THERMAL ACTION OF RADIATION PULSES AT WAVELENGTH 1.06 μ ON RETINAL TISSUE

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Thermal action of radiation pulses at a wavelength of 1.06 μ upon retinal tissue is studied experimentally and theoretically.

1. Introduction. The most important mechanism for use of intense optical radiation in technology is nonresonant thermal action, leading to heating, thermochemical conversions, etc. [1, 2]. Recently there has been much interest in thermal processes occurring during action of optical radiation on heterogeneous layered media such as dielectrics, multilayer dielectric coatings, and layered heterogeneous biotissues [3, 4]. The present study will perform an experimental and theoretical study of the thermal action of radiation pulses at wavelength $\lambda = 1.06$ μ with durations of $\sim 10^{-2}$-10^{-10} sec with layered heterogeneous retinal tissue. Such studies are important for development and optimization of methods and dosages for use of intense optical radiation in ophthalmology. On the other hand, with the wide use of laser technology in industry and science it has become of great practical importance to develop scientifically based safety norms, since existing ones [5] are in need of refinement and justification.

2. Results of Experimental Studies. The thermal biological action of collimated optical radiation with $\lambda = 1.06$ μ on the retinal tissue of a rabbit was studied.

Ophthalmological and histological studies of irradiated tissue were carried out. It was established that the ophthalmological pattern of threshold changes in the rabbit eye was identical, independent of the radiation pulse duration. At the moment of application greyish-white spots ~15-20 μ in diameter were observed, while within 1 hour after the application the spot diameter increased, the boundaries became more well defined, and the color, white. The presence of threshold changes was considered in an alternative form – whether or not damage could be detected immediately after application or not. The experimental data were processed by the Miller–Teitner method using the method of least squares to create a regression curve for determination of the appearance of ophthalmological threshold damage. The radiation pulse energy upon entrance to the eye ED_{50} which would produce threshold damage to the retina with a probability of 50% was determined. Also determined was the pulse energy which produced threshold damage to the rabbit tissue 0.1% of the time, $ED_{0.1}$. This value was chosen as a "zero" probability for appearance of threshold damage to the retina. For impulses with duratins $t_i = 3.5 \cdot 10^{-3}$; $3 \cdot 10^{-4}$; $1 \cdot 10^{-5}$; $5 \cdot 10^{-8}$; $1 \cdot 10^{-10}$ sec, the threshold energies ED_{50} were: $ED_{50} = (3.1 \pm 0.4) \cdot 10^{-3}$; $(2.2 \pm 0.1) \cdot 10^{-3}$; $(3.7 \pm 0.3) \cdot 10^{-4}$; $(2.2 \pm 0.3) \cdot 10^{-4}$; $(\delta \pm 1) \cdot 10^{-5}$ J [6]. Figure 1 shows some experimental values of ED_{50} and $ED_{0.1}$.

The histological data for threshold damage were quite similar for all pulse durations t_i. In essence the ophthalmologically defined hearth for retinal damage is a coagulation reaction (thermodenaturization) of the tissue upon irradiation. It should be noted that at $t_i = 1 \cdot 10^{-10}$ sec and threshold pulse energy there was a clearly expressed mechanical destruction of tissue, which was practically absent at $t_i > 10^{-9}$ sec. These results are also supported by analogous data of histological studies for threshold damage in [7]. Thus, the experimental results confirm the dominant role of the thermal thermodenaturization mechanism for formation of threshold damage in retinal tissue for action of radiation pulses in the duration range $10^{-9} > t_i > 10^{-2}$ sec.

3. Theoretical Study of Thermal Action of Radiation Pulses. We will consider results of a theoretical study of action of radiation pulses with $\lambda = 1.06$ μ with threshold and sub-

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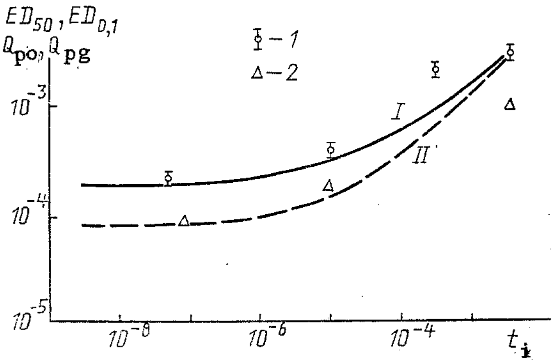

Fig. 1. Experimental values of ED_{50} (1), $ED_{0.1}$ (2) and calculated dependence upon t_i of energies Q_{po} (I), Q_{pg} (II) for pulses with $\lambda = 1.06$ μ on rabbit cornea. ED_{50}, $ED_{0.1}$, Q_{po}, Q_{pg}, J; t_i, sec.

threshold energy values on retinal tissue. The tissue at the back of the eye is a complex multilayer structure. A significant feature of one of the retinal layers, the pigmented epithelium (PE) is heterogeneous (granular) structure. The PE layer contains pigmented melanoprotein granules of spherical and spheroidal form with characteristic dimensions ~1 μm, which selectively absorb up to 90% of the radiant energy absorbed by the entire PE layer. During radiation pulse action the granules are overheated relative to their surroundings and release energy to the surrounding biotissues by thermal conductivity. Models and numerical methods for study of thermal processes during action of radiation pulses on heterogeneous retinal tissue were developed in [4, 8], where it was shown that it is necessary to consider the granular structure of the PE when dealing with pulses having $t_i \lesssim 10^{-3}$ sec. As follows from the results of section 2, the basic interaction mechanism for pulses with threshold (and subthreshold) energy values and $t_i > 10^{-9}$ sec is thermodenaturization (coagulation) of biotissue. The system of equations describing the processes of radiation interaction with retinal tissue, with consideration of pulse energy absorption by granules in the PE, their heating, heat exchange, and thermodenaturization of biotissue, includes the following equations: radiation transport, thermal balance of spherical and spheroidal granules in the PE and two-dimensional thermal conductivity for the entire biotissue volume considered, and the kinetic equation for thermodenaturization [4, 8]. Numerical calculations of this system were performed for radiation pulses with $\lambda = 1.06$ μ, durations $10^{-2} > t_i > 10^{-10}$ sec in order to compare the calculated data with the experimental results of section 2.

The geometric and optical (for average pigmentation) parameters of the rabbit eye tissues were taken from [9]. Thermophysical characteristics of individual layers were taken from [10]. The distribution of radiation intensity I over the beam section on the retina is taken as Gaussian: $I = I_0 \exp(-R^2/R_0^2)$, where I_0 is the maximum intensity on the beam axis, R is the radial coordinate, and R_b is the characteristic radius of the beam.

The experimental data indicate the characteristic diameter of the irradiated spot on the retina to be $D_b = 2R_b \approx 100$ μ. Based on these parameter values numerical modeling was used to determine the pulse energy Q_{ro}, leading to formation of a continuous thermodenaturization hearth on the retina with a diameter of ~25 μ at a protein molecule denaturization level f = 0.5 (initial value f = 1), i.e., within the limits of the calculated hearth the fraction of thermally activated protein molecules exceeds 50%.

During the process of laser pulse action the granules in the PE are heated to higher temperatures than the surrounding tissues. Considering the intense dependence of thermodenaturization rate upon temperature, by selection of a proper pulse energy a case can be realized in which thermodenaturization occurs only within and around the granule surface — a granular thermodenaturization hearth is formed [8]. In the given case by granular hearth we understand one localized within and near melanoprotein granules, while on the granule surface the degree of denaturization f = 0.5, i.e., within the granule the fraction of thermally activated molecules exceeds 50%. The thermodenaturization microregions do not intersect each other and do not create a continuous thermodenaturization hearth in the retinal tissues. Selective thermodenaturization of granules in the PE can be accomplished at energy levels Q_{rg} ~ 2-4 times smaller than the threshold pulse energy Q_{ro}.

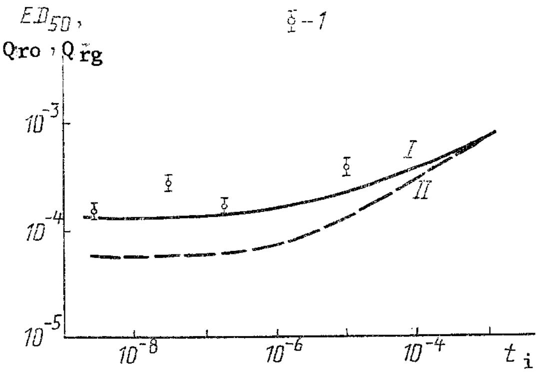

Fig. 2. Experimental ED_{50} values [11] and calculated t_i dependence of Q_{ro} (I), Q_{rg} (II) for radiation pulses with $\lambda = 1.06\ \mu$ on cornea of monkey eye.

Figure 1 shows numerically calculated values of the pulse energies Q_{ro} and Q_{rg} incident upon a rabbit cornea. We note that for $10^{-5} \gtrsim t_i \gtrsim 10^{-8}$ sec a Gaussian time dependence was assumed, while for $10^{-2} \gtrsim t_i > 10^{-5}$ sec a constant I_0 for $0 < t \leq t_i$ and $I_0 = 0$ for $t > t_i$ were used. There is satisfactory agreement between the experimental ED_{50} and theoretical Q_{ro} energy values and a definite correlation between $ED_{0.1}$ and Q_{rg} values. For $t_i \geq 10^{-3}$ sec the calculated Q_{ro}, Q_{rg} values practically coincide, as was noted in [4]. There is a general principle of decrease in ED_{50}, $ED_{0.1}$, and Q_{ro}, Q_{rg} with decrease in pulse duration $t_i < 10^{-2}$ sec, while in the range $10^{-8} < t_i < 10^{-5}$ sec, the energy decrease is slight. These features in the behavior of ED_{50} and Q_{ro} agree with experimental results presented in [11-13]. For $t_i = 1 \cdot 10^{-10}$ sec a calculation using the experimental value ED_{50} indicated the absence of a continuous thermodenaturization hearth in the retinal tissues. On the other hand, calculations of thermal expansion of biotissue upon heating by short radiation pulses has shown the possibility of formation of compression waves with a pressure change of ~10-100 atm as well as the necessity of considering this factor in action of radiation pulses with duration $t_i \lesssim 10^{-9}$ sec and threshold energy levels.

Calculations of thermal processes in the interaction of radiation pulses with wavelength $\lambda = 1.06\ \mu$ and durations $10^{-3} > t_i\ 10^{-9}$ sec with retinal tissue of a monkey were also carried out, for comparison with the experimental data of [11]. Problem parameters were taken from [9-12], with the radius of the irradiated spot on the retina taken equal to $R_b \approx 40\ \mu$. Figure 2 shows experimental ED_{50} values [11] and calculated Q_{ro}, Q_{rg} values, with satisfactory agreement between ED_{50} and Q_{ro}. The experiments of [11] were performed especially to determine the dependence of ED_{50} on t_i in the interval $10^{-5} < t_i < 10^{-9}$ sec, and the dependence found $ED_{50} \approx$ const agrees with the given thermal model.

4. Conclusion. Comparison of the calculated data with the results of the experimental studies indicates the possibility and justifiability of using the thermodenaturization model to describe the process of interaction of radiation pulses with threshold and subthreshold energy values in the duration range $t_i > 10^{-9}$ sec. This conclusion agrees with the results of the theoretical treatment of [12], in which satisfactory agreement of experimental data in the duration range $10^{2} > t_i \geq 10^{-8}$ sec with calculations using a thermal model of biotissue degradation. Thus, proper consideration of PE granularity permits expansion of the range of applicability of the thermochemical model to $t_i > 10^{-9}$ sec (see [14]). We will also note that the results of this study remain valid for study of the action of pulses at other wavelengths at threshold energy levels and can be used to develop safety norms.

NOTATION

λ, radiation wavelength; ED_{50}, radiation pulse energy producing threshold degradation with 50% probability; $ED_{0.1}$, radiation pulse energy producing threshold degradation with 0.1% probability; t_i, characteristic pulse duration; I, radiation intensity; f, degree of molecular thermodenaturization.

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A NEW THERMAL λ-ANOMALY IN IRON GROUP FERROMAGNETICS

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The differential thermal analysis method is used to detect a new phase transition in iron group ferromagnetics. Assuming that this transition is caused by relativistic interactions, a thermodynamic theory is constructed to describe the transition.

The anisotropic magnetic properties of iron, nickel, cubic cabalt, and a number of their compounds show a common feature which has yet to be explained theoretically. In such ferromagnetics, below the Curie point T_C there exists a temperature interval $T_1 < T < T_C$, within which no nonzero magnetic anisotropy constant exists. Since the direction of the easy magnetization axis is defined by nonzero values of the magnetic anisotropy constant [1], in this interval there exists an isotropic, absolutely magnetically soft, magnetic phase, with no easy or difficult magnetization axes. With consideration of this, such technical concepts as magnetically soft or magnetically hard ferromagnetics take on a precise theoretical meaning. The goal of the present study is construction of a phenomenological thermodynamic theory which will permit derivation of the temperature dependence of the magnetic anisotropy constant at high temperatures, close to the Curie point. Results will also be presented from thermal experiments which confirm the existence of a transition from an isotropic magnetic phase to an anisotropic one in iron group ferromagnetics and magnetite (Fe_3O_4).

A thermodynamic description of the transition from a paramagnetic phase to an isotropic magnetic phase in ferromagnetics was presented in [2], and we will concentrate our attention on the transition from the isotropic to the anisotropic phase. The ferromagnetics we are dealing with are cubic, with point octahedral symmetry. Below the Curie point a spontaneous

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