Numerical simulation of changes in the electric properties of biological tissues under local heating by laser radiation

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Abstract. The mathematical model that describes the local heating of biological tissues by optical radiation is introduced. Changes of the electric properties of biological tissues in such process can be used as a reliable tool for analyzing heating and damage degrees of tissues.

1. Introduction
Nowadays, laser radiation is widely applied in modern medicine and cosmetology for treatment and diagnosis (e.g. soft tissue surgery, cosmetic gynecology, and photothermolysis), based on the formation of controlled local damage of tissue induced by incident optical radiation. Treatment of tissues using laser radiation requires strict control of both the domain of optical exposure (area and depth of the irradiated region) and the radiation properties (wavelength, average power, pulse parameters etc.). Improvements of radiation localization and dosing accuracies can be achieved during operations with a simultaneous control of the tissue state [1]

One of the most reliable and accessible methods for diagnostics of biological tissues is the measurement of its electric properties in the radiofrequency (RF) range. The complex electric conductivity of a biological tissue is governed by its physiological state, and considerably depends on temperature [2,3]. So that it is possible to use the electric properties of biological tissues in order to control any induced thermal effects [4].

In order to obtain information about the physiological state of tissues basing on its electric RF properties it is necessary to build physical and mathematical models that properly describe the processes taking place. In the case of tissue local heating by optical radiation the mathematical model should include the interrelated solutions of the problems of radiation propagation, thermal conductivity, and electrodiffusion. Models of heating of biological tissues by optical radiation [5] and models that describe temperature induced changes of RF electric properties of tissues [6] are widely presented in literature. However, to our knowledge there are no models that simultaneously describe the considered phenomena.

In the present work the model that describes changes of the RF electric properties of biological tissues in the process of its local heating by laser radiation is introduced.
2. Model description

The nonstationary problem was considered assuming the cylindrical symmetry of the space with the radial coordinate \( r \) and the axial coordinate \( z \) (see Fig. 1). The local area of the tissue with the initial temperature \( T_0 \), bounded by the plane \( z = 0 \), was illuminated by the laser radiation with the Gaussian profile and the wavelength \( \lambda \), propagating along the \( z \) axis.

The probe harmonic RF field with the frequency \( f \) affected the point \( (r_p, 0) \) of the sample. The electrodiffusion equation was considered for one type of charge carriers that mainly conditioned the electric conductivity.

At each time moment the resulting distributions of optical intensity and RF potential inside the tissue occurs almost instantly compared to that of the temperature. As follows, at each time step it is possible to consider the stationary problems of both the radiation transfer and electrodiffusion. The problems of heat conduction and radiation propagation were solved only in the tissue area \( (0 \leq z \leq Z_0, 0 \leq r \leq R_0) \).

The problem of electrodiffusion was also solved taking into account the distribution of the electric potential in the surrounding air in the region \( (-Z_0 \leq z < 0, 0 \leq r \leq R_0) \).

Numerical simulations were performed using the explicit schemes of the finite difference method. At each time step, the calculations were performed in five stages:

1. The electrodiffusion equation was solved using the Fourier method. The equations for the amplitudes of the potential \( \Phi \), the electric current density \( j \), and the charge density \( q \) can be written as follows:

\[
\nabla (D_E \nabla q) = \left( \frac{\sigma}{\varepsilon \varepsilon_0} + i \cdot 2 \pi f \right) q
\]

\[
\Delta \Phi = -\frac{q}{\varepsilon \varepsilon_0}
\]

\[
j = -D_j \nabla q - \sigma \nabla \Phi
\] (1)
Here $D_E$ – the ion diffusion coefficient; $\sigma, \varepsilon, \varepsilon_0$ – the electric conductivity and permittivities of the tissue and vacuum respectively. For the simplification the complex term was excluded from the ion diffusion equation. Such approximation can be used in the RF range where $f \ll \frac{\sigma}{2\pi\varepsilon\varepsilon_0}$.

At the tissue-air interface, the boundary conditions of the continuity of the potential and the electric induction were adopted, except for the point $(r_p, 0)$ at which the potentials of both air and tissue were equal to $\varphi_p$. Other boundary conditions are shown in Fig. 1.

2. The optical radiation transfer equations (RTE) were solved taking into account the absorption in the diffuse scattering approximation [5]:

$$\nabla(D_L \nabla \Phi_d) = \mu_a \Phi_d - \mu_s \Phi_c$$

$$\Phi_c = \Phi_{c0} \left( \frac{w_0}{w(z)} \right)^2 e^{-\frac{2r^2}{w(z)^2}}$$

$$w(z) = w_0 \sqrt{1 + \left( \frac{z\lambda}{\pi w_0^2} \right)^2}$$

$$D_L = \frac{1}{3(\mu_a + \mu_s(1-g))}$$

$$A = 2D_L \frac{1+R_{eff}}{1-R_{eff}}$$

Here $\Phi_d, \Phi_c$ – the intensities of the diffusely scattered radiation and the incident Gaussian beam with the waist diameter $w_0$ and the intensity $\Phi_{c0}$ at the origin (the point $(0,0)$); $D_L$ – the light diffusion coefficient; $\mu_a, \mu_s, \mu_r = \mu_a + \mu_s$ – the optical, absorption, scattering and attenuation coefficients respectively; $g$ – the scattering anisotropy; and $R_{eff}$ – the effective optical reflection coefficient from the tissue surface [5].

3. The temperature field at the next time step was determined as the solution of the non-stationary heat conduction equation with the heat sources in the optical absorption region governed by the solution of RTE problem.

$$c\rho \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q$$

$$Q = \mu_a(\Phi_d + \Phi_c)$$

Here $T$ – the thermodynamic temperature; $c, \rho, \kappa$ – heat capacity, density, and thermal conductivity of the tissue respectively. At the tissue-air interface, the Newton-Richmann boundary conditions with the heat transfer coefficient $h$ and external temperature $T_0$ were adopted.

4. Basing on the resulting temperature field the conclusion concerning the chemical changes (damage) of the tissue was made in accordance with the representation of the Arrhenius integral [7].

$$G(T,t) = \frac{C(t)}{C(0)} = \exp \left( - \int_0^t K_c e^{\frac{E_a}{kT}} dt \right)$$
Here $C(t)$ – the "concentration" of the native tissue; $G(T, t)$ – the degradation degree; $E_a, K_a$ – the activation energy and the rate of the corresponding chemical degradation reaction; $k$ – the Boltzmann constant.

5. At the last stage, the electric and optical properties of the tissue were calculated for the next time step basing on the temperature field and the distribution of the degradation degree. It was assumed that the degradation only affects the electric conductivity and the scattering coefficients of the tissue [7]:

$$
s = (\sigma_n G + \sigma_d (1 - G))(1 + \chi(T - T_0))$$

$$\mu = \mu_n G + \mu_d (1 - G)$$

(5)

Here the subscripts "n" and "d" correspond to the native and damaged tissues respectively, $\chi$ is the temperature coefficient of the electric conductivity.

3. Results and discussion

The calculations were made for the case of irradiation of the porcine liver ($Z_0 = 0.6$ mm, $R_0 = 3$ mm, the initial temperature $T_0 = 23^\circ C$, the initial degradation degree $G = 1$) by 20 W optical power at 850 nm wavelength. The beam waist diameter was $\omega_0 = 1$ mm. The potential amplitude and the frequency of the probe RF field at the point (1,0) were $\varphi_p = 1$ V and $f = 1$ kHz. The physical properties of the tissue used for the simulations are presented in the table 1.

| Table 1. Physical properties of the porcine liver. |
|-----------------------------------------------|
| Parameter | Value | Parameter | Value |
| Electric properties (1 kHz) | | Optical properties (850 nm) | |
| $\sigma_n$ [8] | 0.1 (S/m) | $\mu_a$ [7] | 0.14 (1/mm) |
| $\sigma_d$ | 1 (S/m) | $\mu_m$ [7] | 10 (1/mm) |
| $\varepsilon$ [8] | $10^5$ | $\mu_{\text{sd}}$ [7] | 45 (1/mm) |
| $D_i$ | $10^{-5}$ (cm$^2$/s) | $g$ [7] | 0.95 |
| $\chi$ [2] | 2 (%/K) | Thermal properties | |
| Degradation properties | | $\rho$ [7] | 1095 (kg/m$^3$) |
| $K_a$ [7] | $10^{70}$ (1/s) | $\kappa$ [7] | 0.46 (W/m/K) |
| $T_d$ | 353 (K) | $c$ [7] | 3375 (J/kg/K) |

Figure 2 shows the typical simulation results of the distribution profiles of the total optical radiation intensity $\Phi = \Phi_d + \Phi$, the temperature $T$, the degradation degree $G$ and the potential $\varphi$ after the irradiation time of 0.1 s. For better visibility the parts of the whole considered region are presented.
Figure 2. Distribution profiles of the total optical radiation intensity (a), temperature (b), degradation degree (c) and electric potential (d) at the time moment 0.1 s.

The heating and the degradation of the sample lead to the change of its electric properties (5), and as a result to the change of the electric potential distribution induced by the probe RF field. In order to analyze the electric response the kinetics of the electric potential of the tissue surface should be considered at the arbitrary distant point \( (r_m, 0) \), e.g. at the point with \( r_m = 2 \) mm.

Figure 3 shows the kinetics of the electric potential at the considered point for the different values of the temperature coefficient \( \chi \) and the conductivity \( \sigma_d \) of the degraded tissue. As it can be seen the increase of the conductivity caused by either degradation or heating leads to the rise of the electric potential. When comparing the curves with the same \( \chi \) and different \( \sigma_d \) the response change associated with the degradation can be observed.

Figure 3. The kinetics of the electric potential at the point \( (r_m, 0) \) at different values of the temperature coefficient \( \chi \) and the conductivity \( \sigma_d \) of the degraded tissue.
However, the complex effect of heating and degradation can be less than the response from either one of them. It can be clearly seen when comparing the curves obtained for the same $\sigma_d$ and different $\chi$. This is due to the fact that the response is determined not only by the change of the resistance between points $(r_p, 0)$ and $(r_m, 0)$, but also by the increase of the conductivity between $(r_m, 0)$ and the substrate surface $(Z_0, r)$, which has zero potential.

It is well known [2,3] that electric properties of tissues at different frequencies depend on temperature and degradation degree in different ways. In the megahertz range electric properties are already weakly related to the polarization of cell membranes and, accordingly, do not change when the last ones are destroyed. In the gigahertz range the properties are mainly governed by the concentration of water contained in the tissue. As follows, here the dielectric properties change with temperature and do not considerably depend on the tissue degradation degree. It means that measurements of the kinetics of the electric response at different frequencies of RF field can be used for the control of both temperature and degradation degree of tissue during its local heating by optical radiation.

4. Conclusions
We introduced the self-consistent model that allows simultaneous solution of the equations of radiation transfer, thermal conductivity and electrodiffusion for biological tissues interacting with optical radiation taking into account the dependence of its physical properties on temperature and the degree of the induced degradation. Such model can be used for the analysis of the kinetics of physical processes of tissues during its local heating by optical radiation. This will help to perform optical treatment of biological tissues with simultaneous diagnostics of its state.

This work was carried out within the framework of the state task.

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