

LASER APPLICATIONS IN MEDICINE

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Optical transmission and laser ablation of pathologically changed eye lens capsule

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Abstract. **Optical transmission and ablation mechanisms in the secondary cataract films under the impact of 1.06-μm laser radiation are studied. The comparison of incident and transmitted (paraxial) radiation power at different values of the power density is carried out for two types of the eye lens capsule tissue (hard and soft) possessing different optical and mechanical properties. It is found that the effective attenuation coefficient for soft films is almost five times as large as that for the hard ones. The obtained measurement data on the transparency variation in the process of laser action allow the temperature evaluation and the determination of dominant mechanism of laser ablation, as well as the development of recommendations, providing the prevention or reduction of possible side effects. The obtained results can be used to optimise the regimes of laser impact in the process of the opacified lens capsule removal.**

Keywords: *laser ablation, optical properties of eye tissue, eye lens capsule.*

1. Introduction

Lasers have been used in ophthalmology for more than 40 years [1]. With accumulation of clinical experience, more and more evidence of different complications developing after laser operations appears, including those after the removal of secondary cataract films (opacification of posterior lens capsule). Moreover, the exposure levels safe for the eye, determined by the normative documents, have a probabilistic character, which does not exclude the possibility of damage in the course of various experiments and technical operations using laser radiation [2]. Numerous publications are devoted to the problem of photodestructive laser action on the anatomical eye structures and artificial intraocular elements (see, e.g., [1 – 12]), in particular, the possibility of complications that develop after the laser section (discission) of the secondary cataract films and pathologic pupillary membranes. These complications include the transitory hypertension, cornea damage and other pathologic phenomena. However, the most frequent complication of using the laser destructor radiation is the damage of the optical part of the implant intraocular lens (IOL) [2, 5, 8 – 10], referred to as the IOL distant damage. Figure 1 presents the schematic diagram of an eye showing the relative position of the eye lens capsule and the IOL implanted into it after the extracapsular cataract extraction (removal the opacified eye lens content with the capsule left undamaged). The opacification of the lens capsule and its induration in the post-operation period reduces the visual function and leads to the necessity of the additional laser operation that is, in turn, related to the risk of the above complications. In this connection, the studies aimed at clarification of the physical causes and minimising the side effects, related to laser ophthalmologic operations, are urgent.

The goal of the present paper is to study the processes of heating and destruction of secondary cataract films (isolated samples of the human eye lens capsule with different types of opacification) under the exposure to sequential laser pulses and their possible influence on the eye heterogeneous structures during the laser ablation of pupillary membranes. The laser ablation is a widely used ophthalmologic method of removing a pathologically changed eye lens capsule affected by secondary cataract. The products of destruction often damage the eye tissues located at a significant distance from the zone of laser exposure, which may cause different complications. The absence of data on the optical properties of pathologic pupillary membranes and the analysis of their laser ablation mechanisms make it difficult to optimise the laser impact. The knowledge of optical characteristics, temperature and specific energy of

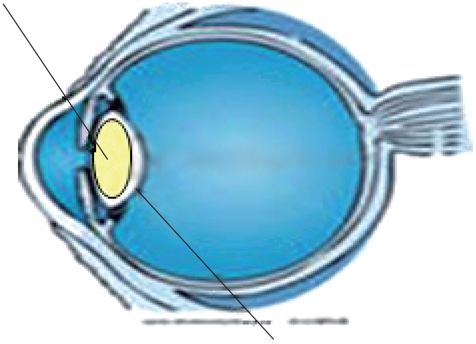

Figure 1. Schematic diagram of an eye.

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laser destruction of the pupillary membranes will allow the determination of the major laser ablation mechanism in the secondary cataract films of different types. Using a simple theoretical model will make it possible to evaluate the mechanical stresses, the pressure of gas bubbles and the kinetic energy of ablation products under the action of a series of laser pulses, which will allow the prediction of localisation and size of damage regions in different structures of eye tissues, including the retina.

2. Materials and methods

We used samples of autopsy material, the opacified posterior capsule of human eye lens with different optical and mechanical characteristics, namely, the hard dense films and relatively soft loose ones. The laser impact was implemented using a Nd : YAG laser (1064 nm) that generated series of 1 – 50 pulses, each having the duration 8 ns and energy 1 – 20 mJ, the diameter of the laser spot being 20, 400 and 1000 μm. This allowed performing the studies at radiation power densities, damaging, modifying and leaving the film unaffected, respectively. The change in the lens capsule transparency in the process of laser impact was assessed by comparing the powers of radiation incident on and paraxially transmitted through films clamped between two transparent glass plates using an IMO-2N energy meter (Russia). The morphometric study of the experimental samples of the eye lens capsule in the zone of exposure and their photographic recording was implemented using the Photomicroscope III (Opton, Germany) with the software – hardware system MEKOS-FDMM (MEKOS, Russia).

3. Results

The laser destruction of hard capsule samples (Fig. 2a) has led to the formation of point reach-through microscopic perforations with the diameter 40 ± 5 μm with radial rays (marked with solid arrows) against the background of the dark zone of non-through ablation of the posterior capsule. Large through perforations with the diameter 70 ± 10 μm appear as a result of merging a few microscopic holes (one of them pointed with a dashed arrow).

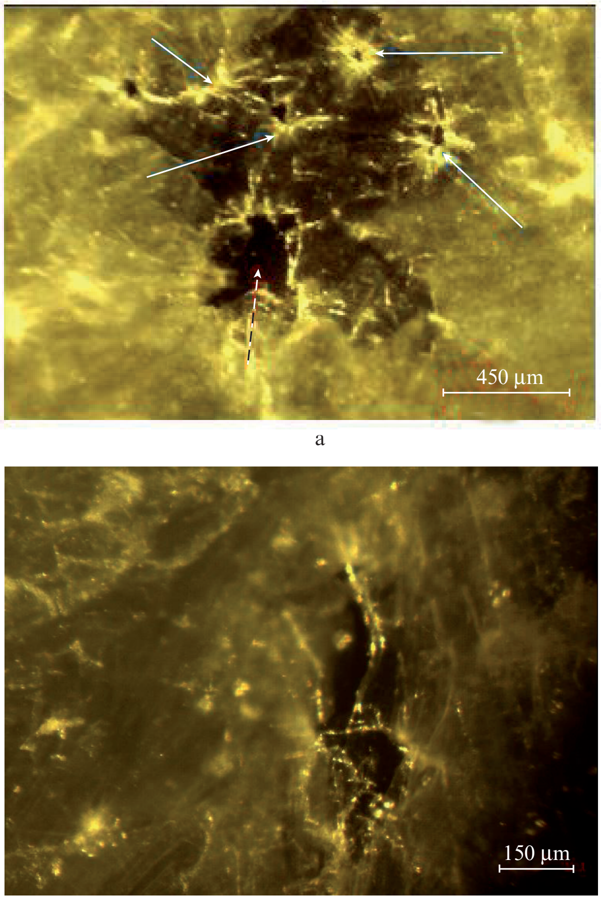
The laser destruction of a soft capsule is characterised by the presence of large defects of irregular shape, the dimension of which is by a few times larger than the defect size in hard films (Fig. 2b). The diameter of such defects amounts to 95 ± 30 μm, and the total damage extent in the zone of exposure approaches 160 ± 40 μm

The ablation zone was surrounded by a ring-shaped (with notched edges) zone of modified tissue, containing numerous bubbles of different size (Fig. 2b).

Under the exposure to tightly focused radiation (the spot diameter 20 μm) the threshold pulse energy for which the damage becomes open-end amounted to 2 mJ for a soft film and 3 mJ for a hard one.

Under the multi-pulse processing with radiation having the spot size 20 μm the total energy of destruction (the pulse energy multiplied by the number of pulses), necessary for the through puncture (ablation) of the film, was almost by an order of magnitude (by 6 – 9 times) higher for hard samples than for soft ones.

For weakly focused radiation with the spot diameter 1000 μm the increase in the pulse energy (from 50 to 100 mJ) did not affect the fraction of the transmitted light. For hard films the effective attenuation coefficient μ_{eff} amounted to 500 cm^{-1}, which is 500 times greater than the absorption coefficient for the wavelength 1.06 μm, so that the major contribution to the light intensity attenuation is caused by scattering of radiation rather than by its absorption. For soft films $\mu_{\text{eff}} = 2400$ cm^{-1}, which is nearly five times higher than in hard films, i.e., the scattering is even stronger (Table 1). The focusing of radiation into the spot with the diameter 400 μm increases the power density by 6.25 times. In this case every new pulse led to the fall of the transmitted light intensity, i.e., to the increase in scattering and μ_{eff}. For soft films μ_{eff} changed insignificantly at the beginning, but then, with the growing number of pulses, rapidly increased. For hard films the coefficient μ_{eff} almost linearly increased with the growing number of pulses, and after nearly ten pulses reached the values, typical for soft films (Fig. 3).



b

Figure 2. Microphotographs of (a) hard and (b) soft human eye lens capsule samples perforated by a series of Nd : YAG laser pulses.

Table 1. Experimental measurements of the transmitted light intensity and effective absorption coefficient for weakly focused radiation (the beam diameter 1000 μm).

Capsule sample	Energy/mJ	Transmitted energy/mJ	Film thickness/μm	μ_{eff}/cm^{-1}
Soft	100	7 ± 1	10.8	2338 ± 60
Hard	100	70 ± 5	4.1	512 ± 35

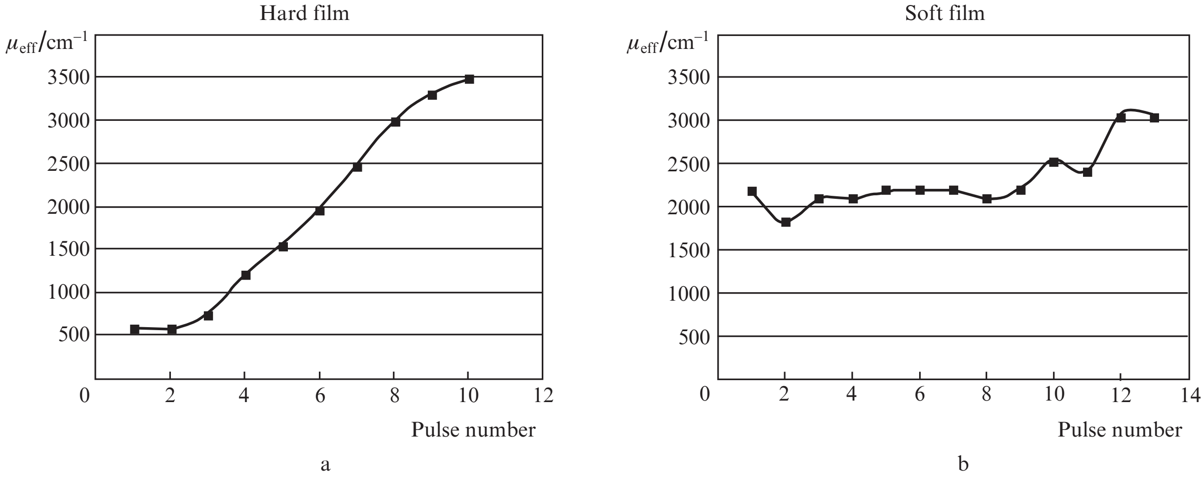


Figure 3. Effective absorption coefficient of (a) hard and (b) soft lens capsule films vs. the number of laser pulses with the beam diameter 400 μm.

4. Discussion

For laser radiation with the wavelength 1064 nm the coefficient of absorption by biological tissue amounts to nearly 1 cm^{-1} [13], which is by three order of magnitude smaller than μ_{eff} measured by us. So large values of μ_{eff} are, probably, due to the enhancement of light scattering by the formation of new scattering centres (bubbles and pores [14]).

In soft films the initial μ_{eff} is large because they possess a lot of inherent structure defects (bubbles and pores). With the growing number of pulses, μ_{eff} at first does not change and then, starting from a certain pulse, sharply increases. This may be due to the avalanche-like formation of bubbles and pores, particularly, in soft films, i.e., the material of smaller mechanical strength. For hard films the coefficient μ_{eff} is initially smaller, but with the growing number of pulses it linearly increases and reaches the level, characteristic for soft films. This allows the assumption that in the process of laser-induced structure modification in the hard film the scattering centres arise, analogous to those initially present in the soft film. The latter means that the laser radiation energy required for ablation of soft films is from five to ten times smaller than that required for destructing hard capsule samples. The light transmission for hard films is nearly five times higher than for soft ones. Therefore, for destructing a unit of volume of the hard film the required energy is nearly two–three times greater than for soft film, which may be due to the difference in structure and the ultimate stress of soft and hard films, as well as by the difference in ablation mechanisms.

Let us consider the possible mechanisms of laser-induced ablation of lens capsules with different types of opacification. A general review of physical processes of interaction of short laser pulses with matter, including the laser breakdown, plasma formation and the appropriate effects in solids, liquids and gases is presented in Refs [15, 16]. Among different laser-induced ablation mechanisms of biological tissues, described in Ref. [16], the possible candidates for eye lens membranes are the evaporation, the thermal expansion of overheated water and the pressure of gas bubbles (both of water vapours and of gas bubbles arising in the interstitial fluid due to the temperature dependence of the solubility of gases). At a short pulse duration (8 ns) many processes have no time to develop. In particular, gas bubbles have no time to grow and the water boiling does not occur, the thermomechanical stresses and acoustic waves having no time to cause destruction, since it needs greater time and often happens after the end of the first pulse [16].

Let us estimate the temperature attained under the action of a single laser pulse and the temperature of ablation for secondary cataract films.

Since the length of heat propagation is $(at)^{1/2} = (2 \times 10^{-3} \times 8 \times 10^{-9})^{1/2} = 4 \times 10^{-6}$ cm and the product $\mu_{eff}(at)^{1/2} = 10^{-2} \ll 1$, the change of temperature under the action of a single laser pulse is determined by the relation [16]

$$\Delta T = BE_p/hCS_0. \quad (1)$$

Here, a is the thermal diffusivity of water; t is the pulse duration; B is the fraction of absorbed (not transmitted through the film) radiation; E_p is the laser pulse energy; h is the film thickness; C is the heat capacity; and S_0 is the laser beam cross-section area.

In soft and hard films a reach-through defect was produced at $E_p = 2$ and 3 mJ, respectively, and ΔT was nearly 60 and 90 °C ($B = 5 \times 10^{-4}$, $C = 4.2$ J cm^{-3}, $S_0 = 4 \times 10^{-6}$ cm^2), so that the temperature T_a of the soft film ablation (provided that the initial eye temperature is 32–25 °C) amounts to 90 °C. The ultimate stress L_{st} for hard films is higher than for soft ones, i.e., they require heating to higher temperatures. In hard films the reach-through defects were obtained at $T_a = 120$ °C. At such temperatures after the end of the laser pulse the film destruction is possible due to both the pressure of escaping gases and the boiling of interstitial water and thermal expansion of overheated water.

The condition when the gas bubble pressure P_b or the pressure P_w caused by the thermal expansion of water becomes equal to the film material ultimate stress (nearly 60 and 20 MPa for hard and soft films, respectively) can be accepted as the destruction threshold condition.

According to Ref. [17],

$$P_b = P_0 \exp[-\sigma V_0/(Rk_B T)], \quad (2)$$

$$P_w = \alpha \Delta T E, \quad (3)$$

where σ is the surface tension; V_0 is the molecular gas volume; R is the bubble radius; α is the water thermal expansion coefficient; and E is the film material elastic modulus. It is known

[18] that as the temperature approaches 100 °C, the coefficient α sharply increases and significantly exceeds the thermal expansion coefficient for the collagen structure of the tissue, and at a certain temperature this may cause the membrane destruction.

The pressure estimates obtained using Eqns (2) and (3) at the temperature 90 and 120 °C, typical for the ablation of soft and hard films, respectively, allow the selection of the process providing a greater pressure and, thus, making a greater contribution to the destruction of films. The comparison shows that the pressure P_w arising due to the expansion of overheated water amounts to 25 MPa for soft films and 60 MPa for hard ones, which is by hundreds of times higher than the pressure in gas bubbles. Therefore, the thermal expansion of water should be recognised to be the dominant mechanism of film laser ablation. At the same time, the formation of gas bubbles also plays an important role. Under the action of several laser pulses the formation of gas bubbles (including the vapour ones) leads to a decrease in the film ultimate stress and to an increase in its effective absorption coefficient μ_{eff} and, therefore, the fraction B of radiation, not transmitted through the film.

To assess the energy capacity of destruction under the multi-pulse laser exposure let us use the energy balance equation

$$BE_pN = h(QS_a + C\Delta TS_T + \Omega S_m) + K. \quad (4)$$

Here, N is the number of pulses; Q is the energy capacity of ablation, defined as the energy required for increasing the thermal stresses up to the ultimate stress of the material L_{st}; S_a, S_T and S_m are the areas of film ablation, heating and modification, respectively; Ω is the energy capacity of tissue structural modification (which can be estimated as the work required for creating new bubble and pore surfaces [19]); $K = \frac{1}{2}mv^2$ is the kinetic energy of the destruction products; m is the mean mass of emerging particles; and v is the velocity of their motion. The values of S_a and S_m can be determined using the data of Table 2. The kinetic energy of destruction products that can move with high velocities and lead to complications after laser surgical operations is an excess energy. The estimate of the kinetic energy of the destruction products shows that for the regimes of laser impact commonly used in operations the excess energy can be as large as 60% of the total energy delivered to the tissue. The range of the destruction products spread can be as large as a few millimetres, which can cause distant destructions of the IOL, damages of the cornea, iris and peripheral regions of retina. This conclusion agrees with the data of Refs [1–6].

Since the kinetic energy of the spreading products of destruction is proportional to the square of their velocity, it is reasonable to reduce the energy of laser pulses, increasing their number if necessary, in order to reduce the probability of distant damages. For the removal of soft films it is reasonable after the first 8–12 pulses with the energy 2–3 mJ to reduce the energy of further pulses to 1–2 mJ, which will reduce the excess energy and the velocity of spreading destruction products. For dissecting hard films the first few laser pulses should have less sharp focusing (with the beam spot diameter 30–35 μm), the energy of the laser pulses being 4–5 mJ. The pores and bubbles arising in this process reduce the strength properties of the hard film, making them closer to those of a soft film, which provides the efficiency of further irradiation with the diameter of laser beam spot 20 μm. Then it is recommended to use the same parameters as for the soft films, i.e., after the first 8–12 pulses with the energy 2–3 mJ one should reduce the pulse energy to 1–2 mJ. The knowledge of ablation mechanisms in the posterior lens capsule is very important for practice, providing not only the correct selection of safe energy parameters of the laser radiation, but also the prognosis of the final result of intervention. Following the above recommendations will allow the laser ablation of pathological pupillary membranes with the minimal risk of complications.

Table 2. Characteristics of multi-pulse laser-induced ablation of eye capsule films.

Capsule sample	Pulse energy/mJ	Number of pulses	Diameter of the destructed region/μm	Diameter of the modified region/μm
Soft	3 ± 1	12	95 ± 30	160 ± 40
Hard	9 ± 2	30	40 ± 5	70 ± 10

5. Conclusions

1. The optical transmission of secondary cataract films of different types (soft and hard) is studied. It is shown that the effective coefficient of light absorption by pupillary membranes for the laser radiation at the wavelength 1064 nm is determined mainly by the processes of light scattering.

2. It is shown that the dominant mechanism of film ablation is the thermal expansion of overheated water, occurring after the end of laser pulses.

3. To reduce the probability of damaging the eye structures and tissues, it is reasonable to decrease the energy of laser pulses, and to correct the irradiation regime in the case of using a train of laser pulses, changing the beam spot diameter and the pulse energy.

References

1. Bol'shunov A.V. (Ed.) *Voprosy lazernoy oftalmologii* (Problems of Laser Ophthalmology) (Moscow: Aprel, 2013).
2. Zheltov G.I. In: *Voprosy lazernoy oftalmologii* (Problems of Laser Ophthalmology) (Moscow: Aprel, 2013).
3. Arestova N.N. *Avtoref. Dokt. Diss.* (Author's Abstract of the Doctor of Sci. Dissertation) (Moscow: Helmholtz Moscow Scientific Research Institute of Eye Diseases, 2009).
4. Gamidov A.A., Sonnovskii V.V., Boyev V.I., Buzykanova M.A. *Vestn. Oftalmol.*, (5), 28 (2006).
5. Gamidov A.A., Borodina N.V. *Tezisy nauch.-prakt. konf. 'Sovremennye metody diagnostiki i lecheinya zabolevaniy rogovitsy i sklery'* (Abstracts of Scientific and Practical Conference 'Modern Methods of Diagnostics and Treatment of Cornea and Sclera Diseases') (Moscow, 2007) Vol. 1, p. 217.
6. Gamidov A.A., Bolshunov A.V. In: *Voprosy lazernoy oftalmologii* (Problems of Laser Ophthalmology) (Moscow: Aprel, 2013) Ch. 9, p. 106.
7. Ivanov A.N. *Vestn. Oftalmol.*, (3), 13 (2002).
8. Krasnov M.M. *Vestn. Oftalmol.*, (1), 3 (1973).
9. Birngruber R., Hillencamp F., Gabel V.P. *Health Phys.*, **48** (6), 781 (1985).
10. Chofflet J., Amar J.P., Deidier D. *Fortschr. Ophthalmol.*, **88** (6), 806 (1991).
11. Fankhauser F., Kwasniewska S. *Laser in Ophthalmology. Basic, Diagnostic and Surgical Aspects* (Hague: Kugler Publ., 2003).
12. Katzen L.E., Flischman J.A., Trockel S.L. *Am. Intraocul. Implant. Soc. J.*, **9** (3), 148 (1983).

13. Popp J., Tuchin V.V., Chiou A., Heinemann S.H. (Eds) *Handbook of Biophotonics* (Weinheim: WILEY-VCH Verlag, 2012) Vol. 3.
14. Yuzhakov A.V., Sviridov A.P., Shcherbakov E.M., Baum O.I., Sobol' E.N. *Kvantovaya Elektron*., **44** (1), 65 (2014) [*Quantum Electron*., **44** (1), 65 (2014)].
15. Docchio F. *Laser Applications in Medicine and Biology* (New York: Plenum Press, 1991) Vol. 5, pp 85–140.
16. Sobol E.N. *Phase Transformations and Ablation in Laser-treated Solids* (New York: Wiley and Sons, 1995).
17. Babichev A.P., Babushkina N.A., Bratkovskii A.M., et al. *Fizicheskie velichiny* (Physcial Quantities) (Moscow, Energoatomizdat, 1991).
18. Kikoin I.K. *Tablitsy fizicheskikh velichin. Spravochnik* (Tables of Physical Quantities. A Handbook) (Moscow: Atomizdat, 1976).
19. Hirth J., Pound G. *Condensation and Evaporation: Nucleation and Growth Kinetics* (London: Pergamon, 1963; Moscow: Metallurgiya, 1966)].