for all the pregnant woman models at 3 mGA to correctly discretise the fetal skin, due to its thinness.

The conductivities of most of the woman's tissues were assigned according to the data available in the literature[24–26]. All the fetal tissue conductivities were assigned as the adult ones apart from fetal brain, bone and fat to account for the higher water content in these tissues during the prenatal life[27]. A summary of the chosen conductivity values is reported in Table 3.

Three orthogonal orientations of the magnetic field at a frequency of 50 Hz were studied to acquire results for Ella's body in front-to-back, lateral and top-to-bottom exposures (B_{front}, B_{lat}, B_{top}, respectively). The incident magnetic field was generated analytically, by calculating the vector potential **A** and the magnetic flux density **B** in the simulation box containing the pregnant woman model in order to obtain a magnetic field homogeneity equal to 100 % on the pregnant model's body for all orientations. The levels of the MFs were set to the maximum exposure levels

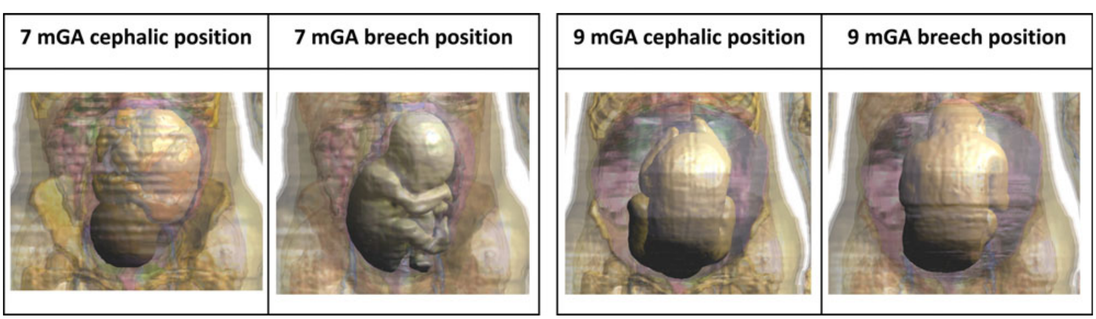

Figure 1. Fetal position at 7 and 9 months of GA. The position indicated as 'cephalic position' is the reference one. The pictures are taken from the pregnant woman's front view.

Table 3. Woman and fetal tissue conductivities.

Woman tissue	σ [S m^{-1}]	Reference	Woman tissue	σ [S m^{-1}]	Reference
Adrenal gland	0.521	(24) (source: gland)	Uterus	0.229	(24)
Artery	0.650	(26)	Vagina	0.0545	(24)
Bone	0.095; 0.35 for the fetus	(26) Fetus: (27)	Vein	0.650	(26) (source: blood)
Cartilage	0.171	(24)	Vertebrae	0.095	(26) (source: bone)
Connective tissue	0.270	(24)	Air internal	0	(24)
Bladder	0.205	(24)	Brain grey matter	0.185; As fetal brain	(26) fetus: (17)
Fat	0.078; 0.12 for the fetus	(25); Fetus: (27)	Brain white matter	0.369	(26)
CSF	1.790	(26)	Breast	0.0226	(24) (source: breast fat)
Gallbladder	0.900	(24)	Bronchi	0.300	(24)
Heart muscle	0.292	(26)	Bronchi lumen	0	(24)
Heart lumen	0.650	(26) (source: blood)	Cerebellum	0.579	(26)
Intervertebral disc	0.171	(24)	Commissura anterior	0.369	(26) (source: white matter)
Kidney cortex	0.089	(24)	Commissura posterior	0.369	(26) (source: white matter)
Kidney medulla	0.089	(24)	Diaphram	0.286	(26) (source: muscle)
Large intestine	0.055	(24)	Ear cartilage	0.171	(24) (source: cartilage)
Large intestine lumen	0.286	(24) (source: muscle)	Ear skin	0.100	(13)
Larynx	0.171	(24) (source: cartilage)	Oesophagus	0.521	(24)
Liver	0.092	(25)	Oesophagus lumen	0	(24) (source: air)
Lung	0.158	(26) (source: lung deflated)	Eye-vitreus humour	1.500	(24)
Marrow red	0.101	(24)	Eye lens	0.200	(24)
Meniscus	0.171	(24) (source: cartilage)	Hippocampus	0.185	(26) (source: grey matter)
Muscle	0.286	(26)	Hypophisis	0.521	(24) (source: glands)
Nerve	0.027	(24)	Hypothalamus	0.521	(24) (source: glands)
Ovary	0.321	(24)	Mandible	0.095	(26) (source: bone)
Pancreas	0.521	(24)	Midbrain	0.277	(Average grey matter and white matter)
Patella	0.095	(26) (source: bone)	Mucosa	0.000427	(24)
Skin	0.100	(13)	Pharinx	0	(24)
Small intestine	0.522	(24)	Pons	0.277	(Average grey matter and white matter)
Small intestine lumen	0.286	(26) (source: muscle)	Skull	0.095	(26) (source: bone)
Spinal cord	0.027	(24)	Teeth	0.095	(26) (source: bone)
Spleen	0.086	(24)	Thalamus	0.185	(26) (source: grey matter)
Stomach	0.521	(24)	Tongue	0.271	(24)
Stomach lumen	0.233	(24)	Trachea	0.301	(24)
SAT	0.078; 0.12 for the fetus	(25) (source: fat); fetus: (27)	Trachea lumen	0	(24)
Tendon ligament	0.270	(24)	Pineal body	0.521	(24) (source: glands)
Thymus	0.521	(24)	Medulla oblongata	0.277	(Average grey matter and white matter)
Thyroidal gland	0.521	(24)	Cornea	0.421	(24)
Ureter	0.261	(24)	Eye sclera	0.503	(24)
Placenta	0.7	(15)	Amniotic fluid	1.28; 1.27; 1.10	(17)

permitted by the legislative acts considered in this study, i.e. the 100 μT reference level for the general public[2] and the 1 and 6 mT ALs for workers[3]. In this way, the worst-case exposure scenario according to the current regulations is modelled.

Exposure assessment of pregnant women

The compliance with the basic restriction for exposure to MF at 50 Hz suggested by the European Recommendation 1999/519/EC[2] was verified in the woman's CNS tissues, i.e. the brain and the spinal cord tissues, by means of the calculated peak of induced current density (J_{peak}).

The Recommendation 1999[2] stating: 'However, since the basic restriction refers to adverse effects on the central nervous system, this basic restriction may permit higher current densities in body tissues other than the central nervous system under the same exposure conditions', implicitly allows the assessor to make decisions about the level of risk in specific tissues of the pregnant woman other than the CNS. Therefore, the authors decided to consider also the level of exposure of the fetus in the assessment of the compliance.

The worker Directive 2013[3], in contrast to the Recommendation 1999[2], provides no details on how to assess ELVs and ALs but clearly states that these physical quantities for allowed exposures are based on the recommendations of the ICNIRP and should be considered as in accordance with ICNIRP concepts. Considering this, here the compliance is estimated on the basis of the ICNIRP Guidelines 2010[1], and the induced electric field is determined as a vector average of the electric field in a small contiguous tissue volume of $2 \times 2 \times 2$ mm[3]. In reference to the metric to be adopted, the Directive defines the spatial peak values of the internal electric field in the entire body or in the head of the exposed subject as the relevant value to be compared with the corresponding ELVs. According to the ICNIRP Guidelines 2010[1], the 99th percentile value of the induced electric field (E_{99th}) in each tissue has been used as a stable approximation of the peak value.

According to the Directive 2013[3], the Health Effects ELVs are considered in the entire exposed subject, and the authors pursued the most conservative approach, i.e. they calculated the E_{99th} for each specific pregnant woman tissue, and the highest value is reported. Since the Directive states that the health effects are related to the electric stimulation of the PNS and CNS tissues of the body and head, the E_{99th} has been investigated in all tissues of the pregnant woman body, with a deeper analysis in the CNS tissues of the head and trunk (i.e. brain and spinal cord), and in the PNS tissues (i.e. the nerves).

The same approach was applied to the investigation of compliance with the Sensory Effects ELVs, in which the electric fields were estimated in all tissues of pregnant woman's head, as indicated in the Directive 2013[3].

As stated above, no explicit action is specified in the Directive 2013[3] in the case of pregnancy, apart from a general recommendation to the employer. To provide a scientific support for this recommendation, the authors have therefore calculated E_{99th} in each fetal tissue for exposure to both high and low ALs and in the fetal head tissues only for exposure to low AL. This was done to provide additional information to be integrated into the assessment of the compliance of the woman's exposure.

As an alternative, the induced electric fields in the fetus were also compared with the basic restrictions for the general public in the ICNIRP guidelines 2010[1], for exposure of the pregnant woman at the maximum permitted MF levels of 1 mT and 6 mT for workers. For this comparison, the electric fields in the CNS tissues of the fetal head (i.e. brain) and in all the other fetal tissues of the head and body were estimated.

In the following, almost all results are reported as mean value and standard deviation of the induced fields across the different available pregnant woman models at the same GA and for each exposure scenario. The variability of the exposure due to the different fetal postures at each GA has been assessed in terms of coefficient of variation, calculated as ratio of the standard deviation to the mean value of the induced fields.

RESULTS

Compliance with the European Recommendation 1999/519/EC for the general public exposure

Table 4 shows the J_{peak} induced in the woman's CNS tissues in the head and trunk in the three models of reference at each GAs and for each **B**-field orientation, indicating also in the brackets in which specific CNS tissue the maximum occurs. At all the stages of pregnancy and for all orientations of the **B** field, the J_{peak} was in compliance with the basic restriction of 2 mA m^{-2} suggested by the Recommendation 1999[2] at 50 Hz for exposure to 100 μT magnetic field. For all GAs, the maximum J_{peak} was found for the top-to-bottom exposure in the cerebellum. For each GA, the differences across all orientations are up to 64.6 % at 7 mGA. These percentages were calculated with respect to the minimum value. Furthermore, for each orientation, differences of up to 41 % are observed among the different GAs for the front-to-back exposure.

Figure 2 represents the mean and standard deviation of J_{peak} in the entire fetus body over all the pregnant models (i.e. reference and the ones with the fetal position changed) at each GA and for each

Table 4. J_{peak} in woman CNS tissues, for each GA and for each magnetic field orientation (B_{front}, B_{lat}, B_{top}).

Woman CNS tissues	J_{peak} [mA m^{-2}]		
	3 months of GA	7 months of GA	9 months of GA
B_{front}	0.78 (cerebellum)	1.1 (cerebellum)	1.02 (cerebellum)
B_{lat}	0.81 (cerebellum)	0.79 (cerebellum)	0.82 (cerebellum)
B_{top}	1.1 (cerebellum)	1.3 (cerebellum)	1.1 (cerebellum)

The magnetic field level was set at 100 μT at the frequency of 50 Hz. In the brackets, the specific CNS tissue, in which the J_{peak} was found, is indicated case-by-case. The maximum permitted current density at 50 Hz is of 2 mA m^{-2}.

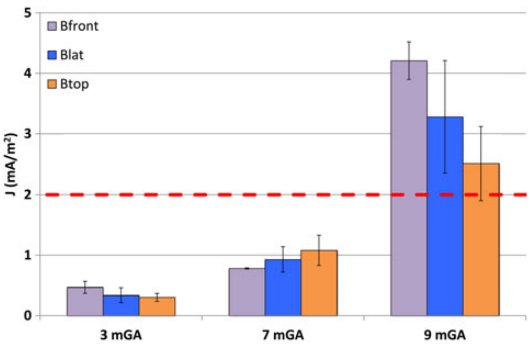

Figure 2. Mean value (bar) and standard deviation (whisker) of the RMS of the J_{peak} (mA m^{-2}) in the entire fetus body over all the pregnant models for each **B**-field orientation (B_{front}, B_{lat}, B_{top}). The error bar indicates the exposure variations due to anatomical variability related to the fetal position at each GA. The basic restriction level suggested by the Recommendation 1999/519/EC at 50 Hz ($J_{peak} = 2$ mA m^{-2}) for the general public is indicated by a dashed line. mGA means 'month of gestational age'.

orientation of the **B**-field with respect to the basic restriction threshold of 2 mA m^{-2} for general public exposure at 50 Hz.

At 3 and 7 mGAs, J_{peak} values are always below the threshold suggested by the Recommendation 1999[(2)]. On the contrary, J_{peak} values induced in the entire fetus body at 9 months of GA are above the limits for all the exposure scenarios (mean value of 4.21 mA m^{-2} for B_{front}, 3.28 mA m^{-2} for B_{lat} and 2.51 mA m^{-2} for B_{top}). More specifically, in the 9-month-old fetus, the mean J_{peak} values above the limits were found in the fetal cerebrospinal fluid (CSF) tissue for all exposure scenarios. Also the fetal eye-humour vitreous, the gallbladder and the intestine show J_{peak} values that exceed the basic restriction limit (up to 2.48 mA m^{-2} in the fetal gallbladder for the B_{top} exposure), whereas J_{peak} values in all the other fetal tissues are lower than the basic restriction threshold. The variation of J_{peak} values in the entire fetal body, expressed as coefficient of variation, due to the change in fetal position is, at maximum, of 37 % at 3 months of GA, of 23 % at 7 months of GA and of 28 % at 9 months of GA.

A further investigation has been performed on the induced current densities in the CNS tissues of the fetal head and trunk, i.e. brain and spinal cord, where the stimulation due to ELF-MF could occur. These J_{peak} values are reported in Table 5 for each exposure scenario considering all the fetal models at each GA. The values of the J_{peak} in the fetal CNS tissues are lower than the limit of 2 mA m^{-2} at all GAs, with a maximum of 0.49 mA m^{-2} at 9 months of GA for the B_{front} exposure with the fetus in the cephalic position. Furthermore, the maximum variation of J_{peak} in the fetal CNS tissues due to the fetal posture is 38 % at 3 months of GA and B_{top} exposure.

Compliance with the European Directive 2013/35/EU for the occupational exposure

Figure 3 shows the induced E_{99th} in the entire body of the pregnant woman exposed to a magnetic field of 6 mT (corresponding to 'High AL' level, as indicated in Table 1), at each exposure scenario and for each GA. The results are represented in terms of mean (bar) and standard deviation (whiskers) of E_{99th} calculated across the pregnant woman models at each GA to take into account the variability of the exposure due to the fetal positions at the same stage of pregnancy. The figure clearly shows that the pregnant woman is always in compliance with respect to the Health Effect ELV of 1.1 V m^{-1}. Negligible variations have been observed among the pregnant woman models at 3 months of GA due to the variation of fetal position, whereas variations up to 9.6 and 7.5 % were found at 7 and 9 months of GA, respectively, mainly for B_{lat} and B_{top} exposures. Therefore, it seems that the variation of fetal position at those stages of pregnancy influences more the pregnant exposure, probably due to the larger dimensions of the fetuses at 7 and 9 months of GA than at 3 months of GA.

As stated in the Directive 2013[(3)], the health effects are believed to occur in the CNS and PNS tissues. Therefore, the evaluation of E_{99th} in those specific tissues has been also carried out considering the reference models at each GA, and the maximum E_{99th}

Table 5. Mean ± standard deviation (over fetal positions) of the RMS J_{peak} in fetal CNS tissues for each GA and for each magnetic field orientation (B_{front}, B_{lat}, B_{top}).

Fetal CNS tissues	J_{peak} [mA m^{-2}]		
	3 months of GA	7 months of GA	9 months of GA
B_{front}	0.17 ± 0.06 (fetal brain)	0.32 ± 0.07 (fetal brain)	0.45 ± 0.06 (fetal brain)
B_{lat}	0.12 ± 0.01 (fetal brain)	0.44 ± 0.04 (fetal brain)	0.37 ± 0.03 (fetal brain)
B_{top}	0.13 ± 0.05 (fetal brain)	0.34 ± 0.02 (fetal brain)	0.28 ± 0.07 (fetal brain)

The magnetic field level was set at 100 μT at a frequency of 50 Hz. In the brackets, the specific fetal CNS tissue in which the J_{peak} was found is indicated case by case.

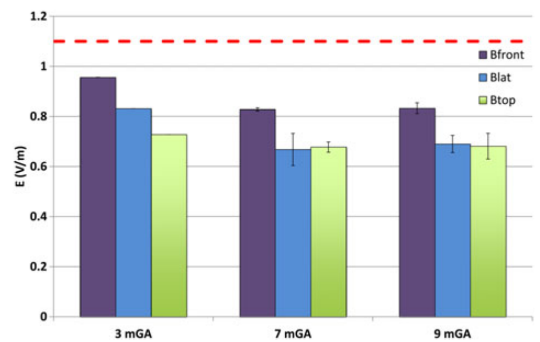

Figure 3. Mean (bar) and standard deviation (whisker) over fetus positions of the maximum E_{99th} (V m^{-1}) induced in the pregnant woman's entire body, according to the analysis of each specific tissue, as a function of GA and magnetic field orientation. The Directive 2013/35/EU Health Effects ELV of 1.1 V m^{-1} is indicated as a dashed line; mGA means 'months of gestational age'. The error bar indicates the exposure variations due to anatomical variability related to the fetal position at each GA.

with the corresponding tissue of the CNS or PNS in which it was found is shown in Table 6. All values are well below the Health Effects ELV of 1.1 V m^{-1} and at all GAs the worst-case exposure scenario is the B_{lat} exposure in the nerves (PNS).

The EU Directive 2013[3] states specific interest also regarding the sensory effects in the head, i.e. the retinal phosphenes and minor transient changes in some brain functions. Therefore, E_{99th} was also analysed in each woman's head tissue for all GAs and exposure scenarios, to investigate whether values higher than those allowed for Sensory Effects ELV might occur in any of them. Figure 4 represents the mean and standard deviation of the maximum E_{99th} found in the woman's head tissues across all available anatomical models at each GA and for all MF orientations. For all cases, E_{99th} was found in compliance with the Sensory Effects ELV. As previously observed in the assessment of the compliance to the Health Effects ELV (Figure 3), the highest variation of E_{99th} due to the fetal posture was up to 9.6 % at 7 months for B_{lat} exposure. Furthermore, at all GAs the tissues of the head, in which the maximum have been found, were the skin for B_{front} and the mucosa for B_{lat} and B_{top}.

Since also the fetus is exposed to the low and high ALs during the pregnant woman's working hours, a similar analysis was also conducted on the entire fetal

Table 6. Maximum E_{99th} (V m^{-1}) induced in the CNS and PNS tissues of the woman models, for each GA and exposure scenario (B_{front}, B_{lat}, B_{top}); the Directive 2013 indicates 1.1 V m^{-1} for the Health Effects ELV.

	Woman CNS and PNS tissues [E_{99th} (V m^{-1})]		
	3 mGA	7 mGA	9 mGA
B_{front}	0.15 (grey matter)	0.18 (nerves)	0.21 (nerves)
B_{lat}	0.27 (nerves)	0.32 (nerves)	0.41 (nerves)
B_{top}	0.17 (nerves)	0.32 (nerves)	0.40 (nerves)

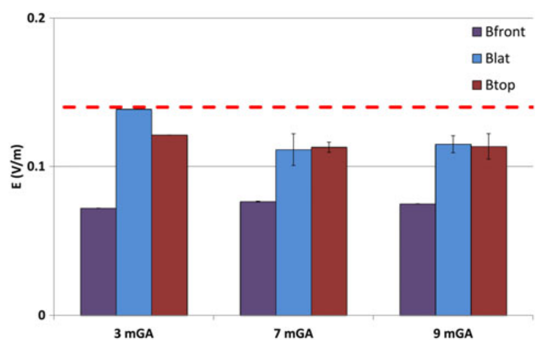

Figure 4. Mean and standard deviation (over fetal position) of the maximum E_{99th} (V m^{-1}) induced in the woman's head tissues, with respect to the Directive 2013/35/EU Sensory Effects ELV of 0.14 V m^{-1} at 50 Hz, indicated as a dashed line, for each GA and magnetic field orientation. The error bar indicates the exposure variations due to the variability of the fetal position at each GA.

body exposed at low and high ALs of the magnetic field. The mean and standard deviation of E_{99th} calculated across all the available models at each GA and for each exposure scenario is represented in Figure 5. Also in this case, the E_{99th} is lower than the Health Effects and Sensory Effects ELVs. The maximum exposure for both the high AL and the low AL occurs at B_{front} orientation in the skin tissue at 9 months of GA and reaches mean E_{99th} values of 0.45 V m^{-1} for exposure to high AL (Figure 5a) and of 0.07 V m^{-1} for exposure to low AL (Figure 5b), respectively.

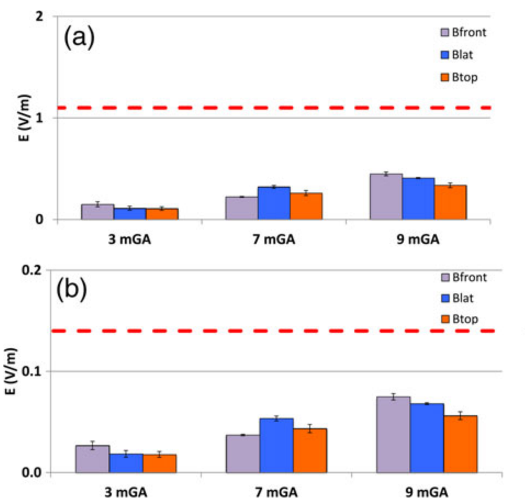

Figure 5. Mean and standard deviation (over fetal position) of the maximum E_{99th} in the entire body of the fetus at each GA and for each **B**-field orientation: (**a**) E_{99th} for the magnetic field set to High AL. (**b**) E_{99th} for the low AL case. In both cases, Directive 2013/35/EU Health (a) and Sensory (b) ELV limits are indicated with dashed lines. The error bar indicates the exposure variations due to the variability of the fetal position at each GA.

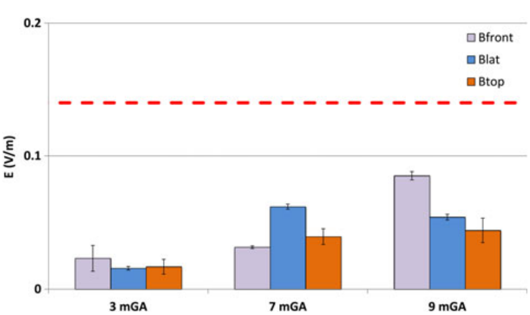

Figure 6. Mean and standard deviation (over fetal position) of the maximum E_{99th} (V m^{-1}) in the tissues of the fetal head at each GA and for each **B**-field orientation. The Directive 2013/35/EU Sensory Effects ELV is indicated by the dashed line. The error bar indicates the exposure variations due to anatomical variability related to the fetal position at each GA.

The variation of the fetal exposure due to the change in the fetal position reaches values up to 18 % for B_{lat} at 3 months of GA for the Health and Sensory Effects. As expected, this variation is higher than the one observed in the analysis of the woman's entire body exposure, which was always lower than 10 %.

Additionally, E_{99th} induced in all fetal head tissues was compared with the Sensory Effects ELV to directly investigate the region of interest for the sensory effects. The results in Figure 6 show that the E_{99th} is lower than the limit at all GAs with a maximum of 0.09 V m^{-1} at 9 month GA for the B_{front} exposure, when the fetus is in the cephalic position. Furthermore, the variation of the fetal head tissues exposure due to the posture in its mother's womb reaches value up to 42 % at 3 months of GA.

Finally, the fetal exposure has been also compared with the limits of the induced electric field at 50 Hz–0.02 V m^{-1} and 0.4 V m^{-1} for the CNS tissues of the head and for all the other tissues of the head and body, respectively—suggested by the basic restriction of ICNIRP 2010[1] for exposure of the general public. In Figure 7, mean and standard deviation (over the fetal positions) of the maximum induced E_{99th} for both the fetal CNS tissues of the head and for all the other tissues of the head and body exposed to 1 and 6 mT (Figure 7a and b, respectively) are represented together with the basic restriction levels, shown as dashed lines, for comparison. From Figure 7a, it can be observed that the E_{99th} values induced by MF at 1 mT (Low AL) in all other tissues of the head and body are significantly lower than the limit of 0.4 V m^{-1} at all GAs and exposure scenarios, as well as for the CNS tissues of the head at 3 months with respect to the threshold of 0.02 V m^{-1}. However, at both 7 and 9 months of GAs, the fetuses present E_{99th} values in the CNS tissues of the head up to 70 % higher than the ICNIRP limit for general public. Regarding the exposure to 6 mT (high AL, Figure 7b), E_{99th} in the fetal CNS tissues of the head resulted at all GAs and exposure scenarios above the threshold with values up to 10 times higher than the limit at 7 and 9 months of GAs. For all the other tissues of the head and body, E_{99th} was lower than the limit, except for the B_{front} and B_{lat} exposures at 9 months of GA.

DISCUSSION AND CONCLUSIONS

There is increasing interest regarding the exposure of pregnant women to ELF MFs in daily life as well as in the workplace. In the European Union, the Recommendation 1999/519/EC[2] for the general public and the Directive 2013/35/EU[3] for workers are the legislative acts currently available that recommend [Reference (2)] and establish [Reference (3)] the minimum health and safety requirements regarding

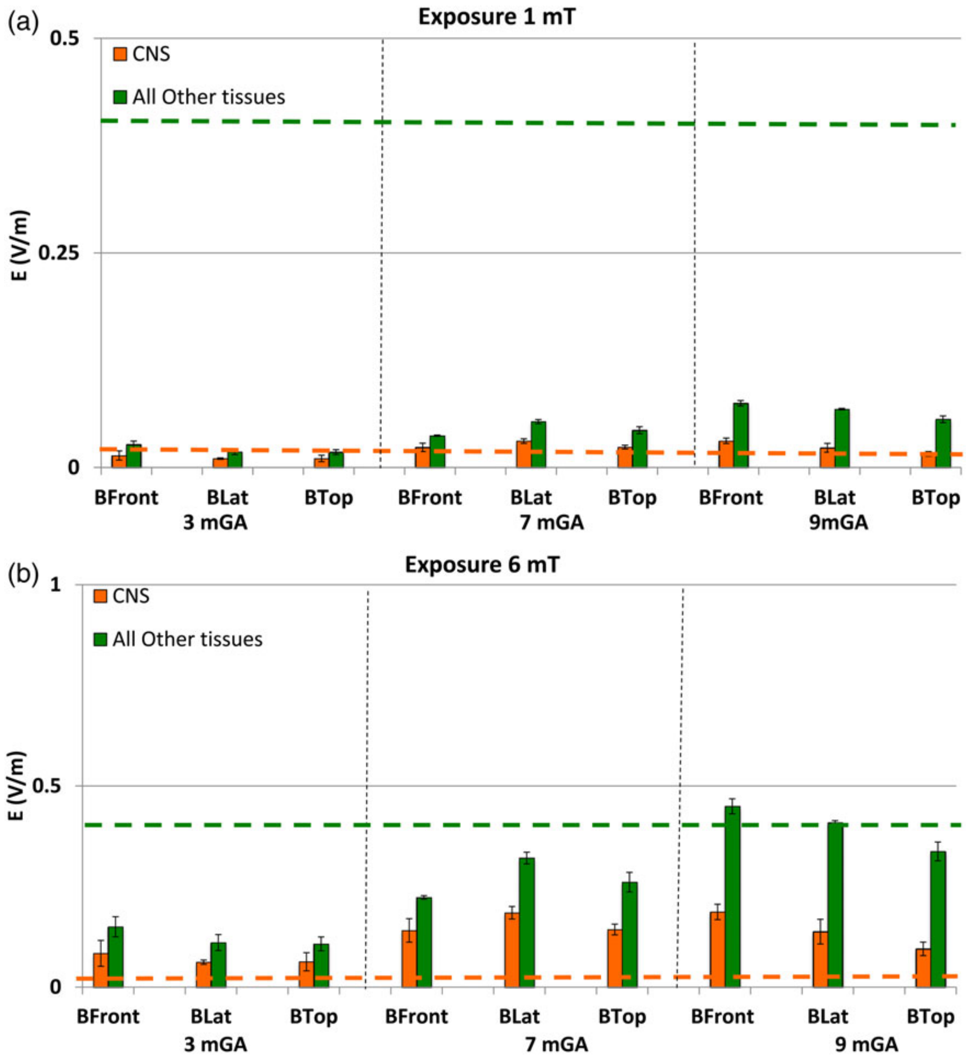

Figure 7. Mean and standard deviation (over fetal position) of the maximum E_{99th} (V m^{-1}) in the fetal CNS tissues of the head and in all the other tissues of the head and body. (**a**) Fetal exposure to 1 mT; (**b**) fetal exposure to 6 mT. In both graphs, the basic restrictions of the ICNIRP 2010 for the general public are indicated with dashed lines: the limit for the CNS tissues of the head is of 0.02 V m^{-1}, and the limit for all the other tissues of the head and body is of 0.4 V m^{-1}. The error bar indicates the exposure variations due to the variability of the fetal position at each GA.

the exposure to EMFs. In this study, the assessment of compliance with the limits indicated in these acts is addressed by computational electromagnetic techniques in pregnant women at 3, 7 and 9 months of GA upon exposure to a uniform magnetic field at 50 Hz. The uniform exposure represents a conservative exposure scenario that ensures automatic compliance with all non-uniform exposure conditions. In order to draw general conclusions for the pregnant women at different stages of pregnancy, several anatomical models have been analysed to assess the variability of the exposure due to the fetal posture in the woman's womb (i.e. three positions at 3 months of GA and two positions at 7 and 9 months of GAs). However, these results provide a general picture of the exposure of the entire pregnant woman population. Indeed, one should take into account that the results presented in this study are valid for this specific evaluation, in which only some anatomical differences among pregnant women at the same stage of pregnancy (i.e. the fetal posture) have been considered and hence the statistical power is still low.

As to the compliance to the EU Recommendation 1999[2], J_{peak} levels induced in the CNS tissues of the pregnant women were always found within the limits at each GA, with maximum J_{peak} always located in the cerebellum for the top-to-bottom exposure (Table 4). Also the fetal exposure has been assessed with respect to the limit for the general public considering all the models for each GA and exposure scenarios. In this case, for all the exposure scenarios at 9 months of GA, the J_{peak} was always found to be higher than the limit of the Recommendation (Figure 2) in some tissues, which do not belong to the CNS tissues of head and trunk (Table 5), where the stimulation due to ELF-MF exposure could occur.

As to worker exposure, according to the Directive 2013[3], the induced electric fields (E_{99th}) in the pregnant woman were always in compliance with respect to the Health and Sensory Effects ELVs at the level of, respectively, the entire body (Figure 3) and of all head tissues (Figure 4). The variation of pregnant exposure due to the change in the fetal posture at each GA for both the Health and Sensory Effects has always been found <10 % and the maximum occurred at 7 and 9 months, due to the larger dimensions of the fetuses than at 3 months, in which these variations were always close to zero.

EU Directive 2013[3] gives no specific consideration for the assessment of compliance in the fetus. In this study, the authors performed a double analysis comparing the electric fields in the fetal body induced by Low and High ALs to both the Health and Sensory Effect ELVs for all GAs and exposure scenarios (Figures 5 and 6), as previously done for the mother, and, for a more conservative approach, to the basic restriction of the ICNIRP 2010[1] for the general public. E_{99th} in the fetus always resulted lower than the limits of the Directive 2013[3], with a variation of the exposure due to the fetal posture higher than the one observed in the woman, showing a maximum <20 % in the entire fetal body for the Health Effects and >40 % in the fetal head tissues for the Sensory Effects. On the contrary, the comparison of the fetal-induced electric fields to the basic restriction of the ICNIRP Guidelines 2010[1] for the general public shows that E_{99th} values in the fetal CNS tissues of the head were higher than the limits and therefore not intrinsically compliant with these safety recommendation at 1 mT in 7 and 9 months of GA and at 6 mT in all GAs (Figure 7).

In conclusion, this study provides a general framework of the exposure to ELF-MF of pregnant woman population during daily life as member of the general public and during the working hours, aiming to check the compliance with respect to the limits established by both the Recommendation 1999[2] and the Directive 2013[3]. Moreover, the results reported in this work could be of particular interest for the generation of new guidelines for the Directive 2013[3] currently in progress.

ACKNOWLEDGEMENTS

The software SEMCAD X was provided by SPEAG (http://www.speag.com, Zürich, Switzerland) for research purposes. The authors would like also to thank Helmholtz Zentrum München Deutsches Forschungszentrum für Gesundheit und Umwelt (HMGU) for the voxel data used in the development of the 9-month pregnant woman model.

FUNDING

This work was supported by the European Union's Seventh Programme for research, technological development and demonstration under Grant Agreement No 282891 (European project ARIMMORA -Advanced Research on Interaction Mechanisms of electroMagnetic exposures with Organisms for Risk Assessment).

REFERENCES

1. ICNIRP 2010. *Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)*. Health Phys. **99**(6), 818–836 (2010).
2. EU Council Recommendation 1999/519/EC. Official Journal of the European Communities L199/59-70.
3. Directive 2013/35/EU of the European Parliament and of the Council. Official J European Union L179/1-21.
4. *Eurostat—Economically active population by sex, age and NUTS 3 regions.* Available on http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=lfst_r_lfp3pop&lang=en (June 2013, date last accessed).
5. Feinberg, J. S. and Kelley, C. R. *Pregnant workers: a physician guide to assessing safe employment*. Western J. Med. **168**, 86–92 (1998).
6. Figà-Talamanca, I. *Occupational risk factors and reproductive health of women*. Occup. Med. (Lond) **56**, 521–531 (2006).
7. Hocking, B. and Gobba, F. *Medical aspects of over-exposure to electromagnetic fields.* J. Health Saf. Environ. **27**(3), 185–195 (2011).
8. Gobba, F., Tavani, M. and Bianchi, N. *Evaluation of the occupational risk related to exposure to electromagnetic fields according to the EC Directive 2004/40/EC: Exposure during pregnancy.* Giornale Italiano di Medicina del Lavoro ed Ergonomia **29**, 3 (2007).
9. Dawson, T., Caputa, K. and Stuchly, M. *High-resolution organ dosimetry for human exposure to low-frequency electric fields.* IEEE T. Power Deliver. **13**, 366–373 (1998).
10. Dimbylow, P. *Induced current densities from low-frequency magnetic fields in a 2 mm resolution, anatomically realistic model of the body.* Phys. Med. Biol. **43**, 221–230 (1998).
11. Stuchly, M. and Dawson, T. *Interaction of low-frequency electric and magnetic fields with the human body.* P. IEEE **88**, 643–664 (2000).
12. Hirata, A., Caputa, K., Dawson, T. W. and Stuchly, M. A. *Dosimetry in models of child and adult for low-frequency electric field*. IEEE T. Bio-Med. Eng. **48**(9), 1007–1012 (2001).

13. Dimbylow, P. *Development of the female voxel phantom, NAOMI, and its application to calculations of induced current densities and electric fields from applied low frequency magnetic and electric fields.* Phys. Med. Biol. **50**, 1047–1070 (2005).
14. Dimbylow, P. *Quandaries in the application of the ICNIRP low frequency basic restriction on current density.* Phys. Med. Biol. **53**, 133–145 (2008).
15. Dimbylow, P. *Development of pregnant female, hybrid voxel-mathematical models and their application to the dosimetry of applied magnetic and electric fields at 50 Hz*. Phys. Med. Biol. **51**, 2383–2394 (2006).
16. Dimbylow, P. and Findlay, R. *The effects of body posture, anatomy, age and pregnancy on the calculation of induced current densities at 50 Hz*. Radiat. Prot. Dosim. **139**, 532–535 (2010).
17. Liorni, I., Parazzini, M., Fiocchi, S., Douglas, M., Capstick, M., Gosselin, M. C., Kuster, N. and Ravazzani, P. *Dosimetric study of fetal exposure to uniform magnetic fields at 50 Hz*. Bioelectromagnetics, **35**(8), 580–597 (2014).
18. Xue, C., Wood, A. W. and Dovan, T. *Induced current density in the fetus of pregnant workers in high magnetic field environments.* Australas. Phys. Eng. Sci. Med. **27**(4), 199–206 (2004).
19. Cech, R., Leitgeb, N. and Pediatis, M. *Current densities in a pregnant woman model induced by simultaneous ELF electric and magnetic field exposure.* Phys. Med. Biol. **53**, 177–186 (2008).
20. Christ, A., Guldimann, R., Buehlmann, B., Zefferer, M., Bakker, J. F., van Rohn, G. C. and Kuster, N. *Exposure of the human body to professional and domestic induction cooktops compared to the basic restrictions.* Bioelectromagnetics **33**(8), 695–705 (2012).
21. ICNIRP 1998. *Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)*. Health Phys. **74**(4), 494–522 (1998).
22. *SEMCAD X v. 14.8.4 by SPEAG Schmid & Partner Engineering AG, Zürich, Switzerland*. Available on http://www.speag.com. (February 2014, date Last accessed).
23. Christ, A., Kainz, W., Hahn, E.G., Honegger, K., Zefferer, M., Neufeld, E., Rascher, W., Janka, R., Bautz, W., Chen, J. *et al. The Virtual Family-development of surface-based anatomical models of two adults and two children for dosimetric simulations.* Phys. Med. Biol. **55**(2), N23–N38 (2010).
24. Gabriel, C., Gabriel, S. and Corthout, E. *The dielectric properties of biological tissues: 1. Literature survey.* Phys. Med. Biol. **41**(a,b,c), 2231–2249, 2251–2269, 2271–2293 (1996).
25. Gabriel, C., Peyman, A. and Grant, E. H. *Electrical conductivity of tissue at frequencies below 1 MHz*. Phys. Med. Biol. **54**(16), 4863–4878 (2009).
26. Hasgall, P. A., Neufeld, E., Gosselin, M. C., Klingenböck, A. and Kuster, N. *IT'IS Database for thermal and electromagnetic parameters of biological tissues Version 2.2*, July 11th. Available on http://www.itis.ethz.ch/database. (February 2014, date last accessed).
27. Peyman, A., Gabriel, C., Grant, E. H., Vermeeren, G. and Martens, L. *Variation of the dielectric properties of tissues with age: the effect on the values of SAR in children when exposed to walkie-talkie devices.* Phys. Med. Biol. **54**(2), 227–241 (2009).