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MATHEMATICAL MODELING OF THE DAMAGE THRESHOLD OF CORNEA TISSUES BY SHORT IR LASER PULSES

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A series of experimental data on threshold energy levels of cornea damage by IR radiation pulses with duration shorter than 1 μs is generalized. Mathematical modeling of the radiation energy thresholds is based on the concept of the removal of a surface layer of the cornea tissue without a phase transition as a result of the work of pressure forces.

An important requirement that should be met by methods of calculation of the action of laser radiation on living tissue is the possibility to predict the threshold irradiation level. Such a value of the energy density is usually taken as a threshold at which the tissue being irradiated is damaged with the predetermined probability of 50% (this quantity is usually denoted by H_{50}). Knowledge of the irradiation energy thresholds for various types of lasers and pulses of various durations is a necessary condition for evaluation of levels of the therapeutic action on pathology zones and for calculation of maximum permissible levels (MPL) of laser irradiation. For IR laser pulses with duration from 10^{-4} to 1 sec the damage is of a thermochemical nature and connected with heating of tissues being irradiated. The mathematical model for calculation of the energy necessary to obtain an observable thermal damage of the cornea tissue is built on the basis of the classic heat conduction equation for an incompressible medium and the equation of thermochemical macrokinetics of irreversible protein denaturation [1, 2]. Cornea tissues consist of collagen to the extent of 15% and 5% solvable proteins. The thickness of the human cornea is 0.5 mm, and its diameter is 12 mm. The front cornea surface is covered by a 7 μm-thick lachrymal film. The coefficient of heat transfer is preset on this surface. Using the thermal model we calculated threshold irradiation levels of cornea by IR radiation of lasers of various types within the spectral region from 1.4 to 20 μm at pulse durations up to 1 sec. Calculated values of the threshold energy density agree well with experimental data for pulse durations within several orders of magnitude [3]. An attempt to extend this model to shorter laser pulses was not successful for the following reason. Numerical calculations of the temperature of the cornea surface yield temperature values obviously insufficient to obtain the minimum observable thermal damage (burn) of the tissue. This is indicative of the fact that at shorter laser pulses the tissue damage is of a different nature. It is assumed in the aforementioned thermochemical model that all the energy supplied is transformed into enthalpy i of the tissue being irradiated. As is known from thermodynamics, this corresponds to conditions of the isobaric process. However, for laser pulses with duration less than 10^{-6} sec this assumption is not satisfied due to the high heating rate combined with localization of the heating zone within a small area at low absorption depth. For example, at a pulse duration of about 20 nsec the distance to which the pressure wave resulting from the local heating propagates with the speed of sound equals 30 μm, i.e., much less than the dimensions of the irradiated area.

Therefore, due to the fact that the shifts taking place during the pulse are insignificant, the process of heat supply can be considered isochoric. In an isochoric process all the energy supplied goes to the internal energy $u = i - pv$. Taking into account the fact that the cornea contains 78% water we use the common tables of properties of water and steam [4] for calculation of the equilibrium thermodynamic state of the cornea tissue resulting from irradiation by a short (from 1 to 250 nsec) IR radiation pulse in the isochoric process. Irradiation conditions

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TABLE 1. Experimental Values of the Threshold Energy Density on Cornea for Various Laser Types and Pulse Durations

λ, μm	τ_p, nsec	k, m^{-1}	H_{50}, J/m^2	Reference
10.6	1.4	95,000	2000	[6]
10.6	1.7	95,000	3300	[5].
10.6	25.0	95,000	5400	[5]
1.54	40.0	1050	47,000	[7]
2.61–2.87	45.0	17,000	6200	[6]
2.06	42.0	2820	52,000	[8]
1.54	50.0	1050	210,000	[6]
1.54	100.0	1050	250,000	[9]
3.55–3.98	100.0	15,000	15,100	[6]
10.6	250.0	95,000	1800	[5]

correspond to threshold energy values. Experimental data on threshold values of the laser radiation energy density H_{50} on the surface of cornea of laboratory animals for various wavelengths from the near IR region were taken from [5-9]. These data correspond to wavelengths from λ = 1.54 μm to λ = 10.6 μm and pulse durations τ_p from 1.4 nsec to 250 nsec. Assuming that thermal properties of the tissues are determined by properties of water whose initial state corresponds to the pressure 1 Bar and temperature 30°C, we determine the initial value of the internal energy: $U = i - pv$ = 126 kJ/kg. It was assumed that the absorption depth at the level exp (-1) is the quantity inverse to the spectral absorption coefficient $k(\lambda)$. All data specified are presented in Table 1. The volume density of absorbed energy ($H_{50}k$) calculated using these data appeared to be constant irrespective of the wavelength and pulse duration. The value of the volume density of absorbed energy $\Delta u = H_{50}k$ for the data from Table 1 is, on average, [10]

$$H_{50}k = 235 \text{ kJ/kg}. \tag{1}$$

This is just about 10% of the latent vaporization heat for water [4]. It should be noted that with increasing pulse duration to values longer than 1 μsec this relationship is violated. Thus, already at τ_p = 2 μsec the threshold density of the energy absorbed, according to [11], equals 574 kJ/kg.

The internal energy for water u found as the sum of the initial and supplied energy is 361 kJ/kg.

At isochoric heat supply this is expended in increasing the internal energy. In order to find an unambiguous relationship between the energy supplied and the pressure increase induced by the energy supply we used data from [4] to calculate the dependence of the pressure in water on the density of the internal energy along the isochore v = 0.001 m^3/kg. The steepness of this dependence

$$\left(\frac{\partial p}{\partial \rho u}\right)_v = \frac{1}{\rho c_v}\left(\frac{\partial p}{\partial T}\right)_v \tag{2}$$

varies slightly and equals 0.25 Pa·m^3/J up to the critical region and 0.40 Pa·m^3/J in the supercritical region. If, in accordance with tables from [4], we find a point on the isochore v = 0.001 m^3/kg that corresponds to the specified value of the internal energy $u = i - pv$. This point will be located within the single-phase region at the temperature t = 90°C and pressure p = 72 MPa.

The outflow rate is determined from the known thermodynamic relationships: by equating the kinetic energy of the flow to the work of pressure forces in the incompressible liquid upon a pressure decrease by Δp we obtain

$$w = \sqrt{2v\Delta p}\ , \tag{3}$$

the velocity $w = 380$ m/sec. This corresponds to the speed of sound in air at a temperature of 86°C.

This approach corresponds to simplification of the statement of the problem formulated in [12] for a multilayer absorbing tissue. The possibility of a more simple approach is connected with the fact that the process takes place at the cornea/air interface and can be reduced to the outflow process. Qualitatively, the result corresponds fully to the experimental investigation [13], where it was found that explosion ablation of tissues by laser radiation proceeds without a phase transition.

Upon the action of nanosecond laser pulses on tissues of the fundus of eye (retina and vascular membrane of the eye) the outflow into the environment is absent, and in order to describe the process, one should use a more complicated mathematical model [12] that, in addition to the energy equation for the multilayer medium, includes two-dimensional equations of motion, the continuality equation, and the equation of state for the liquid.

NOTATION

τ_p, pulse duration, nsec; $u = i - pv$, internal energy, J/kg; λ, wavelength of laser radiation, μm; $k(\lambda)$, spectral absorption coefficient, m^{-1}; $H_{50}(k)$, threshold energy density, W/m^2; w, outflow velocity, m/sec.

REFERENCES

1. A. S. Podol'tsev and G. I. Zheltov, Zh. Prikl. Spektr., **40**, No. 2, 207-211 (1984).
2. A. S. Podol'tsev and G. I. Zheltov, Kvant. Élektron., **16**, No. 10, 2136-2140 (1989).
3. A. S. Podol'tsev and G. I. Zheltov, Gigiena Truda Professional'nye Zabolevaniya, No. 6, 42-43 (1992).
4. S. L. Rivkin and A. A. Aleksandrov, Thermophysical Properties of Water and Steam [in Russian], Moscow (1980).
5. J. A. Zuclich, M. F. Blankenstein, S. F. Thomas, and R. F. Harrison, Health Physics, **47**, No. 6, 829-835 (1984).
6. D. Sliney and M. Wolbarsht, Safety with Lasers and Other Optical Sources. A Comprehensive Handbook, New York, London (1982).
7. P. S. Avdeev, Yu. D. Berezin, Yu. P. Gudakovskii, et al., Kvant. Élektron., **5**, No. 1, 220-223 (1978).
8. B. E. Stuck, D. J. Lund, and E. S. Beatrice, Health Physics, **40**, 835-846 (1981).
9. D. J. Lund, M. B. Launders, G. H. Berznick, et al., Investigative Ophthalmology, **9**, No. 6, 463-470 (1970).
10. A. S. Podol'tsev, in: Pulsed Processes in Mechanics of Continuous Media. Abstracts of the 1st Scientific School, Nikolaev (1994), p. 187.
11. J. T. Walsh and T. F. Deutsch, Lasers in Surgery and Medicine, **8**, 264-275 (1988).
12. G. Zheltov, A. Podol'tsev, A. Kirkovsky, and E. Witkin, in: Ophthalmic Technologies. V. Proc. SPIE, **2393** (1995), pp. 142-147.
13. V. I. Konov, A. M. Prokhorov, A. S. Silenok, et al., Kratkie Soobshchen. Fiz., No. 9, 18-20 (1988).