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THERMAL LOAD BY RF ELECTROMAGNETIC FIELD ABSORPTION IN BIOLOGICAL TISSUE

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Abstract
Reliable information on heat distribution inside biological tissues is essential in planning procedures and optimization experiments, which aim at studying the effects of non-ionizing radiation (NIR). In electrodynamics, the finite element method (FEM) has become the dominant technique utilized for radiofrequency dosimetry assessment. This paper presents a numerical finite element analysis of forearm RF electromagnetic exposure. The objective of our study was to determine thermal load which may be induced in the forearm due to electromagnetic exposure for 60mW radiated power at 2.45GHz. Another objective is to establish the maximum power radiation level at which thermal effects do not occur.

Keywords*: electromagnetic fields (EMF), non-ionizing radiation, finite element method (FEM), thermal load, non-thermal effects*

INTRODUCTION

Exposure to radio frequency radiation (RFR) at sufficiently high intensities produces perceptible increases in tissue temperature. The penetration depth of microwave is small and the heating occurs near the tissue surface [1], [2].

RFR absorption is accompanied by heat generation. A readily understandable mechanism of this RFR effect is tissue heating, or “thermal effect”. Biological systems alter their functions as a result of their change in temperature. However, there is also a question on whether “nonthermal” effects can occur from RF exposure. There are two meanings of the term “nonthermal” effect. It could mean that it occurs under the condition of no apparent change in temperature (e.g., less than 1°C) in the exposed animal or tissue, suggesting that physiological or exogenous mechanisms maintain the exposed object at a constant temperature. The second meaning is that somehow RFR is “temperature-independent”, i.e. it can cause biological effects without the involvement of heat. This is sometime referred to as “athermal effect”. It is very difficult to rule out thermal effects in biological responses to RFR, because heat is inevitably released when RFR is absorbed.

When an object with electric and magnetic properties different of those of the surrounding medium is brought near an electromagnetic field (EMF) source, the EMF distribution is perturbed. In both problems, the EMF (electric field strength **E**, electric displacement **D**, magnetic field strength **H**, magnetic flux density **B**) and its distribution are either computed, or measured. The determination of the electromagnetic absorption inside biological tissue for a given excitation, usually expressed in terms of the specific absorption rate (SAR), is still a highly complicated and challenging scientific task [3].

In general, temperature distribution is the result of the electromagnetic power absorption and of the occurring heat transfer mechanisms (conduction, convection and radiation). However, in living bodies other mechanisms of active heat generation or dissipation, such as metabolism, blood flow, evaporation (sweating) etc., are equally important. Although the time scale of their dynamics is substantially different, the process of electromagnetic absorption and the heat transfer may become dependent, if there is a significant temperature elevation inside the body. In this case the dielectric properties of tissue may vary with temperature leading to a different deposition pattern of the electromagnetic energy.

In the area of bioelectromagnetism, the thermal load assessment is crucial in the context of dosimetry for bioexperiments. One point of interest in the planning and optimization of bioexperiments is the maximum expected thermal load, which may be induced in the biological tissue. This information is important especially for experiments which are set up to test the effect of low-level NIR exposure and is often lacking in accounts of published experiments.

COMPUTATIONAL 3D FEM MODEL

Electromagnetic exposure

The numerical work presented here is concerned with the analysis of the EMF heat transfer problem related to the RF exposure of the human forearm. The microwave power is transmitted from the generator by a coaxial cable to a strip-line antenna of a few centimeters wide (~ 2 cm) – in our study it is modeled as a "folded dipole" type antenna. The FEM analysis is based on wave equations derived from Maxwell's EMF laws.

The microwave generator output power is 30mW and its frequency is 2.45GHz. The human forearm is exposed at a distance of 0.5cm, in the near-field of the antenna. Table 1 gives the values of the electric and thermal properties, mass densities and dimensions for the subdomains. The dimensions for the antenna are: radius 1mm, length 20mm.

	Muscle	**Bone**
	Dimensions	
Radius [mm]	40	20
Length [mm]	80	80
	Electrical properties	
Conductivity at 2,45 GHz [S/m]	2	0.1
Relative permitivity at 2,45 GHz	45	4.2
	Thermal properties	
Thermal conductivity [W/m·grd]	0.518	0.3
Specific heat [J/kg·grd],	2,000	2,000
Mass density [kg/m^3]	1,100	1,600

Table 1. Electric and thermal properties, mass densities and dimensions

The time-harmonic EMF distribution is given by the Helmholtz partial differential equation [5],

$$\nabla \times \left(\mu_r^{-1} \nabla \times \underline{\mathbf{E}}\right) - k_0^2 \left(\varepsilon_r - j\sigma/\varepsilon_0\right)\underline{\mathbf{E}} = 0 . \qquad (1)$$

$\underline{\mathbf{E}}$ is the complex electric field strength (harmonic). The interaction of the electromagnetic field and human body at microwave frequencies is usually described in terms of the *complex permittivity* $\varepsilon_c = \varepsilon_r - j\sigma/\varepsilon_0$, where ε is the dielectric permittivity, σ is the electric conductivity, $\omega = 2\pi f$ is the angular frequency of the electromagnetic field, $k_0 = \omega\sqrt{\varepsilon_0 \mu_0} - \omega/c_0$ is the wave number of the free space, and c_0 is the velocity of light in vacuum. In anatomical tissues, the dielectric permittivity is $\varepsilon_0 = \left(4\pi \cdot 9 \cdot 10^9\right)^{-1}$ F/m , as for air.

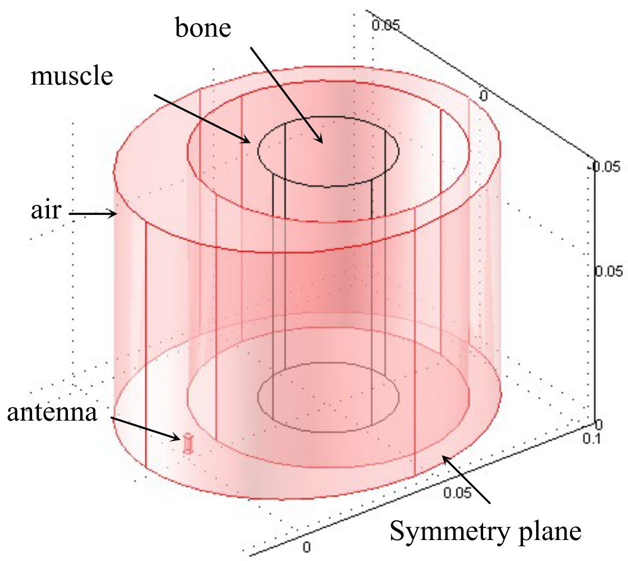
In this study we used a simplified 3D model (geometry) of the human forearm, defined as a cylindrical two-layer (muscle-bone) structure, and used symmetry to reduce the computational effort (Fig.1). The forearm size (length) in the model was taken large enough such that the local RF heating does not influence the rest of forearm. To do this, we used a trial and error procedure: the temperature at the top and bottom sections equals the normal biological value within prescribed accuracy limits.

The mathematical model is implemented and solved in the FEMLAB environment. We utilized the *hybrid-mode waves*, *time-harmonic* FEM model. As the computational domain boundary is actually not a physical boundary, we assumed a *low-reflecting* condition (only a small part of the wave is reflected, and the rest propagates through the boundary as if it was not present) [5]

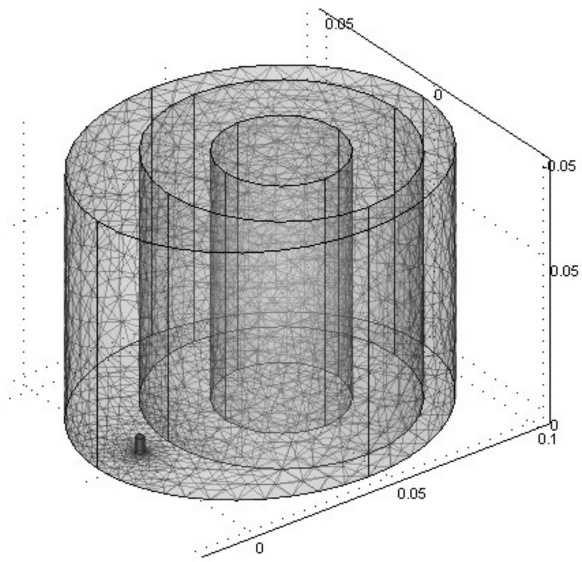
$$\sqrt{\frac{\mu_0\mu_r}{\varepsilon_c}}\mathbf{n}\times\underline{\mathbf{H}}+\underline{\mathbf{E}}-\left(\mathbf{n}\cdot\underline{\mathbf{E}}\right)\cdot\mathbf{n}=0\,, \tag{2}$$

except for the bottom surface which (to observe the EMF symmetry) is defined as *perfect magnetic conductor* [5].

$$\mathbf{n}\times\underline{\mathbf{H}}=0\,, \tag{3}$$



a. Computational domain



b. FEM mesh

Fig.1 Computational domain – forearm (bone and muscle), antenna, and surrounding air

The EMF source is introduced through a nonhomogeneous Dirichlet, tangential magnetic field strength boundary condition on the inner boundary that is the antenna surface, by a predictor-corrector scheme such that the power emitted by the antenna reaches the 60mW value. The top end of the antenna is assumed perfect conductor, i.e. $\mathbf{n}\times\underline{\mathbf{E}}=0$.

The Delaunay tetrahedral FEM mesh that we utilized for solving the EMF and heat transfer problems is composed of more than 30,000 tetrahedral vector elements [Femlab]. The algebraic system was solved with a direct linear stationary solver based on Gaussian elimination.

The grid-independence of the solutions was assessed through accuracy tests, using the energy balance between the radiated power and the power absorbed in the forearm as criterion.

Bioheat transfer

The estimation of the maximum thermal load delivered to the tissues is an application in the context of low-level exposure bioexperiments. It is important then to be able to *a priori* predict the highest temperature rise that occurs in the living tissue in order to facilitate the determination of exposure estimation that can explicit thermal effect. In this case, the *in vivo* calculation of the steady-state temperature distribution inside biological bodies would require a model like the "bioheat transfer equation" (BHTE).

Biological tissues interact thermally with their environment by several physical and physiological mechanisms, and the studies concerned with NIR exposure have to account for all occurring heat transfer mechanisms within the tissue: heat conduction is present in all situations, whereas convection, in form of blood flow, exists only inside living bodies. This is a difficult task due to the variability of biological parameters, such as the perfusion rate, the blood temperature, and the nonlinear nature of physiological processes. Although many models address heat transfer in tissues (Arkin, 1994 [1]), the BHTE model (Pennes, 1994) is most widely used.

There is still a *worst case approach*, which aims at a conservative estimation of the maximum permissible exposure level for studying non-thermal effects of NIR can neglect the exchange mechanisms like convection and radiation. Hence, blood flow inside the biologic bodies can be omitted, and thermal insulation at their boundaries can be assumed. The temperature rise inside the biological tissue is calculated using the heat conduction equation [3],

$$\rho c \frac{\partial T}{\partial t} = \nabla\left(k \nabla T\right) + Q_{EM} , \qquad (4)$$

where T is the temperature inside the living tissue, ρ is the mass density, c is the specific heat, k is the thermal conductivity and Q_{EM} is the heat generation rate due to the deposited electromagnetic power. The computational domain in this case is made of the forearm only: the surrounding space is discarded and either a natural convection boundary condition or a fixed temperature ($T = 37°C$) condition are set on the forearm; insulation (top) and symmetry (bottom) conditions for ends.

In the thermal modeling of tissue, the correct description of heat transfer related to the blood flow is very important. Relatively cold blood entering a volume with inside heating will cool the tissue. The thermal model used here is the Pennes bio-heat equation,

$$\rho_t c_t \frac{\partial T}{\partial t} = \nabla\left(k_t \nabla T\right) - W_b \rho_b c_b \left(T - T_b\right) + Q_{EM} , \qquad (5)$$

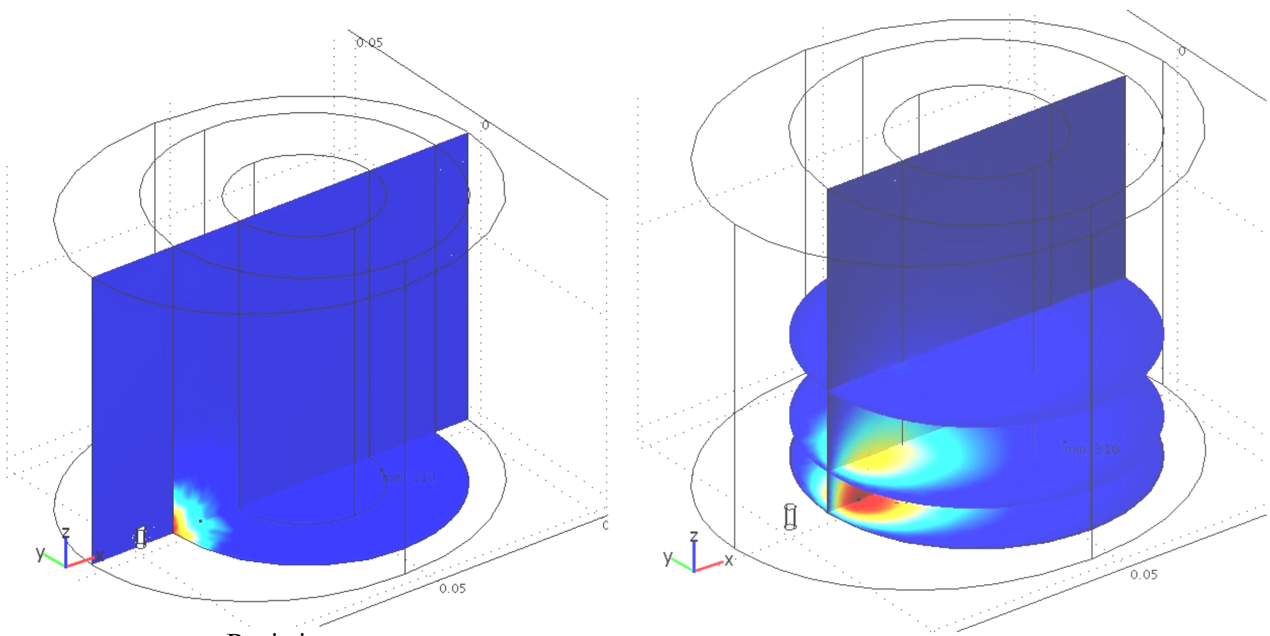
where , ρ_t is the mass density of tissue [kg/m^3], c_t is the specific heat of tissue [J/kg °C], k is the thermal conductivity of the tissue [W/m·grd], W_b is the blood perfusion [ml/ml·s], c_b is the specific heat of blood [J/kg·grd], ρ_b is the mass density of blood [kg/m^3], T is the temperature of living tissue, T_b is the temperature of blood, and Q_{EM} is the resistive heating sourced by the EMF. The boundary conditions were set as convective heat flux (h = 0.2…10W/m^{2}grd) for human forearm surface and insulation for ends.

RESULTS AND DISCUSSION

As the time scales of the EMF field and heat transfer problems are very different, we decided to decouple them: first, we solved the EMF problem (harmonic regime) and found the resistive power distribution, that is the EMF heat source in the forearm. Then, we solved the heat transfer problem in the steady state limit using the EMF resistive power as input.

In solving the EMF problem, we found first the value of the tangential magnetic field strength to be set as boundary condition on the antenna surface for a given power level. For example, for P = 63mW we found H_0 = 24.5A/m.

We computed the magnetic field distribution in the human forearm, eq. (1) and next, using the resistive power, we solved for the temperature distribution eq. (4) (Fig. 3). As expected, the highest thermal load is located within the region of highest EMF concentration, the muscle, beneath the surface facing the antenna. A maximum temperature increase of 0.35°C was found.

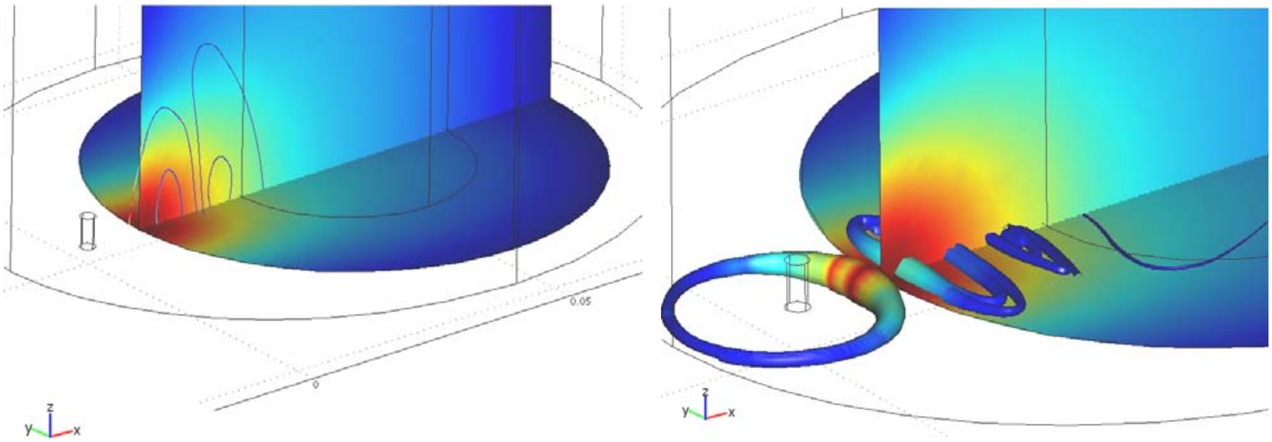


a. Resistive power **b.** Temperature field (T_{max}=37.48°C)

Fig.2 Electromagnetic field spectra and thermal load in the forearm for 60mW emitted power

An objective of this study was the maximum power of microwave radiation for which the maximum temperature rise reaches 1°C. This information is of importance in assessing the no-thermal effect threshold in RF exposure. This threshold is a tradeoff between the antenna RF power and the heat transfer properties of the forearm surface. In our simulation, for the 63mW source (antenna), the muscle region receives 30.5mW. The 1°C threshold was obtained for h < 10W/m^{2}grd. The two heat transfer models presented here (with and without bioheat generation) give different results: in terms of the 1°C threshold, the discrepancies increase with increasing h.

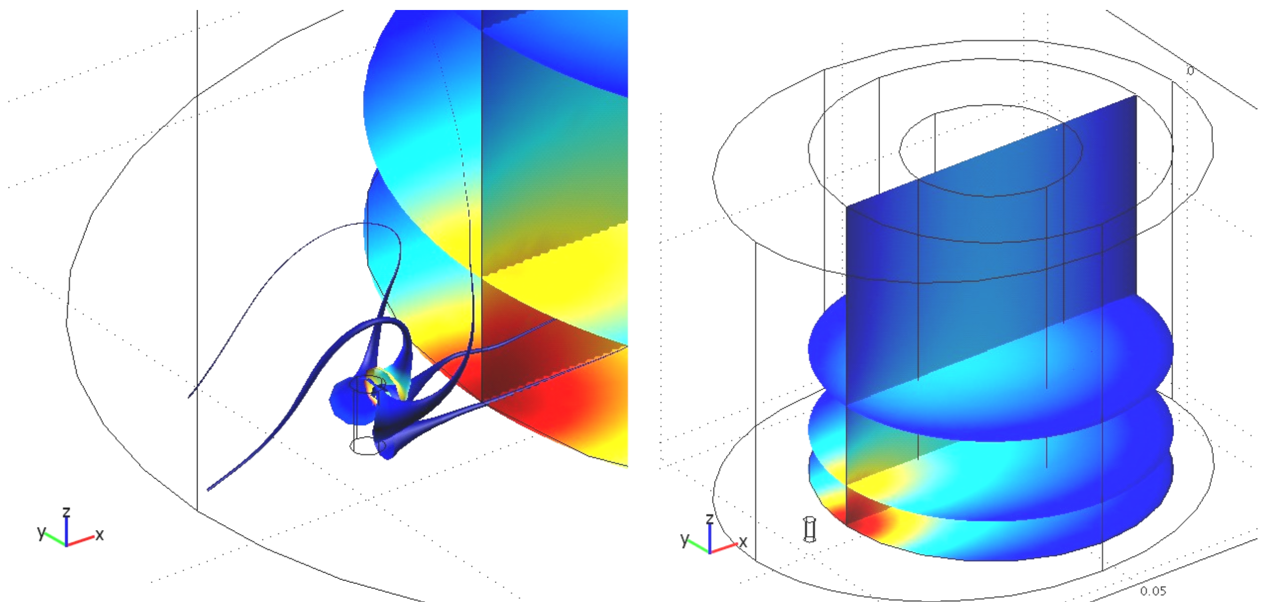
The maximum temperature load was evaluated for the more realistic situation described by eq. (5) when blood perfusion is accounted, W_b = 0.02ml/(ml·s) for bone and W_b = 0.025ml/(ml·s) for muscle [4], reported next. In this case, the maximum temperature rise depends on the heat transfer coefficient that sets the heat transfer condition at the forearm surface.



a. Electric field (the lines) **b.** Magnetic field strength (the tubes)

Fig.3 Electromagnetic field spectra and thermal load (the slices) for h = 0.2W/m^{2}grd

Figure 3 shows the electric field strength (lines), the magnetic field strength (tubes) and the temperature field for h = 0.2W/m^{2}grd. It is interesting to notice the relatively important coupling with the forearm that gives rise to higher thermal load. The complex nature of the electromagnetic field is apparent: the radiant magnetic and electric fields propagate through closed loops, orthogonal to each other. As the distance to the antenna increases, their patterns become complex.



a. Power flow **b.** Temperature field

Fig.4 RF augmented thermal load for h = 0.2W/m^{2}grd

Figure 4 shows the power flow and the temperature field. The RF heating is localized. Remarkably, the top end of the forearm is at the biological value, confirming that the size of the computational domain was properly defined. The highest temperature occurs inside the muscle, close to the surface facing the antenna.

Figure shows the maximum temperature versus the convection heat transfer coefficient, for different ambient temperatures, T_{amb}. For lower T_{amb}, there is a knee for h = 4…8W/m^{2}grd that connects two linear regions. However, the slopes eventually become equal at higher T_{amb}.

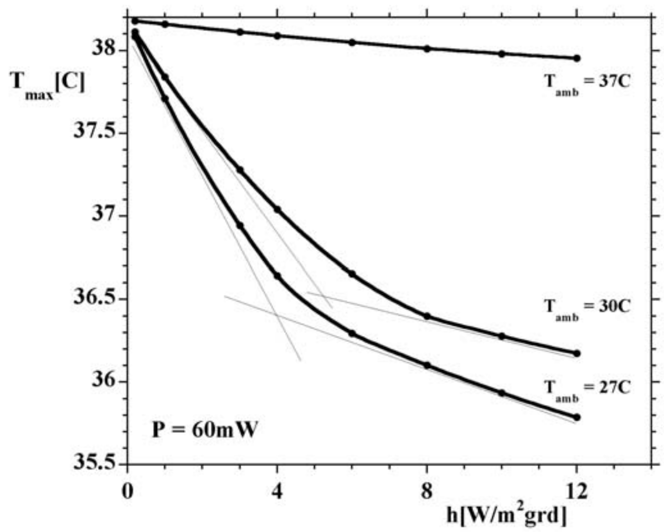


Fig.5 The maximum temperature as a function of *h*.

CONCLUSIONS

The main conclusions of this study are as follows:

- The thermal load by EMF exposure is located close to the forearm surface, on the antenna side. Apparently, the bone region is not likely to be influenced. This result is useful in the effort of keeping the 3D FEM model manageable, of convenient size.
- At the power levels $P < 1$W, the temperature rise by EMF resistive heating is minor.
- The 1°C threshold is a tradeoff between the antenna RF power and the heat transfer properties of the forearm surface. For instance, in our simulation, for the 63mW source (antenna), the muscle region receives 30.5mW. The 1°C threshold is attained for a $h < 2$W/m^{2}grd. This kind of information is useful in the design of an experimental setup where RF heating is of interest.
- The two heat transfer models (with and without bioheat generation) behave differently: in terms of the 1°C threshold the discrepancies increase for higher *h*.
- The derma layer was not accounted for in the present study. This layer is likely to insulate the forearm, preventing heat loss. Hence, its presence would contribute to higher than the here reported values for the temperature increase.
- The FEMLAB FEM model we used may within satisfactorily accuracy limits give an estimate of the EMF stress and the associated thermal load in the RF exposure of biological tissues.

Acknowledgement

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References

[1] Arkin, H., Xu, X. and Holmes, K.R., 1994, "Recent Developments in Modeling Heat Transfer in Blood Perfused Tissues", *IEEE Trans. Biomed. Eng.*, vol. 41, no. 2.

[2] Chou, C.K.; Guy, A.W.; McDougall, J.; Lai, H. – "Specific absorption rate in rats exposed to 2450-MHz microwaves under seven exposure conditions", *Bioelectromagnetics* 6:73-88; 1985

[3] Samaras, T.; Regli, P.; Kuster, N. – "Electromagnetic and heat transfer computations for non-ionizing radiation dosimetry", *Phys. Med.Biol.*, 45, 2000

[4] www.boomer.org/c/p1/ch18/ch1803.html

[5] FEMLAB 3.0a, *User's Guide* and *Electromagnetics Module*, COMSOL AB., 2004