ФІЗІКА

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INFLUENCE OF SELF-ABSORPTION OF 213 nm RADIATION ON LASER TREATMENT OF CORNEA

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The laser ablation efficiency of cornea at 213 nm radiation was investigated and optimized. It is shown that self-absorption of radiation at 213 nm in a thin cloud of ablated material takes place and strongly influences the ablation efficiency. Ablation products are being blown out in the lateral direction along the cornea surface, as a result of which the pulse fluence at the pit boundary F_{bnd} is more than the threshold fluence F_{th}. As a consequence, a pit radius r_{bnd} is less than a laser beam radius r_{th} corresponding to the threshold fluence F_{th} that should be taken into account in planning ablation surgery at 213 nm radiation.
Keywords: cornea, laser ablation, 213 nm, ablation threshold.

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САМОПОГЛОЩЕНИЕ ИЗЛУЧЕНИЯ НА ДЛИНЕ ВОЛНЫ 213 нм ПРИ ЛАЗЕРНОМ ВОЗДЕЙСТВИИ НА РОГОВИЦУ ГЛАЗА

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Исследована и оптимизирована эффективность лазерной абляции роговицы глаза УФ-излучением с длиной волны 213 нм. Показано, что самопоглощение лазерного излучения 213 нм в тонком облаке испаренного материала сильно влияет на эффективность абляции. Продукты абляции выбрасываются в боковом направлении вдоль поверхности роговицы, в результате чего плотность энергии импульса на границе абляционной лунки F_{bnd} выше, чем пороговая плотность энергии F_{th}. Как следствие, радиус лунки r_{bnd} меньше радиуса r_{th} лазерного луча, соответствующего пороговой плотности энергии импульса F_{th}, что необходимо учитывать при планировании абляционной хирургии глаза излучением 213 нм.
Ключевые слова: роговица глаза, лазерная абляция, 213 нм, порог абляции.

Introduction. In recent years, femtosecond lasers have attracted a lot of attention and in the first clinical applications in refractive and corneal surgery [1–3] much work has already been done with far UV excimer lasers at 193nm, e. g. in photorefractive keratectomy (PRK), Laser Epithelial Keratomileusis (LASEK), and Laser in Situ Keratomileusis (LASIK).

Due to the complexity and the cost of the lasers of these types, attention has also been focused on solid state lasers in the far UV range [4–7]. Currently the 5th harmonic (213 nm) of a Nd:YAG laser is also in use for LASIK and PRK.

During UV laser ablation cornea treatment, for the purposes of correction of eye vision a big spatially profiled volume of stroma is removed in accordance with a program allowing for the cornea ablation threshold F_{th}, the laser pulse energy, the pit radius r_{bnd}, and some other features. (F_{th} is the minimum laser beam intensity, for some pulse duration Δt and a number of N pulses per pit which stays an observable mark of damage at a cornea surface).

The present study is concerned with establishing some mechanisms of 213 nm laser ablation treatment of cornea by laser beams of small diameter and processes that influence the pit radius r_{bnd}.

Experimental. UV 213 nm cornea ablation investigations were carried out on a number of cuts made on freshly enucleated eyes at a constant depth of 260 μm to provide a flat surface of the 6–8 mm dia cornea (one eye gives one cut).

A laser setup for UV 213 nm cornea treatment is described in detail elsewhere in [8].

12 ablation pits were regularly done on the periphery of the round flat surface of a cornea slice to guarantee identical cornea ablation properties. Pits were treated in air at room temperature by N focused pulses in one spot with UV radiation of the fifth harmonic (213 nm) of the Nd:YAG laser with an energy of up to 15 mJ, a pulse duration of 10–15 ns, and a repetition rate of 1 Hz. For reproducibility of results, the enucleated eye was kept pressed at 26 mm Hg in a special holder, which allowed the flat surface of the cornea to be practically normal to the 213 nm laser beam (angle of not more than 5º).

A confocal Zeiss LSM 510 laser scanning microscope was used to determine a maximum pit depth H, a pit radius r_{bnd}, and a pit volume V_{exp}. The volume V_{exp} was calculated with the use of a specially developed program. A laser depth ablation rate $h = H/N$.

For each pit, the 213 nm laser pulse fluence $F_{213,max}$ in the pit center and the laser pulse fluence at the pit boundary F_{bnd} were determined from the experimentally measured energy E_{213} and the real laser beam distribution, which was close to the Gaussian distribution. In the experiment conducted, the Gaussian radius w_0 = 347 μm for the 213 nm laser beam. (For w_0, $F(w_0) = 1/e^2$).

A number of eyes were investigated under various conditions.

Results and discussion. Fig. 1 presents the typical one laser pulse ablation output V/NE and H/NE versus laser pulse energy E_{213} and laser pulse fluence $F_{213,max}$ in the pit center at $N = 40$ for one of the investigated eyes.

The optimum for the one laser pulse ablation output V/NE and H/NE lies in the range of $F_{213,max}$ from 0.2 to 0.4 J/cm^2. With increasing the laser pulse fluence within the range of 0.4–2.2 J/cm^2, V/NE and H/NE decrease.

Fig. 2 shows the typical $F_{213,max}$ dependence of the pulse fluence F_{bnd}, the optical densities $D_{bnd} = \lg(F_{bnd}/F_{th})$, and $D_0 = \lg(F_{213,max}/F_{th})$ of the ablated cloud of cornea material at the pit boundary and in the pit center, respectively, for one of the investigated eyes for $N = 40$.

The behavior is likely explained by self-absorption of 213 nm radiation in a thin cloud of the material removed. In the nanosecond range, the cloud of the removed practically undecomposed cornea material with high absorptance, mainly consisting of collagen and water vapor, appears at a forthcoming front of the laser pulse and effectively absorbs laser radiation at the backward front of the pulse.

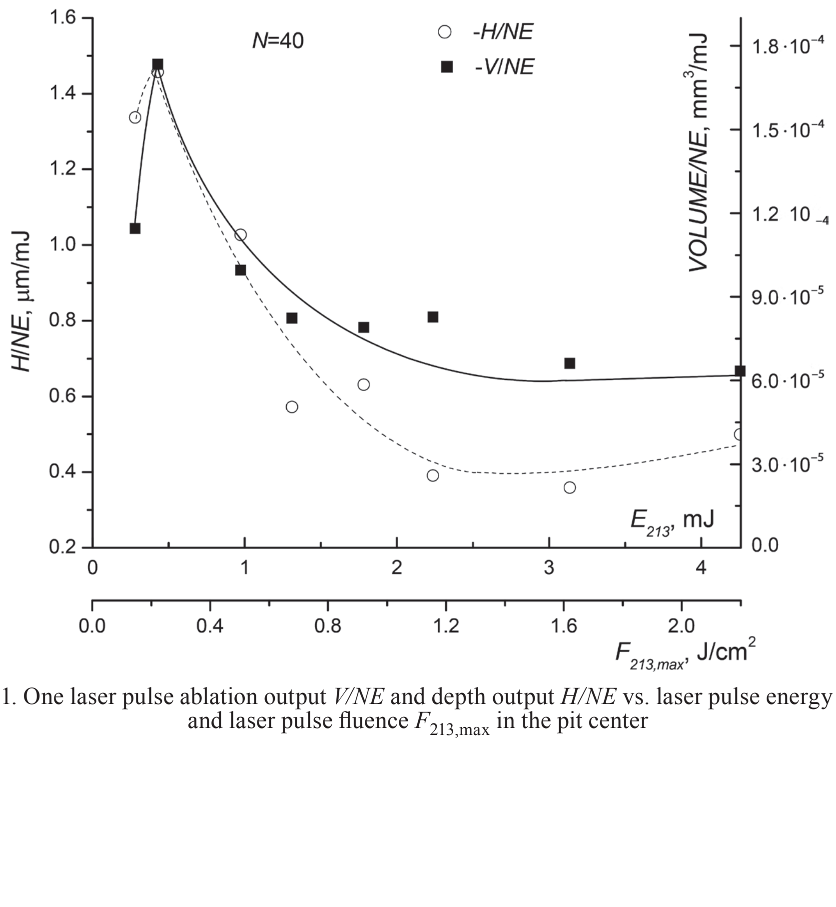

Fig. 1. One laser pulse ablation output V/NE and depth output H/NE vs. laser pulse energy E_{213} and laser pulse fluence $F_{213,max}$ in the pit center

The data obtained allow evaluating F_{th} in the absence of self-absorption. At the time, when a damage mark appears on the cornea only at the top of the laser beam distribution, no cloud exists, self-absorption is absent, and the minimum value of $F_{bnd} = F_{th} = F_{213,max}$.

To get F_{th} from the experimental data in Fig. 2, find the intersection of auxiliary dotted line 1 built at several initial points of the experimental dependence and auxiliary straight line $F_{th} = F_{213,max}$ built in Fig. 2. The intersection point gives the value of the threshold $F_{th} = F_{213,max}$ provided that no re-absorption takes place. Fig. 2 gives the value of F_{th} ~0.03–0.04 J/cm^2. F_{th} is an individual eye property.

Fig. 2 illustrates that D_{bnd} significantly increases from 0.2–0.4 to 1.0–1.2 for the range of $F_{213,max}$ = = 0.2–0.4 J/cm^2 to 1.7–2.2 J/cm^2.

In essence, D_0 and D_{bnd} represent h_0^{cl} and h_{bnd}^{cl}, respectively. They are the equivalent thicknesses of the cloud in the center and at the boundary of the pit normalized to the initial state of the cornea before treatment. A conclusion can be made that D_0/D_{bnd} smoothly decreases from a value of about 5 for $F_{213,max}$ = 0.2–0.4 J/cm^2 to 1.8–2.2 for the range of $F_{213,max}$ = 0.5–2.2 J/cm^2 . It is possible to say that at high fluencies the equivalent thickness of the cloud h_{bnd}^{cl} is approximately constant at the pit boundary. It is a result both of light self-absorption in the cloud and of sweeping off the evaporated material from the center of the laser beam to its periphery.

As a consequence, the pit radius r_{bnd} is less than the radius r_{th} of a laser beam with the threshold fluence F_{th}. This is illustrated in fig. 3 showing the dependences of r_{bnd} and r_{th} on $F_{213,max}$. It is seen that for the value of $F_{213,max}$ rather more than optimal, there is a significant difference between r_{th} and r_{bnd}.

The cloud ablation propagation velocity v_{cl} along the eye surface can be approximately estimated from the expression $v_{cl} = (r_{th} - r_{bnd})/\Delta t$ where Δt is the laser pulse duration.

Fig. 3 also depicts the dependence of v_{cl} on $F_{213,max}$ for Δt = 15 ns.

Fig. 3 shows that the cloud ablation propagation velocity v_{cl} along the eye surface can reach 2–12 km/c. First v_{cl} sharply increases and then is saturated with $F_{213,max}$. Assuming the stability of material absorptance ability in the cloud, for the material with high absorptance (10^3 cm^{-1} or more, as in the case of the cornea) a significant part of laser energy is absorbed in the cloud and less affects the material surface. As a very high pressure is realized in the cornea ablation zone, ablation products form a cloud, quickly propagating in all possible directions. The high cloud propagation velocity v_{cl} along the eye surface provides for a displacement of ablation products along the surface by 100–150 μm or more in the course of the laser pulse duration. For smaller laser spots and for longer laser pulses, the effect is more

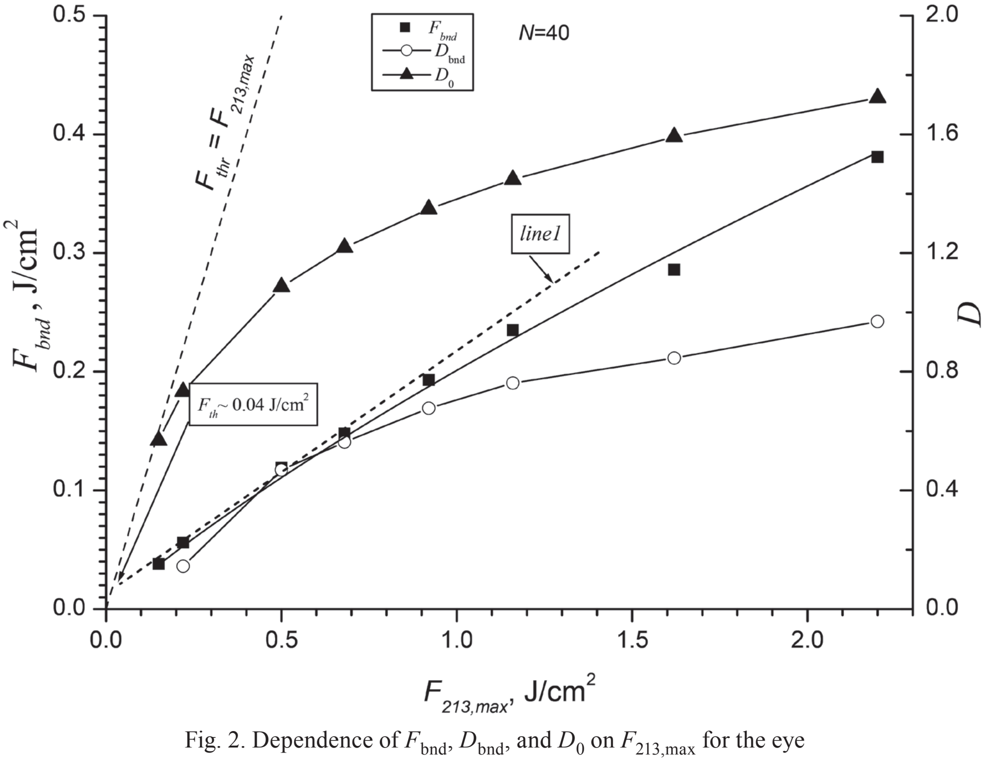

Fig. 2. Dependence of F_{bnd}, D_{bnd}, and D_0 on $F_{213,max}$ for the eye

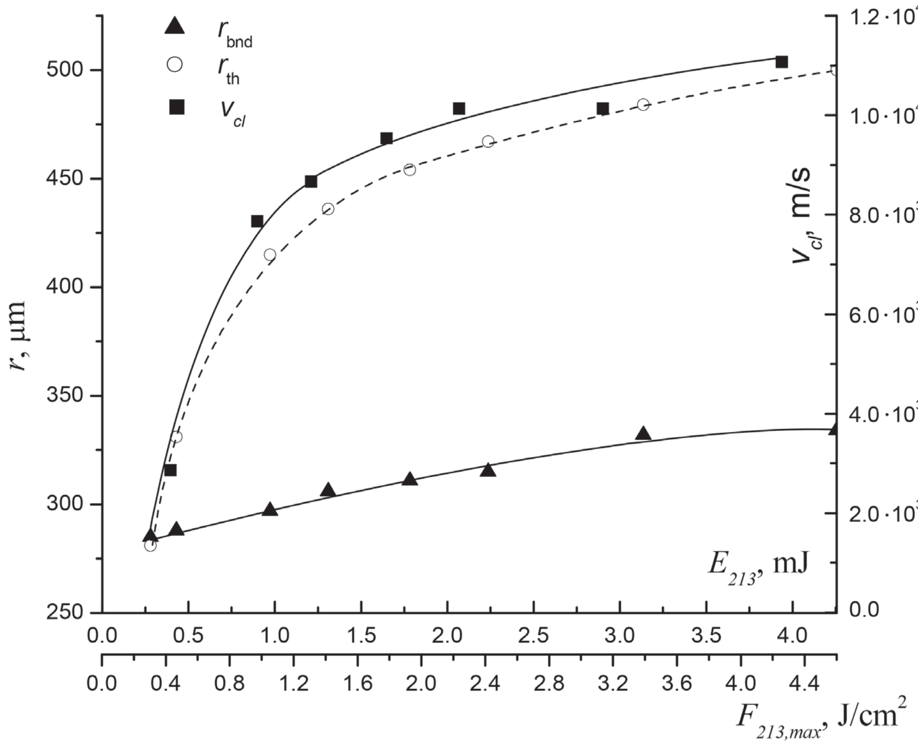

Fig. 3. The pit radius r_{bnd}, the radius r_{th} of a laser beam with the threshold fluence F_{th} , and the cloud ablation propagation velocity v_{cl} along the eye surface as a function of $F_{213,max}$

pronounced and should not be noticeable for femtosecond pulses. This mechanism effectively enhances F_{bnd} with increase in $F_{213,max}$. It is necessary to emphasize that the increase in F_{bnd} is connected with blowing out the ablation products in the lateral direction along the cornea surface.

For practical cornea laser ablation surgery, it is necessary to take into account that the value F_{th} defines a pit depth at given $F_{213,max}$, and the value F_{bnd} – an ablation pit size at the pit boundary. For example, fig. 3 shows that in the range of $F_{213,max}$ = 0.3–2.2 J/cm^2 , r_{bnd} changes in a rather narrow range of 270–320 μm, but at the same time r_{th} changes in a wider range of 270–520 μm. These considerations are substantial for the cornea ablation treatment technology by a laser beam of small radius.

Conclusion. The laser ablation efficiency of the cornea at 213 nm was investigated and optimized. It is shown that self-absorption of radiation at 213 nm in a thin cloud of ablated material takes place and strongly influences the ablation efficiency. Ablation products are being blown out in the lateral direction along the cornea surface. As a result, the pulse fluence at the pit boundary F_{bnd} is more than the threshold fluence F_{th}. As a consequence, the pit radius r_{bnd} is less than the radius r_{th} of a laser beam with the threshold fluence F_{th}, which should be taken into account while planning ablation surgery at 213 nm radiation.

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