MODELLING OF THERMAL DAMAGE IN LASER IRRADIATED TISSUE WITH EMBEDDED NANOPARTICLES

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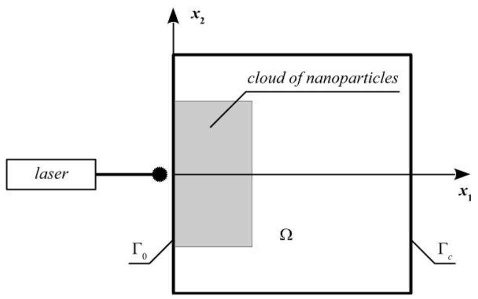
1. Formulation of the problem

The purpose of this paper is to analyze the phenomena occurring in the laser-treated soft tissue wherein the cloud of nanoparticles is placed. The 2D domain of homogeneous biological tissue subjected to the laser action (Fig.1) is considered. The analysis is based on the Pennes bioheat transfer equation in the form [1]

$$\mathbf{x} \in \Omega: \quad c\dot{T} = \lambda \nabla^2 T + Q_{perf} + Q_{las} + Q_{met} \tag{1}$$

where λ [$Wm^{-1}K^{-1}$] is the thermal conductivity, c [$Jm^{-3}K^{-1}$] is the volumetric specific heat, Q_{perf}, Q_{met} and Q_{las} [Wm^{-3}] are the heat sources connected with the perfusion, metabolism and laser radiation, respectively, while $T = T(\mathbf{x}, t)$ is the temperature. Equation (1) is supplemented by appropriate boundary conditions: Robin condition on the external tissue surface Γ_0 and no-flux condition on the internal tissue surface Γ_c. The initial distribution of temperature is also known.



Figures 1: The domain considered.

In order to determine the internal heat source concerning information about laser irradiation the collimated and diffuse part of fluence rate must be determined. The diffuse fluence rate ϕ_d is calculated on the base of the steady-state optical diffusion equation [2,3]

$$\mathbf{x} \in \Omega: \quad D\nabla^2 \phi_d(\mathbf{x}) - \mu_a \phi_d(\mathbf{x}) + \mu'_s \phi_c(\mathbf{x}) = 0 \tag{2}$$

while the collimated fluence rate ϕ_c is given as [1]

$$\phi_c(\mathbf{x}) = \phi_0 \exp\left(-\frac{2x_2^2}{r^2}\right)\exp(-\mu'_t x_1) \tag{3}$$

where D [m] is the diffusion coefficient, μ_a, μ'_s and μ'_t [m^{-1}] are the absorption, effective scattering and effective attenuation coefficient of tissue, respectively, ϕ_0 [Wm^{-2}] is the surface irradiance of laser, r is the radius of laser beam.
The final form of the source function connected with the laser heating is described by the formula

$$Q_{las}(\mathbf{x}, t) = \mu_a \phi(\mathbf{x})\, p(t) \tag{4}$$

where $\phi(\mathbf{x})$ [Wm^{-2}] is the sum of collimated and diffuse parts of fluence rate and and $p(t)$ is the function equal to 1 when the laser is *on* and equal to 0 when the laser is *off*.

Damage of biological tissue resulting from temperature elevation is modelled by Arrhenius injury integral, defined as [2]

(5) $$\Psi(\mathbf{x},t^F)=\int_0^{t^F} P\exp\left[-\frac{E}{RT(\mathbf{x},t)}\right]\mathrm{d}t$$

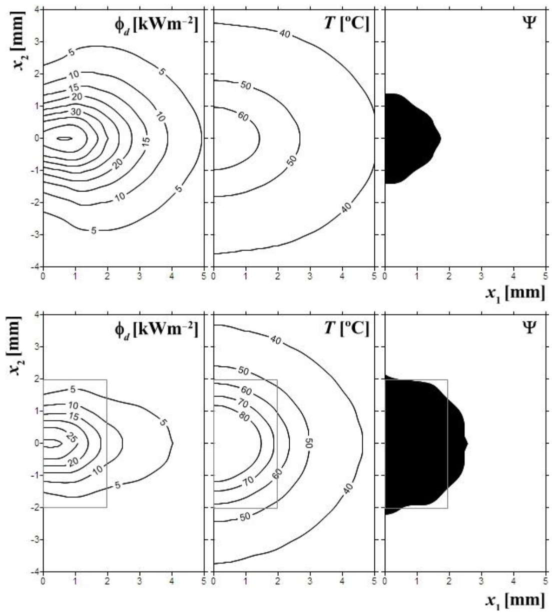
where R [J mole^{-1}K^{-1}] is the universal gas constant, E [J mole^{-1}] is the activation energy and P [s^{-1}] is the pre-exponential factor. The criterion for tissue necrosis is $\Psi(\mathbf{x})\geq 1$.

2. Results of computations

As was mention previously the 2D domain of homogeneous biological tissue subjected to the laser action was considered. Two simulations were carried out – with and without the cloud of nanoparticles which was situated near the external surface of the tissue (Fig. 1). It should be pointed out that optical properties of tissue with nanoparticles were calculated on the basis of formulas [2,3]

(6) $$\mu_{ap}=\mu_a+0.75 f_v\frac{Q_a}{a},\quad \mu_{sp}=\mu_s+0.75 f_v\frac{Q_s}{a}$$

where Q_a and Q_s are the dimensionless efficiency factor of absorption and scattering for single particles, respectively, f_v is the volume fraction of nanoparticles while a is the particle radius.
The bioheat problem (1) has been solved using the 1st scheme of the BEM for 2D transient heat diffusion while the optical diffusion equation (2) has been solved by the finite difference method.



Figures 2: Distribution of diffuse fluence rate ϕ_d, temperature and Arrhenius integral after 10 s.

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References

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