Journal of Engineering Physics and Thermophysics, Vol. 78, No. 4, 2005

RADIAL STRUCTURE OF THE TEMPERATURE FIELD IN BIOLOGICAL TISSUE UNDER IRRADIATION BY A LASER BEAM

V. V. Barun and A. P. Ivanov

UDC 536.33

Using the previously developed method, we have obtained analytically the Green function in the time and radial coordinates for the problem on medium heating under external irradiation. On this basis, the radial structure of the temperature field in the biological tissue has been investigated. The influence of the radial diffusion of light on the thermal conditions of the tissue has been estimated, and it has been shown that at fairly large times after irradiation such diffusion can be neglected. Examples of radial and depth temperature distributions at various optical parameters of the tissue are given.

The heating of biological tissues by laser radiation is of both scientific and applied interest in solving various medico-biological problems. In the majority of published papers, the authors show interest in the maximum temperature of the tissue, which naturally, takes place in the center of the laser beam. And this is clear, because in performing surgical operations or low-intensity laser therapy one tries to provide the strongest thermal action on the tissue. Meanwhile the laser beam has an intensity-inhomogeneous cross section of finite size. This leads to the fact that with time the heating zone expands in the radial direction. and the tissue temperature varies within the beam. Therefore, under a prolonged laser action larger and larger portions of the tissue will be irradiated not only in the depth, but also in the transverse direction. All these processes depend on the irradiation power and duration and on the optical and thermophysical characteristics of the medium.

In connection with the foregoing, many questions can be posed. How does the spatial form of the laser beam influence the temperature regime of the tissue portions situated at a distance from the irradiation axis? What are the sizes of the elevated temperature zone? Answers to these questions are not only of academic character. It is known that even if the tissue is slightly heated at a distance from the beam axis, changes in the degree of oxygenation and the relative concentration of hemoglobin can occur in the blood [1], an increase in the microcirculation can be observed [2, 3], and other physical, biophysical, and biochemical processes can proceed [4]. The causes of such changes are still not clear, and many investigations of the influence of a weak heating on the optical [5, 6], structural, and other parameters of blood and tissue are being carried out. Knowledge of the radial temperature distribution under laser irradiation can throw some light on this matter. The smooth increase in the temperature with departure from the heating axis presents an ideal experimental situation for elucidating, e.g., the threshold character of changes in tissues.

The present study is based on [7–9], where an analytical approach to the solution of the system of equations of heat conduction in biological tissues under external irradiation by a narrow laser beam was developed. The axial and radial heat transfer in a medium, the heat exchange between the capillaries and the tissue surrounding them, as well as the heat transfer into the environment were taken into account. Analytical formulas describing the space-time temperature distributions in the tissue, which practically do not require programming for calculations, were obtained. The solution of the problem on the heat transfer in the tissue was obtained on the substantiated assumption that the source function associated with the laser irradiation can be given in the form

$$S(t, z, r) = u(t)\, U_1(z)\, U_2(r)\,, \tag{1}$$

B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, 68 Nezalezhnasti Ave., 220072, Minsk. Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 78, No. 4, pp. 82–86, July–August, 2005. Original article submitted July 29, 2004.

TABLE 1. Optical Parameters of the Biological Tissue

λ	k	β	z_0	R, %
418	94.9	17.2	0.058	5.89
700	0.382	0.462	2.17	65.4

i.e., the temporal variable t and the spatial variables z and r can be separated. Relation (1) means that the radial structure of the beam is preserved at any depth z in the tissue. In the case of the shortest possible light pulse, $u(t) = \delta(t)$. Under irradiation by a pulse of duration t_p its temporal form can be arbitrary and, in particular, represent a unit step:

$$u(t) = \begin{cases} 1 & \text{at} \quad t \le t_p ; \\ 0 & \text{at} \quad t > t_p . \end{cases} \tag{2}$$

The function describing the dependence of irradiance on the depth z is of the form

$$U_1(z) = \frac{k}{c\rho} \frac{(1 - R_1)(1 + R)}{1 - RR_2} \exp(-\beta z) . \tag{3}$$

Giving the Gaussian form of the function $U_2(r)$ with radius r_0 on the $1/e^2$ level for the $\delta(t)$-pulse, we can write

$$U_2(r) = \frac{2W}{\pi r_0^2} \exp\left(-2r^2/r_0^2\right) \tag{4}$$

and an analogous relation for the pulse of finite duration with the replacement of the energy W by the power P. In [7–9], we obtained the following analytical form of the Green function for the problem on tissue heating under irradiation by a space-limited $\delta(t)$-pulse (4) with energy W:

$$T_\delta(t, z, r) = \frac{2W}{\pi} T_{\delta,\infty}(t, z) \frac{\exp\left\{-r^2/\left[4\left(r_0^2/8 + \eta t\right)\right]\right\}}{8\left(r_0^2/8 + \eta t\right)} . \tag{5}$$

Here $T_{\delta,\infty}(t, z)$ is the Green function under irradiation of the medium by a $\delta(t)$-pulse of infinite width with a unit surface energy density [10, 11].

Note that as $r_0 \to 0$, from (4) $U_2(r) \to W\delta(r)$ follows [12]. Passing in (5) to the limit as $r_0 \to 0$, we obtain the Green function of the problem on the medium heating under its irradiation by an infinitely short and infinitely narrow pulse:

$$T_{\delta,\delta}(t, z, r) = \frac{2W}{\pi} T_{\delta,\infty}(t, z) \frac{\exp\left\{-r^2/(4\eta t)\right\}}{8\eta t} . \tag{6}$$

The analytical form (6) makes it possible to fairly easily, by calculating the convolution integrals, investigate the thermal regime of the tissue irradiated by a pulse of arbitrary space and time structure. This requires neither special software nor the development of complex computational algorithms. Below, we consider the case of stationary irradiation, i.e., in formula (2) the duration t_p exceeds the moment t of observation.

Thus, we emphasize again that, as follows from (1), (3), and (4), at a fixed spatial structure of the laser beam the light intensity in the medium depends only on its optical characteristics. Form (5) or (6) of the Green function shows that a change in the temperature T in the depth z is associated with the optical and thermophysical characteristics, and the dependence of T on r is only determined by the thermophysical properties.

We now turn to the analysis of the results. The optical characteristics of the tissue needed for the calculations are given in Table 1. Here k and β are, respectively, the light attenuation index in the depth regime and the absorption index [13], $z_0 = 1/\beta$ is the depth of light penetration into the medium, and R is the reflection coefficient of the tissue

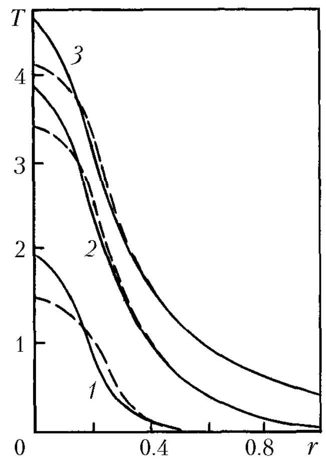

Fig. 1. Dependence of T on r for the Gaussian (solid curves) and the cylindrical (dashed curves) laser beam at t = 10 (curves 1), 100 (2), and 1000 sec (3); P = 0.2 W, λ = 700 nm, r_0 = 0.25 cm, z = 0.

layer. The choice of the wavelengths λ = 418 and 700 nm is due to the maximum and minimum absorption of light by blood at these λ. The data given in Table 1 were taken from the opto-thermophysical model of tissue [7, 10] for the volume concentration of the blood vessels (relative blood filling) 0.05, hematocrit 0.4, the volume fraction of hemoglobin in erythrocytes 0.25, and the degree of oxygenation of the blood 0.75. The principles of constructing the model and to what it corresponds, as well as the approximations and assumptions used to obtain the results presented below, are given in [14]. Since here we considered soft tissues consisting mainly of water, it was assumed that the thermal diffusivity η = 0.0014 cm^2/sec and the product $c\rho$ = 4.2 J/($cm^3 \cdot K$). The heat-transfer parameter at the tissue–air interface is equal to 40 m^{-1}. Below, by T is meant the temperature excess (over the tissue temperature at the moment of onset of the laser action) as a result of the irradiation.

Consider Fig. 1, which shows the influence of the laser-beam form on the radial temperature distribution over the tissue surface at z = 0. For comparison we chose the Gaussian beam (4) and the cylindrical beam

$$U_2(r) = \begin{cases} P/(\pi r_0^2) \ \text{at} \ r \le r_0 \,; \\ 0 \ \text{at} \ r > r_0 \end{cases} \tag{7}$$

of equal power P = 0.2 W and radius r_0 = 0.25 cm. Apparently, the temperature on the beam axis at r = 0 is determined by the power density or the irradiance, especially at short instants of time when the effect of the radial diffusion of heat is not yet strong. In the Gaussian beam (solid curves), the irradiance is twice as large and, therefore, the tissue temperature here is also higher compared to the cylindrical beam (dashed curves). However, in the time interval under consideration, the excess by a factor of 2 is not observed. While at small t (curves 1) the difference between the temperatures is about 40%, 15 min after irradiation (curves 3) it is already 15%. This is due to the radial diffusion of heat, which at the initial instants of time is stronger for the Gaussian beam because of the corresponding radial temperature gradients at r = 0.

Note another interesting regularity. At distances from the beam axis of the order of r_0 and larger the temperature values are practically the same for the two considered radial profiles of irradiation. The profiles themselves differ from each other rather widely. For instance, while the Gaussian beam power decreases smoothly with increasing r, in the cylinder beam there is a clearly defined boundary. As is seen from Fig. 1, no marked differences between the functions $U_2(r)$ in the thermal field structure (in absolute units) outside the direct light zone are observed. As mentioned above, in obtaining the analytical form of the Green function (5), the radial diffusion of the laser beam was ignored. It turns out (and this is confirmed by the data of Fig. 1) that upon lapse of a not very long time after the onset of irradiation (after 1 sec) the real radial structure of the irradiation becomes immaterial. A second after, however, the tissue just begins to be heated so that its temperature reaches appreciable values. Obviously, the radial diffu-

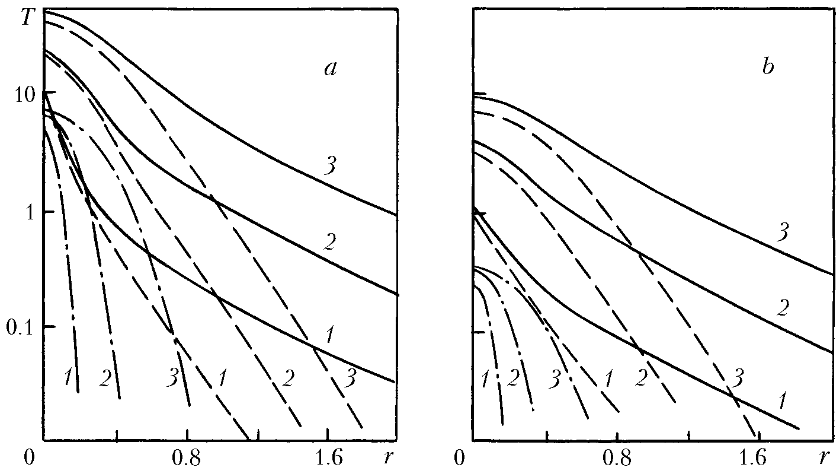

Fig. 2. Dependence of T on r for the Gaussian beam at λ = 418 (a) and 700 nm (b), t = 1 (dash-dot curves), 100 (dashed curves), and 1000 sec (solid curves), r_0 = 0.1 (curves 1), 0.25 (2), and 0.5 cm (3), z = 0.

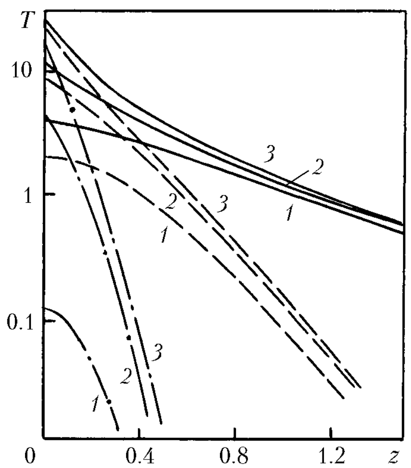

Fig. 3. Dependence of T on z for the Gaussian beam at t = 10 (dash-dot curves), 100 (dashed curves), and 1000 sec (solid curves), r = 0 (curves 1), 0.25 (2), and 0.5 cm (3), λ = 418 nm, r_0 = 0.25 cm.

sion of the light beam in the thermal problem can be ignored, at least under the conditions given in Fig. 1. In any event, these estimates will require further investigations.

Next we shall consider only the Gaussian beam. We assume that the radiance on its axis at z = 0 is 2 W/cm^2. Figure 2 illustrates the radial temperature distribution over the tissue surface at different instants of time at various values of r_0. To interpret the results, it will be recalled that in [10, 11] the characteristic times of the processes in the medium that permit visual analysis of the laws of change in the temperature were introduced. Thus, the temperature equalizing time in the tissue thickness $\tau_\eta = 1/(\beta^2\eta)$, the radial heat-transfer time $\tau_r = r_0^2/(2.5\eta)$, and the time of heat exchange between the surface and the environment $\tau_h = 1/(h^2 r)$. In the case given in Fig. 2, at λ = 418 and 700 nm, respectively, we have τ_η = 0.011 and 27 sec. The time $\tau_h = 3\cdot10^5$ sec is independent of λ. From this it follows that at a tissue–air contact the heat transfer into the environment is negligibly small compared to its transfer in the tissue. Obviously, at the very first instants of time when $t \ll \tau_r$ the form of the radial temperature distribution is similar to $U_2(r)$. For the conditions of Fig. 2 this holds to about 1 sec (not shown). With increasing t the thermal spot noticeably blurs. In so doing, the rate of decrease in $T(r)$ with increasing r no longer depends on the laser-beam radius. From Fig. 2 it is seen that the curves drop practically in parallel to one another, and the temperature values are determined by the irradiation power alone. Note that, unlike Fig. 1, here the curves are normalized to equal irradiance at the beam center and, consequently, the initial power is proportional to r_0^2. This confirms once again the conclusion drawn in considering Fig. 1 that at distances from the beam axis the radial structure of the light spot is immaterial. Naturally, under irradiation in the violet region (Fig. 2a) higher temperatures than in the red region (Fig. 2b) are attained because of the stronger adsorption.

Figure 3 characterizes the temperature change with depth z at various distances from the beam axis at different instants of time at λ = 418 nm. The fact that the curves approach one another, especially at large t and z, points to a strong radial spread of the elevated temperature zone in the tissue. Note that upon irradiation for about 15 min (solid curves) a fairly marked heating of the tissue (by about 1 K) both to a depth of up to 1 cm and in the radial direction up to 0.5 cm takes place. The above geometric distances considerably exceed the depth of penetration of light into the tissue at the given wavelength, so that the radiation here is absent. This is only the result of the initial temperature field diffusion.

In conclusion, note that the analytical method for calculating the temperature field described in the present paper and the examples given make it possible to answer the questions posed in the beginning of the article. In so doing, it is very easy to pass to arbitrary spatial energy distributions in the irradiating beam, as well as to its arbitrary time structure.

This work was supported by the Belarusian Republic Basic Research Foundation, grant No. F01-009.

NOTATION

c, specific heat capacity, J/(kg·K); h, parameter of heat exchange between the tissue and the environment, m^{-1}; k, absorption index of the tissue, cm^{-1}; P, laser-radiation power, W; r, current radial coordinate, cm; r_0, effective radius of the beam, cm; R, reflection coefficient of the layer thickness; R_1, reflection coefficient of the tissue surface under external irradiation; R_2, reflection coefficient of the tissue surface under irradiation from the inside of the medium; S, source function, K/sec; t, current times, sec; t_p, irradiation-pulse duration, sec; T, temperature excess above normal, K; u, time pulse form; U_1, depth part of the source function, cm^2·K/J; U_2, radial part of the source function, W/cm^2; W, energy of the irradiation $\delta(t)$-pulse, J; z, depth, cm; z_0, depth of light penetration into the tissue, mm; β, depth attenuation index of the tissue, mm^{-1}; δ, delta-pulse; η, thermal diffusivity, cm^2/sec; λ, wavelength, nm; p, density, kg/cm^3; τ_h, characteristic time of heat exchange with the environment, sec; τ_r, characteristic time of radial heat transfer, sec; τ_η, characteristic time of heat transfer into the tissue depth, sec. Subscripts: ∞, infinitely wide irradiation beam; p, finite-duration pulse; η, heat transfer into the tissue depth.

REFERENCES

1. A. A. Stratonnikov, N. V. Ermishova, and V. B. Loshchenov, Diagnostics of the response of the capillary channel of tissues to laser radiation, *Kvantovaya Élektron.*, **32**, No. 10, 917–922 (2002).
2. A. N. Korolevich, L. G. Astafyeva, N. S. Dubina, S. I. Vecherinsky, and M. S. Belsley, Increase of blood microcirculation under the influence of low-intensity laser radiation, *Proc. SPIE*, **5254**, 24–29 (2003).
3. A. N. Korolevich, L. G. Astaf'eva, N. S. Dubina, S. I. Vecherinskii, and M. S. Belsley, *In vitro* Doppler spectroscopy of blood under the action of low-intensity laser radiation, *Opt. Spektrosk.*, **96**, No. 3, 458–464 (2004).
4. O. S. Khalil, S. Yeh, M. G. Lowery, X. Wu, et al., Temperature modulation of the visible and near infrared absorption and scattering coefficients of human skin, *J. Biomed. Opt.*, **8**, No. 2, 191–205 (2003).
5. A. M. K. Nilsson, G. W. Lucassen, W. Verkruysse, S. Andersson-Engels, and M. J. C. van Gemert, Changes in optical properties of human whole blood *in vitro* due to slow heating, *Photochem. Photobiol.*, **65**, No. 2, 366–373 (1997).
6. A. M. K. Nilsson, C. Sturesson, D. L. Liu, and S. Andersson-Engels, Changes in spectral shape of tissue optical properties in conjunction with laser-induced thermotherapy, *Appl. Opt.*, **37**, No. 7, 1256–1267 (1998).
7. V. V. Barun and A. P. Ivanov, Light and thermal fields in multicomponent biological tissues, *Nauka Innovatsii*, Nos. 3–4, 37–51 (2003).
8. V. V. Barun and A. P. Ivanov, A simple model to study heat transfer in two-component biological tissues under laser irradiation, *Proc. SPIE*, **5254**, 44–51 (2003).

9. V. V. Barun and A. P. Ivanov, Study of heating and cooling of biological tissues under irradiation by a light pulse of arbitrary duration, in: *Proc. Int. Conf. "Laser Physics and Laser Application"* [n Russian], Minsk (2003), pp. 281–282.
10. V. V. Barun and A. P. Ivanov, Thermal action of a short light pulse on biological tissues, *Int. J. Heat Mass Transfer*, **46**, No. 17, 3243–3254 (2003).
11. V. V. Barun and A. P. Ivanov, *Thermal Action of Powerful Light Irradiation on Biological Tissues* [in Russian], Preprint No. 739 of the Institute of Physics, National Academy of Sciences of Belarus, Minsk (2003).
12. G. A. Korn and T. M. Korn, *Mathematical Handbook* [Russian translation], Nauka, Moscow (1977).
13. E. P. Zege, A. P. Ivanov, and I. L. Katsev, *Image Transfer in a Scattering Medium* [in Russian], Nauka i Tekhnika, Minsk (1985).
14. V. V. Barun and A. P. Ivanov, Influence of optical and thermophysical characteristics of biological tissue on its thermal conditions under laser irradiation, *Inzh.-Fiz. Zh.*, **78**, No. 3, 15–21 (2005).