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ESTIMATION OF CORNEA EFFECTIVE ABSORPTION COEFFICIENT AT 213 NM FROM ABLATION MEASUREMENTS

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It is shown experimentally that a cornea represents a 213 nm UV inhomogeneous material both at depth and around a surface in relation to UV effective absorption coefficient and local laser depth ablation rate, which should be taken into account for a more exact planning of a profile of removed cornea collagen material during eye vision correction.
Keywords: cornea, ablation, Nd: YAG laser, absorption, threshold.

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ОЦЕНКА ЭФФЕКТИВНОГО КОЭФФИЦИЕНТА ПОГЛОЩЕНИЯ РОГОВИЦЫ ГЛАЗА НА ДЛИНЕ ВОЛНЫ 213 НМ ИЗ АБЛЯЦИОННЫХ ИЗМЕРЕНИЙ

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Экспериментально показано, что роговица глаза для УФ-излучения (213 нм) представляет собой неоднородный материал как по глубине, так и вдоль поверхности, в отношении эффективного коэффициента поглощения и локальной скорости абляционного удаления материала роговицы, что необходимо учитывать для более точного планирования профиля удаляемого коллагена роговицы при операциях коррекции зрения.
Ключевые слова: роговица, абляция, Nd:YAG-лазер, поглощение, порог.

Introduction. Far UV excimer lasers at 193 nm have found wide use in refractive and corneal surgery e.g. in photorefractive keratectomy (PRK), Laser Epithelial Keratomileusis (LASEK) and Laser in Situ Keratomileusis (LASIK).

Due to the complexity and the cost of these-type lasers, attention has also been paid to solid state lasers in the far UV range [1, 2]. Currently, the 5th harmonic (213 nm) of an Nd: YAG laser is also employed for these purposes.

During UV laser ablation cornea treatment a large amount of spatially profiled stroma is removed in accordance with a program taking into account cornea features**.**

A cornea effective absorption coefficient K_{eff} at ablation wavelengths, also including light scattering, incubation and non-linear effects, is a feature that significantly affects the results of laser ablation surgery. Measurement results for the effective absorption coefficient K_{eff} in the UV range, corresponding to the most popular ablation wavelengths of 193 nm and 213 nm, are very contradicting and are in the range 2300–40000 cm^{-1} [3, 4]. Finally, the reason for such a big discrepancy is not clear, but it is most due to the fact that the optical methods for measuring the cornea absorption coefficient K_{eff} in the UV range use thin slices of cornea or homogenized cornea mass taken from different cornea places and give the K value averaged over a large cornea cross section and depth. Also, they do not include the incubation and non-linear effects that take place at cornea ablation. As a result, the traditional methods do not allow evaluating the distribution of the effective absorption coefficient K_{eff} at the cornea depth for real optimal experimental conditions.

The present study is focused on estimating a 213 nm cornea effective absorption coefficient K_{eff} and its 3D distribution using the ablation measurements. The dependence of a local laser depth ablation rate $h = H/N$ on the cornea depth is also analyzed.

Experimental. The UV 213 nm cornea ablation investigations were carried out on a number of freshly enucleated calf eye cuts at a constant cornea depth of 260 μm to provide a cornea flat surface with diameters of 6–8 mm.

The optical scheme of the laser ablation research setup is shown in Fig. 1. The laser setup is described in detail in [5].

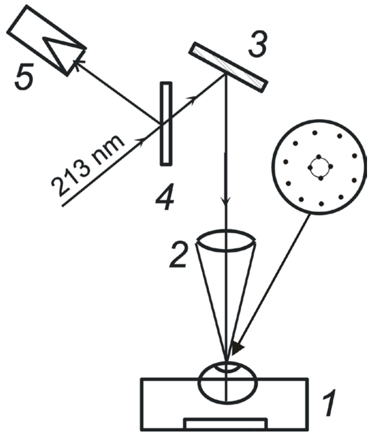

Fig. 1. Optical scheme of the laser ablation research setup: *1* – eye in the holder; *2* – focusing lens; *3* – deflecting mirror; *4* – reflecting quartz plate; *5* – energy meter

Ablation pits (Fig. 1) were regularly made on the periphery of the round flat surface of a cornea slice in effort to guarantee identical cornea ablation properties. Pits were also made on the inner radius. Pits were treated in the air at room temperature by focused N pulses on one spot with UV radiation (fifth harmonic of Nd: YAG laser, 213 nm) with a pulse duration of 10–15 ns and a repetition rate of 1 Hz. For reproducibility, the enucleated eye was kept pressed at 26 mmHg in a special holder that allowed the cornea flat surface to be practically normal to the 213 nm laser beam (the angle is not more than 5°).

A confocal Zeiss LSM 510 laser scanning microscope was used to determine a maximum pit depth H. The measuring accuracy of the pit depth was about ±3 μm.

For each pit, the 213 nm laser pulse fluence $F_{213,\max}$ in the pit center was determined from the experimentally measured energy E_{213} and the real laser beam distribution which was close to the Gaussian distribution. In the experiment, 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. For one of the eyes, Fig. 2 shows the dependence of the pit depth H on a number of N pulses at $F_{213,\max}$ =0.79 J/cm^2 (curve *1*). A number of pits were done on the periphery of an eye slice and 4 pits – on the inner radius of the circle (Fig. 1). These 4 pits give the points with * in the rectangle corresponding to the dependence of H on N.

Fig. 2 also illustrates the dependences of the average laser depth ablation rate $h_{av} = H/N$ (curve *2*) and the local laser depth ablation rate h_{loc} (curve *3*) on the pit depth H. To get a local laser depth ablation rate h_{loci} at some depth H_i, the next layer by layer procedure was used. For the first upper surface layer, $h_{loc1}(H_1) = H_1/N_1$, where H_1 is the depth of the first most shallow pit made by N_1 pulses. For the next layer, $h_{loc2}(H_2) = (H_2 - H_1)/(N_2 - N_1)$. For the *i*-th pit with the depth H_i made by N_i pulses, $h_{loc\_i}(H_i) = (H_i - H_{i-1})/(N_i - N_{i-1})$. We consider that all laser pulses have the same energy and the features of cornea material are axis-symmetric.

In Fig. 2, h_{loc} for the pits on the inner radius of the circle at N = 40 is shown as the points with * in the ellipse corresponding to the dependence of h on H.

It is seen from curve *2* (Fig. 2) that h_{av} lies within the range 1–2.5 μm, which is in a good agreement with [6, 7]. It has a maximum in the depth range 160–260 μm, which reaches 2.5 μm. Curve 3 for the local laser depth ablation rate h_{loc} demonstrates a much more distinct maximum which reaches 8 μm over the depth range 250–290 μm. The points in the ellipse are placed at a depth H of about 320 μm, which corresponds to the depth for the uncut eye. It is seen that h_{loc} for the pits on the inner radius of the circle good fit curve 3 at a depth of about 320 μm.

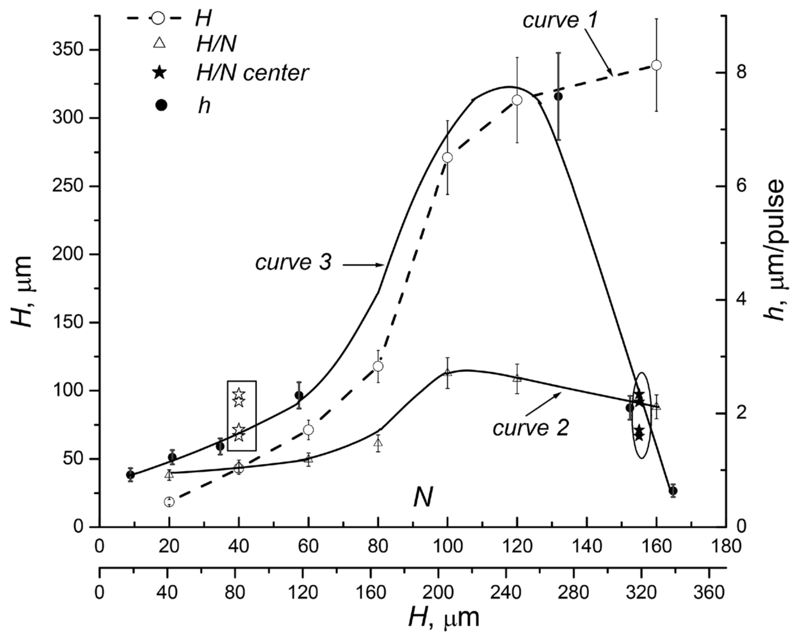

Fig. 2. Dependence of the pit depth H on a number of N pulses (curve *1*), dependences of the average laser depth ablation rate $h_{av} = H/N$ (curve *2*) and the local laser depth ablation rate h_{loc} (curve *3*) on the pit depth H at $F_{213,max} = 0.79$ J/cm^2

For each laser pit made at some depth in a homogeneous material, the effective absorption coefficient K_{eff}, which includes light scattering, incubation and non-linear effects, can be calculated in accordance with [8]:

$$K_{eff} = (1/h)\cdot\ln(F_{213,max}/F_{thr}). \tag{1}$$

Here $h = H/N$ is the ablation depth per one laser pulse.

For the pits shown in Fig. 2, to find the depth distribution, local $K^{loc}_{eff}(H_i)$ was calculated according to (2).

$$K^{loc}_{eff}(H_i) = [\ln (F_{213,max}{}^{i}/\mathrm{F}_{thr}{}^{i})]/h_{loc\_i}(H_i) = [\ln (F_{213,max}{}^{i}/\mathrm{F}_{thr}{}^{i})]/((H_i - H_{i-1})/(N_i - N_{i-1})). \tag{2}$$

Here i is the ordinal number of a pit on the periphery of the round flat surface of the cornea; $F_{213,max}{}^{i}$ is the laser beam fluence in the i-th pit center; $F_{thr}{}^{i}$ is the threshold laser pulse fluence for the i-th pit; H_i is the depth of the pit i, $H_0 = 0$; N_i is the number of laser pulses used to create the i-th pit, $N_0 = 0$. For all i $F_{213,max} = 0.79$ J/cm^2 and $F_{thr}{}^{i} = 0.04$ J/cm^2.

$K^{loc}_{eff}(H)$ was calculated layer by layer beginning from a minimum experimental depth. $K_{eff}(H_i)$ was considered to be constant in each i-th layer for all pits done on the periphery of an eye slice.

As a result, calculation gives a real profile of the effective absorption coefficient $K_{eff}(H)$ with depth.

Fig. 3 demonstrates the dependence of the effective absorption coefficient $K^{loc}_{eff}(H)$ on the pit depth given in Fig. 2. Fig. 3 also shows $K^{loc}_{eff}(H)$ for the pits on the inner radius of the circle (in the ellipse).

A total accuracy of h and $K^{loc}_{eff}(H)$ is evaluated to be about ±6÷10 %.

From Fig. 3 it is distinctly seen that $K^{loc}_{eff}(H)$ first smoothly decreases from approximately 32000 cm^{-1} at the cornea surface to approximately 7000–9000 cm^{-1} at a depth of 100–240 μm and then increases to approximately 50000 cm^{-1} at a depth of 300–340 μm. At the same time, $K^{loc}_{eff}(H)$ for the pits in the centre of the flap lies in the middle range 12000–18000 cm^{-1}.

The data show that $K^{loc}_{eff}(H)$ for the cornea is not uniform in volume.

It is most likely due to the next. As our cornea experiments show, the cornea represents a structure that consists of 20 % collagen with a very high absorption coefficient and of 80 % water with a low absorption coefficient of about 0.12–0.15 cm^{-1}, which may be neglected. Collagen is distributed hetero-

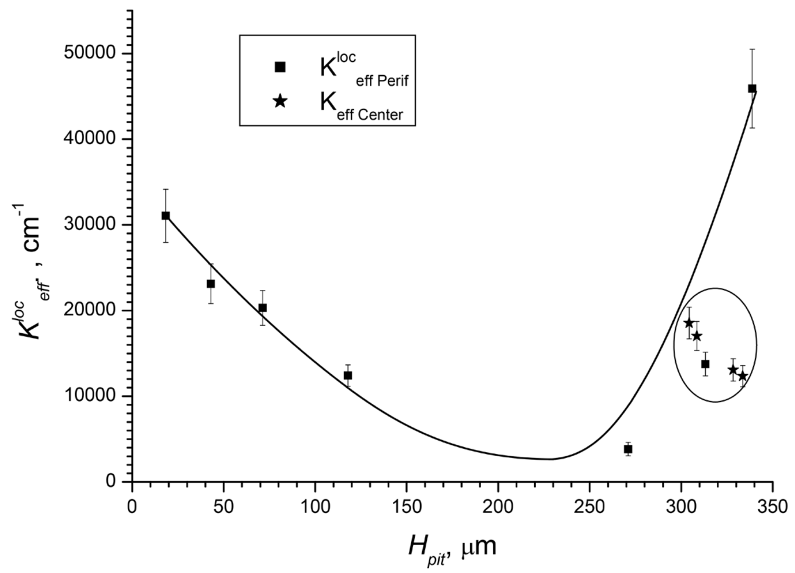

Fig. 3. Effective absorption coefficient $K^{\mathrm{loc}}{}_{eff}(H)$ as a function of pit depth H on the periphery and for the pits on the inner radius of the circle (in the ellipse)

geneously in the cornea. Superficial cornea layers are more dense and strong due to a higher content of collagen, and in the cornea inner layers the content of collagen is less, which is reflected in the $K^{\mathrm{loc}}{}_{eff}(H)$ dependence.

Conclusions. It is shown experimentally that a cornea represents an UV inhomogeneous material both at depth and around a surface due to the UV effective absorption coefficient and the local laser depth ablation rate. The fact should be taken into account for a more exact planning of a profile of the cornea removed collagen material during of eye vision correction.

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