

THERMOREGULATORY RESPONSE TO ELECTROMAGNETIC PLANE-WAVE EXPOSURE AT 900 MHZ

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ABSTRACT

In electromagnetic dosimetry the mobile phone antenna scenario is the typical problem and consequently far-field exposure has received less attention. International safety limits provide reference levels expressed in terms of EM field strengths, which are evaluated in the absence of a person and derived from plane-wave incidence and CW exposure, which is limited to far-field situations. The rationale for deriving basic restrictions and their associated safety margins is not fully standardized and diverse values are employed depending upon the thermal effect being considered. In this contribution, more realistic exposure scenarios and response effects are evaluated, including a $10\text{W}/\text{cm}^2$ plane-wave incident exposure. SAR is provided for all tissues, and the hybridization between EM field exposure and thermoregulatory response has provided interesting results, such as the additional thermal safety factor that the skull represents for the human body under EM field exposure. The described model could be useful for surgery operations like DBS, etc.

1. INTRODUCTION

Since the use of mobile phone antennas is the typical problem under evaluation, near-field conditions are normally employed when evaluating electromagnetic field exposure, and far-field scenarios have received considerably less attention, wherein exciting antennas are normally placed far away from the human model and corrections for non-planar wavefronts produced by the antennas are also normally introduced [1] [2] [3].

Yet, international safety limits also provide reference levels expressed in terms of electromagnetic field strengths, which are evaluated in the absence of a person. They are derived using worst case conditions of electrical coupling, but also from plane-wave incidence and CW exposure, which is limited to far-field situations. The rationale for deriving basic restrictions and their associated safety margins is not fully standardized, and diverse values are employed depending upon the thermal effect being considered for deriving the basic restriction [4].

In this contribution more realistic exposure scenarios and response effects are evaluated. Plane-wave incident exposure was used as the exciting electromagnetic wave. Following recent guidelines for exposure studies [5], the study is performed at the exposure strength as high as the occupational ICNIRP limit, e.g., $10\text{ W}/\text{kg}$, and SAR is provided for all tissues.

2. METHODS AND MODELS

In order to be able to measure SAR values, homogeneous models are required wherein a solo tissue is employed, characterised by properties averaged over a certain number of tissues. The choice of the equivalent tissue for the homogeneous model is still the subject of research [6] [7], since early studies use muscle or 2/3-muscle tissue whereas CENELEC [8] recommends a head simulating liquid (HSL) similar to brain for compliance testing.

Heterogeneous models of man have been used by selecting a limited number of tissues [1] [9] [10] or with a large number of available tissues [11]. While for near-field exposure the homogeneous models represent an overestimation of SAR respect to that obtained with heterogeneous models [12] [13] [14], for far-field plane-wave exposure the situation depends strongly on the frequency of operation and the portion of the body under test. For the human head, considerable higher both electric field and SAR values are obtained with heterogeneous models [1], normally due to the larger conductivity of the typically used muscle tissue related to the averaged one employed for homogeneous models.

The head model developed in this research represents the tissues found in the Visible Human Project directly from the ear reference point (ERP), that is, at a lateral distance of 15 mm from Tragon (entrance to the ear canal, EEC) [15], as depicted in Fig. 1. Homogeneous equivalent models have also been developed for comparison purposes.

The electrical and thermal properties for materials have been reported from the literature and their values are listed in Tab. 1 [16].

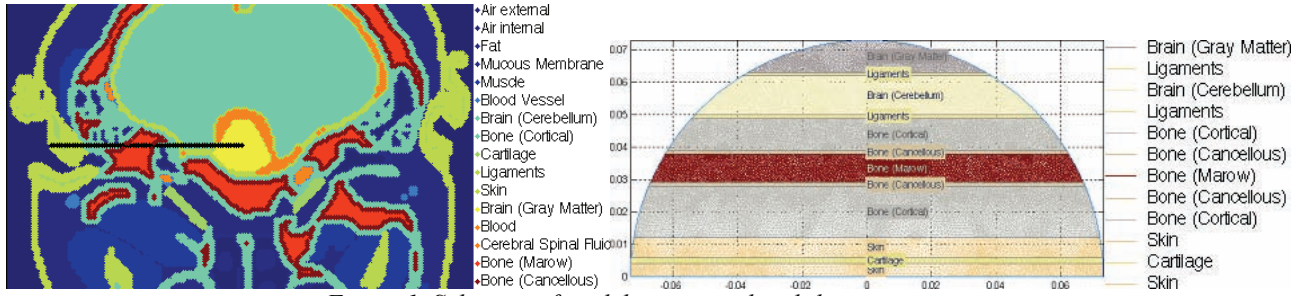


Figure 1. Selection of model tissues and multilayer structure

Tissue	ϵ_r	σ (S/m)	ρ Density (Kg/m ³)	c_p Specific heat capacity (J/Kg \cdot °C)	k_T Thermal conductivity (W/m \cdot °C)	A0 Metabolic heat production (W/m ³)	B Blood flow associated term (W/m ³ ·°C)
Skin	41.4	0.87	1125	3610	0.42	2190	12310
Cartilage	42.7	0.78	1097	3586	0.5	10	60
Bone (Cortical)	12.5	0.14	1990	1650	0.3	0	0
Bone (Cancellous)	20.8	0.34	1920	2150	0.3	2510	14120
Bone (Marrow)	5.5	0.04	1040	2700	0.22	5020	28230
Ligaments	45.8	0.72	1220	2802	0.31	860	4830
Brain (Cerebellum)	49.4	1.26	1038	3687	0.57	10040	56490
Brain (Gray Matter)	52.7	0.94	1038	3687	0.57	10040	56490

Table 1. Electrical and thermal properties of tissues selected.

Likewise, in order to provide some insight into the electromagnetic coupling mechanisms, thermal safety factors have recently been proposed to more accurately describe electromagnetic exposure [17], yet more complicated prediction tools are required, which necessarily hybridized Maxwell equations with heat transfer mechanisms. By accurately computing temperature increase in the model, direct comparison to adverse thermal effects can be evaluated, their more realistic associated SAR values identified and some insight into unclear physiological safety factors can be obtained, reducing their inherent scientific uncertainties. Thus, the human thermoregulatory response to RF energy absorption has received some attention recently [18] [19].

In this contribution Maxwell equations have been hybridized to heat and mass transfer equations through a modified bioheat equation [20]:

$$\rho \cdot c_p \frac{\partial T}{\partial t} - \nabla \cdot (k_T \nabla T) = \rho SAR + A0 + B(T_b - T) \quad (1)$$

The in-house thermal model includes heat diffusion and convection, metabolic heat production and heat-sink from tissue volume by blood perfusion, so that thermoregulatory control can be achieved in the head model in real time, which can keep a constant temperature under no RF exposure being slightly altered by the heat loss in body surface due to intimate contact to air. Thermal conditions in this contribution are kept

under the vasomotor adjustment, that is, under the lower critical temperature (LCT) [18]. In this way, no vaporization is evaluated and harsh electromagnetic exposure is out of the scope for this contribution, that is, mass transfer and their associated heat-transfer mechanism are avoided.

3. SIMULATED RESULTS

Despite the aim of international safety guidelines being to provide recommendations to governments so as to avoid whole-body heat stress and excessive localized heating of tissues, current safety limits are derived in terms of averaged SAR, that is, power absorbed by the tissue per unit of mass and incident field values, as a way of preventing possible health hazards due to temperature increases in critical zones. As an example, the hypothalamus must not overpass a temperature increment of 0.3 °C [21].

As expected, modelling head with a heterogeneous model instead with a homogeneous one provides higher peak SAR, particularly in the skull, but surprisingly smaller temperature increases in cerebellum, the critical zone, as depicted in Fig. 2. Tab. 2 shows temperature increments in the cerebellum for both the developed heterogeneous model and an equivalent homogeneous model with diverse solo tissues, that is, muscle, 2/3-muscle, and HSL. Peak and tissue-averaged values have been calculated in the simulated zone at the end of the averaging time periods of the ICNIRP (6 min) and IEEE (30 min) standards.

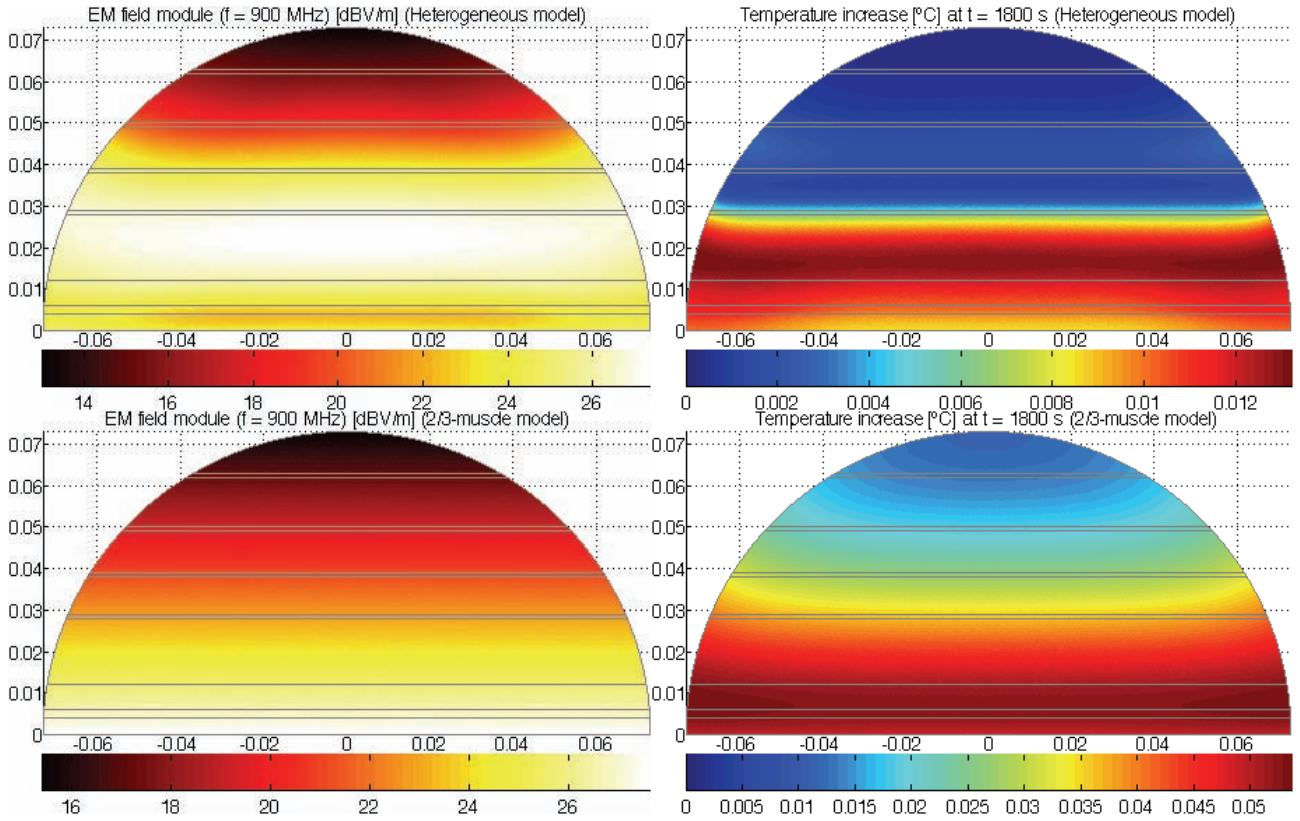


Figure 2. Electric field distribution and temperature increase in the simulated models.

ΔT in cerebellum (10^{-3}°C)	Peak (6min)	Average (6min)	Peak (30min)	Average (30min)
Heterogeneous model	1.38	0.73	2.05	0.85
Homogeneous model (Muscle)	1.93	1.4	9.27	6.34
Homogeneous model (2/3-Muscle)	6.04	4.56	23.38	17.23
Homogeneous model (HSL)	1.38	1	2.97	2.05

Table2. Simulated results.

It is worth mentioning that averaged temperature increments using homogeneous models can be as high as nineteen times those calculated with more realistic heterogeneous model, as it happens when one compares the 30 min tissue-averaged results for the 2/3-muscle homogeneous model to the heterogeneous model developed in this contribution, illustrated in the last column of Tab. 2. Likewise, we can observe that peak values at 6 min are very similar when the HSL solo tissue is employed in the homogeneous model compared to the more realistic heterogeneous model, suggesting that some differences make arrive between the safety limits considered by ICNIRP and IEEE when thermal results are evaluated, which is in line with what other authors have highlighted recently [22] [23].

4. CONCLUSIONS

Despite the simple heterogeneous model, the hybridisation between electromagnetic field exposure and thermoregulatory response has provided interesting

results, such as the additional thermal safety factor that the skull represents for the human body under electromagnetic field exposure where heterogeneous models are used instead of homogeneous.

The described model could be useful for relatively new surgery operations like implanted deep brain stimulation (BDS) wherein electrodes could provide tissue heating under MRI scans when evaluating Parkinsons' or Alzheimer' diseases, for proper evaluation of body responses to heart-pacemaker or cardioverter-defibrillator leads during RF-pulsation or for the response of neuro-stimulators or hydrocephalus valves to mobile phone exposure.

There are yet many other factors to be accounted for, such as sweating, panting, heat loss in lungs, capillarity, vasodilatation, variable blood flow or metabolism, clothing, circadian rhythm or even alterations in the thermoregulatory response itself due to temperature increase in the hypothalamus provided by the deposited

RF energy, etc. With the powerful computing resources available today, however, it is not risky envisaging the possibility of reducing current scientific uncertainties for human exposure to electromagnetic fields regarding human thermal response, thus being able in the near future to derive basic restrictions with more accurate safety factors.

5. REFERENCES

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