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INFLUENCE OF WIRE GEOMETRY ON TEMPERATURE DISTRIBUTION IN HUMAN BODY DURING RF HYPERTHERMIA

ABSTRACT *A numerical model which is an example of local-regional RF hyperthermia is presented. Human body is surrounded by an elliptical wire with exciting current and the electromagnetic energy is concentrated within the tumor. The presented issue is therefore a coupling of the electromagnetic field and the temperature field. For simplification a two-dimensional model which is a cross section through the human body is adopted. Using the finite element method exciting current density in human body has been calculated, and then bioheat equation under transient-time condition has been resolved. Finally, the obtained simulation results for several wire configurations are presented.*

Keywords: *hyperthermia, bioheat equation, FEM.*

1. INTRODUCTION

Hyperthermia is one of the ways of treating malignant tumors, in which cancerous pathological tissues are exposed to a high temperature. Clinical trials have shown that heating the tumor to temperatures 40-44°C can lead to damage or completely destruction of cancer cells, simultaneously minimally

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affecting normal tissues surrounding the tumor. There is also evidence that the effectiveness of hyperthermia is significantly increased in combination with other cancer treatments like radio- or chemotherapy [1, 2].

Apparently, an extremely important issue is to control the temperature distribution in the treated area to avoid excessive temperature increase in the normal tissues surrounding the tumor [3]. There are many studies on the treatment of cancer using hyperthermia which demonstrates that this aspect is still important and more research is needed in this matter [5, 6].

2. GOVERNING EQUATIONS

Let us consider a cross section of the human body as shown in Figure 1. The human body is approximated to an ellipse whose semi-axes are respectively a = 20 cm and b = 12 cm. Inside the body there is a tumor with the radius of r = 2.5 cm. An elliptical wire with the semi-axes A = 50 cm and B = var is placed around the human body. Through the wire an alternating current flows in clock-wise direction with the amplitude I_m = 16 A and frequency f = 100 MHz. The exciting current generates a sinusoidal electromagnetic field, which next induces eddy currents in human body. Eddy currents are a source of heat and after transient time a temperature distribution in human body is established. Therefore, in the analyzed model, we deal with the electromagnetic field coupled with the field temperature. Moreover, the human body and the tumor are treated as homogeneous media with averaging material parameters.

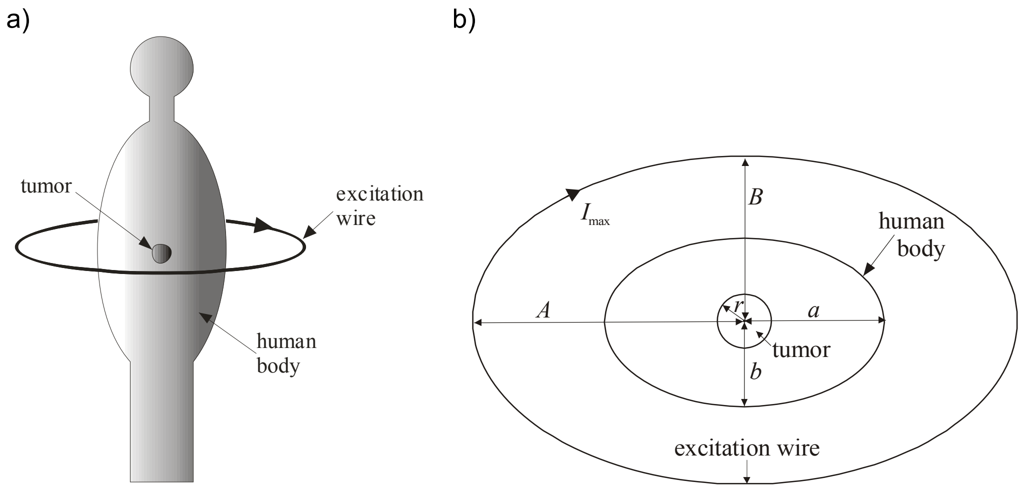

Fig. 1. Schematic view of the human body surrounded by wire with exciting current (a) and cross section of the human body with a tumor inside surrounded by excitation wire together with geometrical dimensions (b)

Let us start with Maxwell's equations in the time domain:

$$\nabla \times \mathbf{H} = \mathbf{J}_{\mathrm{i}} + \mathbf{J}_{\mathrm{c}} + \frac{\partial \mathbf{D}}{\partial t} \tag{1}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

where $\mathbf{E}$ and $\mathbf{H}$ are respectively the electric and magnetic field strengths, $\mathbf{J}_{\mathrm{i}}$ is an impressed current density, which is treated as a source of electromagnetic field, $\mathbf{J}_{\mathrm{c}}$ is conduction current resulting from the existence of an electric field according to Ohm's law

$$\mathbf{J}_{\mathrm{c}} = \sigma \mathbf{E} \tag{3}$$

Moreover, σ is the electrical conductivity of the body, $\mathbf{D}$ and $\mathbf{B}$ are respectively the vectors of electric displacement density and magnetic induction given in the form of material dependences

$$\mathbf{D} = \varepsilon \mathbf{E}, \qquad \mathbf{B} = \mu \mathbf{H} \tag{4}$$

where ε and μ are respectively the permittivity and magnetic permeability of the medium.

After the introduction of the magnetic vector potential $\mathbf{A}$ in the expression of magnetic induction vector

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{5}$$

we can derive the following equation describing the field distribution:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) + \sigma \frac{\partial \mathbf{A}}{\partial t} + \varepsilon \frac{\partial^2 \mathbf{A}}{\partial t^2} = \mathbf{J}_{\mathrm{i}} \tag{6}$$

Since the magnetic vector potential (as well as other vectors) in the time domain is related with complex amplitude $\hat{\mathbf{A}}(\mathbf{r})$ by

$$\mathbf{A}(\mathbf{r}, t) = \mathrm{Re}\left[\hat{\mathbf{A}}(\mathbf{r})\, e^{j\omega t} \right] \tag{7}$$

where ω is the pulsation of electromagnetic field. Therefore the equation (6) in the complex domain is given by

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \hat{\mathbf{A}} \right) + \left(j\omega\sigma - \omega^2 \hat{\varepsilon} \right) \hat{\mathbf{A}} = \hat{\mathbf{J}}_{\mathrm{i}} \tag{8}$$

where $\hat{\varepsilon}$ is the complex permittivity defined as

$$\hat{\varepsilon}(\omega) = \varepsilon' - j\varepsilon'' \tag{9}$$

where ε' is the real part of the permittivity, which is related to the stored energy within the medium and ε'' is a dielectric loss factor (it is the imaginary part of the permittivity, which is related to the dissipation (or loss) of energy within the medium). For one Debye's process [4] we can assume that

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon_1}{1+(j\omega\tau_1)^{\alpha_1}} - j\frac{\sigma_1}{\omega\varepsilon_0} \tag{10}$$

where

ε_∞ – the high-frequency limit of relative permittivity,
$\Delta\varepsilon_1$ – the relaxation intensity,
α_1 – the Cole–Cole parameter,
τ_1 – the relaxation time [s],
σ_1 – the electric conductivity [S/m],
ε_0 – the permittivity of free space.

Solution of quasi-stationary equation (8) requires the determination of the boundary condition for the magnetic vector potential $\mathbf{A}$. In the presented simulation assumes a zero value of potential on the boundary of calculation area, located at some, but finite distance from the analyzed object.

The second basic equation used in the presented simulation is the so-called bioheat equation given by Pennes [7]. It describes the phenomenon of transport and heat transfer in biological tissues. In transient analysis the bioheat equation is expressed by

$$\rho C\frac{\partial T}{\partial t} + \nabla(-k\nabla T) = \rho_b C_b \omega_b (T_b - T) + Q_{ext} + Q_{met} \tag{11}$$

where

T – the body temperature [K],
T_b – the blood vessel temperature [K],
K – the tissue thermal conductivity [W/(m·K)],
ρ – the tissue density [kg/m^3],
ρ_b – the blood density [kg/m^3],
C – the tissue thermal conductivity [J/(kg·K)],
C_b – the blood specific heat [J/(kg·K)],
ω_b – the blood perfusion rate [1/s],
Q_met – the metabolic heat generation rate [W/m^3],
Q_ext – the external heat sources [W/m^3].

The external heat sources is responsible for the changing of the temperature inside the exposed body according to the following equation

$$Q_{ext} = \frac{1}{2}\sigma\mathbf{E}\cdot\mathbf{E}^* = \sigma|\mathbf{E}|^2 \tag{12}$$

The bioheat equation allows us to assess both the transient response and the steady-state of temperature changes in the human body. Since this is a differential equation in time and space its solution requires to specify both the initial and boundary conditions to be specified. The initial condition is equal to

$$T = T_0 = 37^\circ C \tag{13}$$

which corresponds to the physiological temperature of the human body. The boundary condition explains heat exchange between the surface of the body and the external environment according to the equation given by

$$\mathbf{n}\cdot\left(-k\nabla T\right) = h(T_{air} - T) \tag{14}$$

where

h – the heat transfer coefficient [W/(m^2·K)],
T_{air} – the temperature of the air surrounding the body [K],
$\mathbf{n}$ – the unit vector normal to the surface.

It is worth noting that the term on the right side of above equation describes the heat losses due to convection, therefore a constant h is also named as the convection coefficient.

3. SIMULATION RESULTS

In the analyzed model, the human body and tumor are considered as homogeneous media with averaged material parameters, therefore the simulation results may differ from those obtained in reality during hyperthermia treatment. The physical parameters of the model are given in Tables 1-3. As mentioned before a sinusoidal alternating current in wire with an amplitude I_{m} = 16 A and a frequency f = 100 MHz is the input function. In addition, heat transfer coefficient was assumed equal to $\boldsymbol{h}$ = 10 [W/(m^2·K)], and the temperature of the air surrounding the human body equal to T_{air} = 293.15 [K], which corresponds to room temperature of 20°C.

TABLE 1
Electrical parameters of tissues used in the numerical model [4]

Tissue	ε_∞	$\Delta\varepsilon_1$	τ_1 [ps]	α_1	σ_1 [S/m]
human body	4.0	50	7.23	0.10	0.15
tumor	2.5	18	13.2	0.22	0.07

TABLE 2
Other physical parameters of tissues used in the simulation

Tissue	k [W/(m K)]	ρ [kg/m^3]	C [J/(kg K)]	Q_{met} [W/m^3]
human body	0,22	1050	3700	300
tumor	0,56	1050	3700	480

TABLE 3
Physical parameters of blood taken in the bioheat equation

Tissue	T_b [K]	ρ_b [kg/m^3]	C_b [J/(kg K)]	ω_b [1/s]	
blood	310,15	1020	3640	in human body	0,005
				in tumor	0,0004

Equations (8) and (11) with appropriate initial and boundary conditions were solved using the finite element method. The simulation results are summarized in Figures 2-7. Figure 2 shows the equipotential lines of the module of the magnetic vector potential $\mathbf{A}$ for optimal value of semi-axis B of the excitation wire. This vector lies in x-y plane and its maximum value is close to the wire with the exciting current. On the boundary of calculation area value of magnetic vector potential is equal to zero.

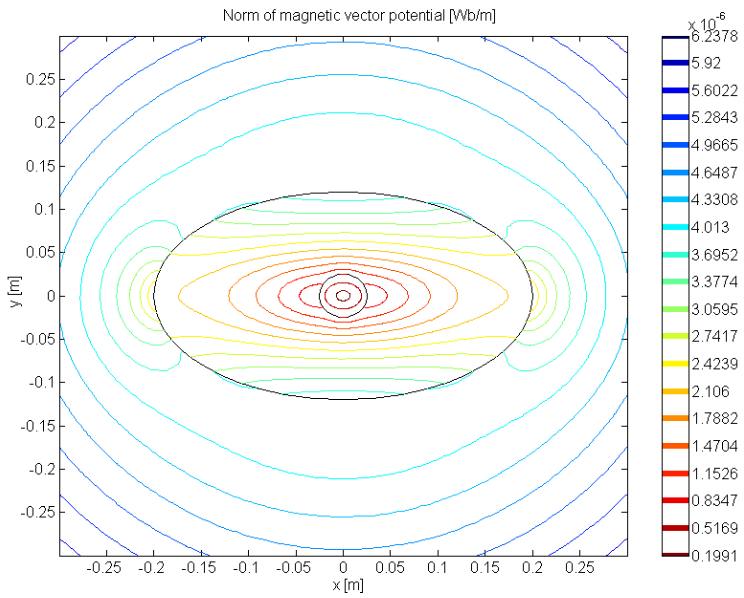

Fig. 2. Equipotential lines of the modulus of magnetic vector potential for B = 0.5 m

Equipotential lines of the vector current density $\mathbf{J}$ induced in the human body are presented in Figure 3. As expected, the highest value occurs within the tumor.

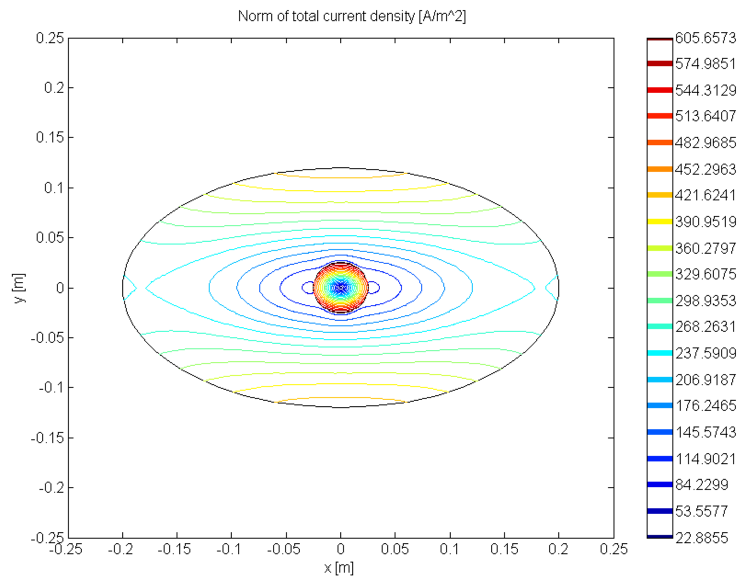

Fig. 3. Equipotential lines of current density induced in the human body for B = 0.5 m

The rest drawings illustrate the temperature dependence within the human body in different form. Figure 4 represents the distribution of isotherms in the analyzed model for the steady state after a time of t = 6000 [s].

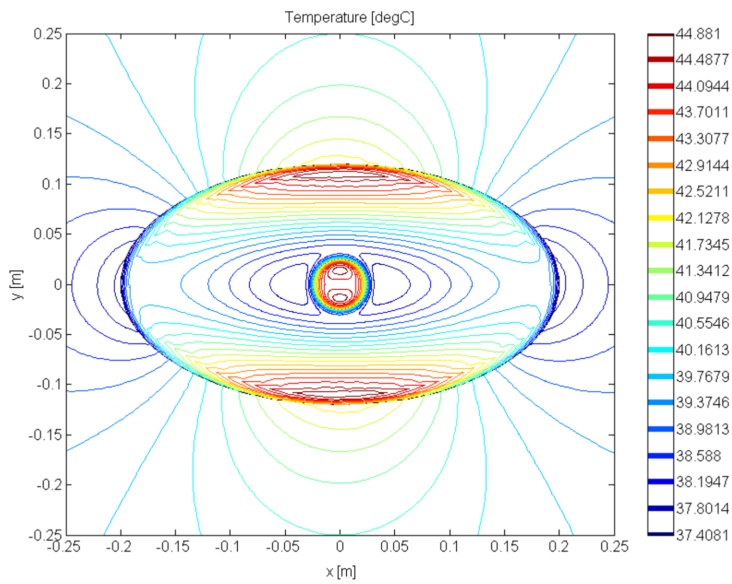

Fig. 4. Isotherms in the human body for the steady state analysis (B = 0.5 m)

Temperature distribution along horizontal and vertical symmetry axes of the human body for different values of semi-axis B of the excitation wire are presented in Figures 5 and 6. Increasing the value of B causes the temperature inside the tumor to rise under the same conditions but only to reach the limit value of B = 0.7 m. The greatest value of the temperature is inside the tumor but there are possible local maxima of temperature near the surface of the body. In order to avoid surface burns the human body would be surrounded with cold water bolus.

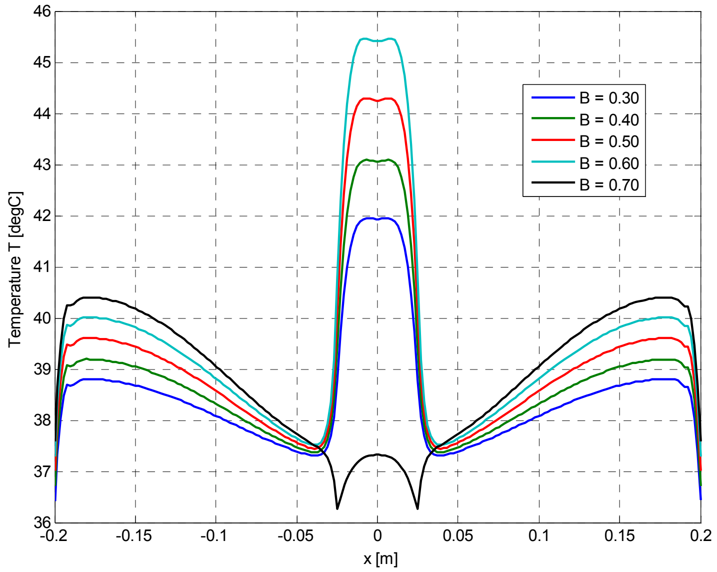

Fig. 5. Temperature distribution along horizontal symmetry axis of the human body for different values of semi-axis of excitation wire B [m] in steady-state

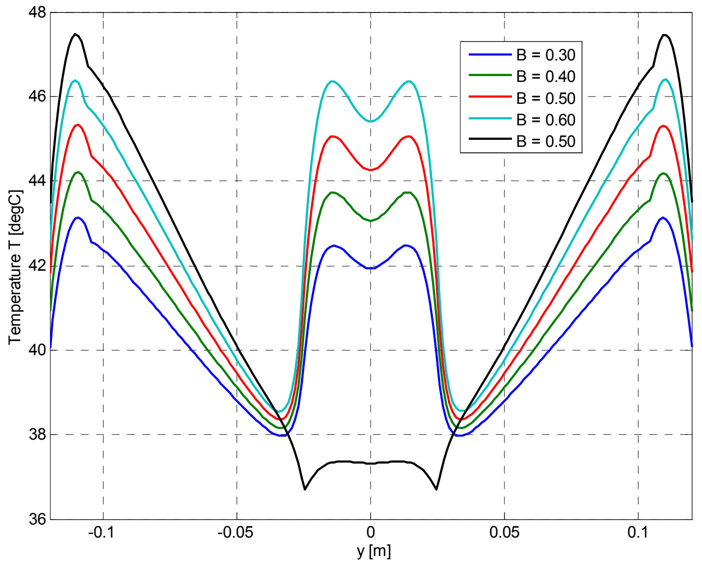

Fig. 6. Temperature distribution along vertical symmetry axis of the human body for different values of semi-axis of excitation wire B [m] in steady-state

Last Figure 7 shows the time dependence of the temperature inside the tumor for different values of semi-axis B of the excitation wire. As we can see, this dependence is characterized by a very long time constant, which causes the temperature inside the tumor can be set up for several minutes. Moreover, after reaching the limit value of $B = 0.7$ m the temperature inside the tumor decreases to about 37.4°C.

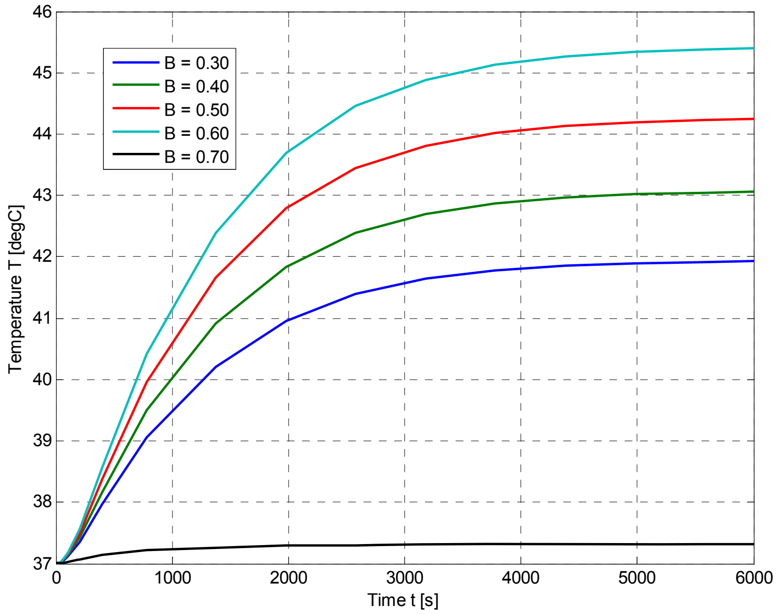

Fig. 7. Time dependence of the temperature in the centre of the tumor for several values of semi-axis of excitation wire B [m]

4. SUMMARY

Local-regional RF hyperthermia is an effective way of heating malignant tumors. Positive therapeutic effects of this treatment depend on the applied temperature, exposure time and the volume of the tissue exposed to electromagnetic fields. The effectiveness of heat treatment can be significantly increased by combining hyperthermia with other cancer treatments such as radiotherapy, chemotherapy, immunotherapy and gene therapy.

Numerical methods are often used for dosimetric calculations for a number of important bioelectromagnetic issues. Thermal analysis of this problem, using the FEM allows the estimation of the influence of semi-axis B of the excitation wire on temperature distribution in the specified area. The presented plots clearly show that increasing the value of B causes the temperature inside the tumor to rise under the same conditions but only to reach the limit value of B = 0.7 m.

Adopted a two-dimensional model represents a major simplification of reality (simple geometry, averaged material parameters of the model, an infinitely thin of excitation wire), but it fully reflects the idea of treating tumors using hyperthermia and can be used to evaluate the actual temperature distribution in the three-dimensional case.

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WPŁYW GEOMETRII PRZEWODU NA ROZKŁAD POLA TEMPERATURY WEWNĄTRZ CIAŁA LUDZKIEGO PODCZAS RF HIPERTERMII

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STRESZCZENIE *W niniejszej pracy przedstawiono model numeryczny stanowiący przykład zastosowania lokalno-regionalnej hipertermii o częstotliwości radiowej. Ciało człowieka otoczone jest eliptycznym przewodem z wymuszającym prądem, a energia elektromagnetyczna koncentrowana jest wewnątrz guza. Dla uproszczenia przyjęto model dwuwymiarowy stanowiący przekrój poprzeczny przez ciało człowieka. Wykorzystując metodę elementów skończonych obliczono gęstość prądu indukowanego w ciele człowieka, a następnie rozwiązano biologiczne równanie ciepła dla przypadku zmiennego w czasie. Na końcu zestawiono uzyskane wyniki symulacji dla kilku konfiguracji przewodu.*

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