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Estimate of the fetal temperature increase due to UHF RFID exposure

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Abstract— **Exposure from electromagnetic (EM) devices has increased during the last decades due to the rapid development of new technologies. Among them, radiofrequency identification (RFID) applications are used in almost every aspect of everyday life, which could expose people unselectively. This scenario could pose potential risks for certain groups of general population, such as pregnant women, who are more sensitive to thermal effects produced by EM exposure. In this paper, the temperature rise at the steady state in two pregnant women models exposed to UHF RFID has been assessed. Results show that heating of tissues is far from the threshold of biological effects indicated by radiation protection guidelines.**

I. Introduction

In the last two decades, the interest in wireless communication systems and the consequent increase of wireless devices have prominently changed exposure from such devices. These changes include the increase of exposure levels, the extension of that exposure to almost all societal classes, a longer time of exposure and the exposure to devices that operate at frequencies that are still biologically unexplored. At the same time, the lack of knowledge of these topics and the potential health effects that such an incredible revolution might provoke, is one of the compelling issues of concern among people. Wireless communications work through electromagnetic (EM) radiation and, as a result, the estimate of the exposure levels corresponds to the assessment of EM fields to which people are exposed.

Among the countless number of wireless communication systems, one of the most promising and fast growing is Radio Frequency Identification (RFID) technology, which allows a rapid, reliable and automatic identification of people and objects. It is based on the communication between a reader and a label (named "tag") which uniquely identifies the object/person [1]. It is used in many ubiquitous applications: asset tracking, manufacturing, supply chain management, payment systems, security and access control, transport systems, electronic passports and ID cards, animal identification, medical applications, sporting events, and any other application that can take advantage by an automatic identification. Among the various operating frequencies of RFID, the devices using the UHF band (i.e., around 870 MHz in Europe), seem to be particularly suitable for a great range of applications that require longer read ranges. Hence, people that occasionally or accidentally pass close to those systems could be exposed to RF radiation. Among them, pregnant women and their fetuses can be considered more vulnerable to EM radiation exposure than others [2], thus making urgent the estimation of exposure levels which are still lacking.

At the typical operating frequencies of UHF RFID system, the main biological effect induced by EM fields exposure is temperature increase in human tissues. The pattern of EM energy absorption is complex and a non uniform heating of tissues can arise, which represents a potentially unique challenge to the thermoregulatory system [3].

This is even more true considering fetal physiology. The fetus is growing in the uterus under aerobic metabolism. Its metabolic rate is higher and its temperature remains 0.3 to 0.5°C higher than that of the mother [4]. Since fetal temperature is higher than maternal temperature, heat is transferred from the fetus to the mother. If heat production and loss from the fetal body remain balanced, fetal temperature stays constant. However, if the heat transfer to the mother is disrupted for any reason, the fetal temperature may increase. Several biological, chemical and physical agents can change the temperature and/or the heat load of either the fetus or the mother and, thus, disturb normal fetal thermoregulation. Among them, prolonged exposure to RF radiation been suggested to be teratogenic [5].

The International Commission on Non Ionizing Radiation Protection (ICNIRP), in a comprehensive review aimed at providing guidelines for limiting exposure [6], concludes that "established biological and health effects in the frequency range from 10 MHz to a few GHz are consistent with responses to a body temperature rise of more than 1°C".

The assessment of the RF exposure levels is often limited to the specific absorption rate (SAR) estimation [7]–[9]. In some other studies [10]–[18], the increase in fetal temperature, due to RF exposure, is estimated using computational methods based on the application of a modified version of the bio-heat equation (BHE) introduced in [19].

The software SEMCAD X was provided by SPEAG (http://www.speag.com) for research purposes.

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In a previous paper [20], we focused on the assessment of exposure to UHF RFID devices of pregnant women; high levels of SAR values in some fetal tissues were found (the maximum peak SAR levels averaged over 10g and normalized to 1 W radiated power of the reader antenna and were close to the limit of 2 W/kg provided by the ICNIRP guidelines [6]). In order to better investigate any potential effects induced by such a high exposure, in this paper the temperature rise in the same exposure scenarios are estimated applying the classical approach based on the BHE numerical solution.

II. Methods

A. Anatomical models and exposure scenario

The realistic models of pregnant women at two gestational ages, i.e., 7 and 9 months, were considered in the simulations. The models were obtained from partial deformations of the womb of the adult female model named "Ella" of the Virtual Family [21] and by integrating the segmented MRI images of pregnant women abdomens [22]. Only the two worst case exposure scenarios in terms of SAR levels obtained in our previous EM computation [20] were studied. These coincide, in particular, with the RFID reader ground plane of the antenna (whose characteristics are detailed in [20]) positioned:

- at 10 cm from the 7-month pregnant woman skin in front of her fetus (position R1);
- at 10 cm from the 9-month pregnant woman, at -45 ° in the x-y plane (position R3);

considering the reference system shown in Fig. 1.

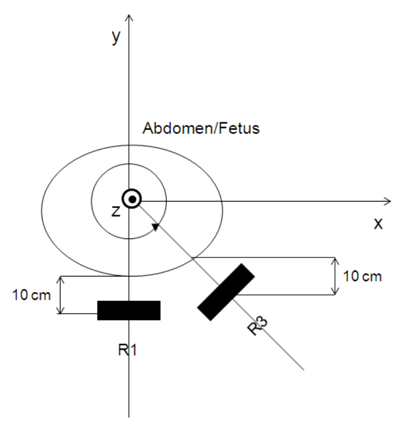

Figure 1. Schematic representation of reader position with respect to the pregnant women models. The center of the local coordinate systems was found through the arithmetic mean of maximum and minimum x, y, and z coordinates (of the original reference system outside the body) of the pregnant women wombs, while the x-,y-,and z- axis were kept parallel to the original reference system. The center of the ground plane of the reader antenna was placed at z=0 (local coordinate systems) and at a distance of 10, 20 and 50 cm from the skin of the model, along the direction defined by the respective angle: R1 (-90º), and R3 (-45º) with respect to x-y plane.

RFID reader antenna is supposed to be continuously transmitting (100% of duty cycle) with an Effective Radiated Power ERP of 1 W.

The mesh in each simulation was kept the same of the previous EM computation [20], where a non-uniform mesh with a maximum spatial step of 4 mm in free space, 1 mm in the anatomical models, and 0.2 mm in the fetal skin to allow a good discretization of thin layers of the body, had been generated.

B. Thermal Model

The temperature increase inside the tissue exposed to the UHF RFID reader was calculated using the BHE [19], as implemented by the thermal solver of the simulation platform SEMCAD X (Schmid & Partner Engineering AG, Zurich, Switzerland) [23].

Since the purpose of the simulation was to obtain the temperature increase (T_{incr}) due to SAR (S) exposure and such increase is expected to be small (< 1 °C), the tissue parameters (density ρ, specific heat c, thermal conductivity k, volumetric blood perfusion rate ω, metabolism Q and blood temperature T_b, density ρ_b and specific heat c_b) and the parameters necessary to define boundary conditions (i.e., the heat transfer rate due to convection cooling through air contact h, the temperature outside the boundary, and the heat flux due to perspiration) can be considered time and temperature independent. Under these hypothesis, it's possible to consider a simplified version of the complete BHE (for further details on this approximation see [24]):

$$\rho c \partial T_{incr}/\partial t = \nabla(k \nabla T_{incr}) + \rho S - \rho_b c_b \rho \omega T_{incr} \quad (1)$$

Mixed boundary conditions:

$$k \partial T_{incr}/\partial n + h T_{incr} = 0 \quad (2)$$

were applied at the interface between maternal skin and air with $h_{skin-air}$=8 W/(m^2·K); between maternal cornea and air with $h_{cornea-air}$=20 W/(m^2·K); and between lung and internal air with $h_{lung-air}$=50 W/(m^2·K) (as in [24]); n is the unitary vector, directed normally to surface of the interface,.

Neumann boundary conditions:

$$k \partial T_{incr}/\partial n = 0 \quad (3)$$

were applied at the interface between air-filled cavities (i.e., internal air, bronchi lumen, esophagus lumen, pharynx and trachea lumen) and the other maternal tissues in contact with them.

Dirichlet boundary conditions:

$$T_{incr} = 0 \quad (4)$$

were applied at the interface between blood (i.e., artery, veins and umbilical cord) and every tissue perfused by blood (all the tissues except air tissues, maternal and fetal CSF, maternal and fetal humor vitreous, amniotic fluid, teeth, stomach lumen and small intestine lumen). Temperature rise at the steady state (by assuming a zero temporal gradient in (1)) was calculated for each exposure scenario in the fetal tissues, placenta and amniotic fluid.

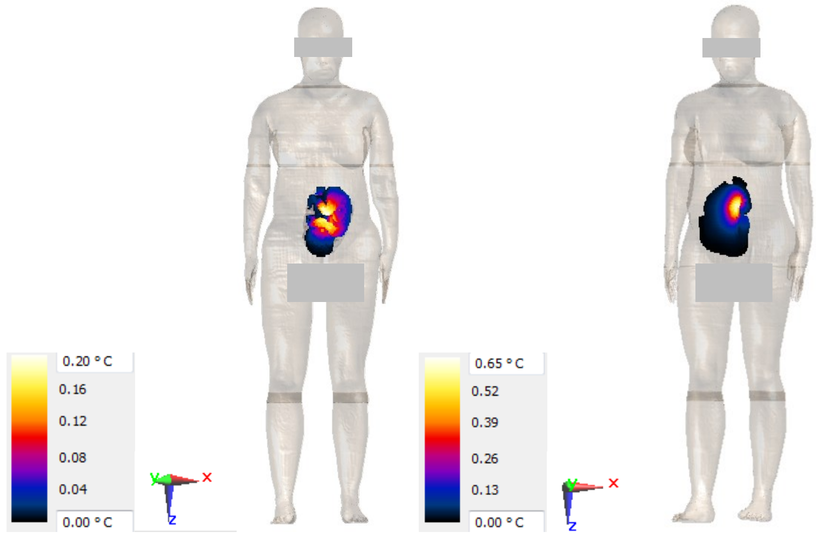

Figure 2. Temperature increase distribution at the steady state on the surface of the fetus for the "7 months pregnant woman exposure" (left) and the "9 months pregnant woman exposure" (right). Color maps are clamped to the maximum of each distribution as shown by the color bars on the right.

C. Thermal parameters

Dielectric properties and density of the tissues of the pregnant women models were the same like those assigned in the electromagnetic simulation to determine SAR distributions [20]. The thermal parameters of mother tissues were taken from [24], with the exception of amniotic fluid and placenta that were taken from [11] and umbilical cord that was considered as blood. Thermal properties of fetal tissues were supposed to be equivalent to the ones used for the corresponding adult tissues.

TABLE I. MEAN AND MAXIMUM OF THE TEMPERATURE RISE DISTRIBUTION AT THE STEADY STATE CALCULATED OVER SOME TISSUES OF THE 7- AND 9- PREGNANT WOMAN EXPOSED TO UHF RFID

Tissue	**7-month pregnant woman exposure**		**9-month pregnant woman exposure**	
	Mean T_{incr} [°C]	*Max T_{incr} [°C]*	*Mean T_{incr} [°C]*	*Max T_{incr} [°C]*
Bone	0.013	0.131	0.012	0.164
Brain	0.001	0.019	0.000	0.002
Fat	0.020	0.175	0.029	0.525
Heart	0.003	0.014	0.001	0.003
Intestine	0.001	0.013	0.006	0.085
Kidney	0.002	0.014	0.003	0.021
Liver	0.004	0.035	0.001	0.006
Lung	0.005	0.063	0.002	0.013
Muscle	0.022	0.148	0.020	0.281
Skin	0.027	0.204	0.030	0.659
Spleen	0.000	0.001	0.014	0.052
Fetus	0.015	0.204	0.020	0.659
Amniotic fluid	0.036	0.245	0.025	0.715
Placenta	0.000	0.006	0.000	0.010

III. RESULTS

Fig. 2 shows the temperature rise distribution, at steady-state, on the surface of the fetus obtained from the simulation with the reader in position R1 for the 7-month pregnant woman exposure and in position R3 for the 9-month pregnant woman exposure (named in the following, for ease of reference, as "7-month pregnant woman exposure" and "9-month pregnant woman exposure"). As expected the position of the maximum values is strongly influenced by the location of the RFID reader.

Table 1 shows the mean and the maximum of the temperature increase distributions for the 7-month pregnant woman exposure and the 9-month pregnant woman exposure". The term "Fetus" in the table refers to all the tissues of the fetus model itself; as a consequence, the "Mean T_{incr}" is the mean value of the distribution of T_{incr} over the whole fetus, and the "Max T_{incr}" is the maximum value of the distribution of T_{incr} over the whole fetus (which coincides with maximum of the "Max T_{incr}" of the same fetal tissues).

Maximum T_{incr} at the steady-state due to UHF RFID exposure was found approximately 0.20 °C in skin, fat, muscle bone (i.e. the most superficial tissues) for the 7-month pregnant woman exposure" and approximately 0.65 °C at the same tissues for the 9-month pregnant woman exposure". Differences between temperature increase values in the 9-month pregnant woman exposure with respect to 7-month pregnant woman exposure are probably due to the larger volume of the high electric and thermal conductive amniotic fluid and the higher peak SAR levels [20] found in the first exposure scenario (reader in R3 for the 9-month pregnant woman exposure), even if, as found by [24], position and value of peak SAR don't correlate exactly with position and value of the maximum temperature increase.

However, as suggested by the T_{incr} distribution shown in Fig. 2, the temperature rise is strongly localized in a small volume. This also explains the great difference between mean and maximum T_{incr} levels.

IV. Conclusion

The results discussed in this paper suggest that prolonged UHF RFID exposure can provoke a localized heating in the fetal tissues up to a maximum of 0.65°C. Moreover the average temperature increase over all fetal tissues of 0.02°C is very far from the threshold of biological effects provided in exposure guidelines [6].

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