УДК 535.21;535.3

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COMBINED 213 nm+1444 nm LASER ABLATION TREATMENT OF BOVINE CORNEA

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The laser ablation efficiency of eye cornea for UV (213 nm) and combined IR+UV (213 nm + 1444 nm) ablation treatment in safe conditions, preventing laser coagulation at 1444 nm, was investigated. It is shown that the IR+UV combination, when, at the first stage of cornea treatment, an IR laser pulse at 1444 nm, falling into a water absorption band with an absorption coefficient of about 31 cm^{-1}, dehydrates a superficial corneal layer and at the second stage, in about 100 μs, a UV laser pulse at 213 nm ablates a thin (about 1–3 μm) collagen layer, gives promising results. Due to the controlled dehydration of the corneal surface, the process of 213 nm + 1444 nm laser ablation ensures a better reproducibility and a higher productivity.

Keywords: cornea, ablation, Nd:YAG laser, absorption, threshold.

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ЛАЗЕРНАЯ АБЛЯЦИОННАЯ ОБРАБОТКА РОГОВИЦЫ ГЛАЗА КОМБИНИРОВАННЫМ ИЗЛУЧЕНИЕМ 213+1440 нм

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Исследована эффективность лазерной абляции роговицы глаза УФ-излучением (213 нм) и комбинированным УФ+ИК-излучением (213 нм + 1444 нм) в условиях обработки, когда лазерная коагуляция на длине волны 1444 нм не происходит. Показано, что комбинированное УФ+ИК-воздействие, когда сначала ИК-лазерный импульс (1440 нм), попадающий в полосу поглощения воды с коэффициентом поглощения около 31 см$^{-1}$, обезвоживает поверхностный слой роговицы и следующий через ~100 мкс УФ-лазерный импульс (213 нм) удаляет тонкий поверхностный слой (1–3 мкм) коллагена, дает многообещающие результаты. Благодаря контролируемому обезвоживанию поверхности роговицы процесс лазерной абляции комбинированным (213 нм + 1444 нм) излучением обеспечивает лучшую воспроизводимость и более высокую производительность.

Ключевые слова: роговица, абляция, Nd:YAG-лазер, поглощение, порог.

Introduction. In recent years, femtosecond lasers found great attention and first clinical applications in refractive and corneal surgery [1–3] after much work had already been done with far UV excimer lasers at 193 nm, 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 [4–7]. Currently, the 5th harmonic (213 nm) of Nd:YAG laser is also used for LASIK and PRK.

During UV laser ablation cornea treatment for purposes of eye vision correction a big spatially profiled volume of stroma is removed in accordance with a program taking into account cornea features.

For improvement of UV laser ablation cornea treatment technology for purposes of eye vision correction an idea of combined laser UV+IR cornea treatment [8] seems to be perspective. The key idea of combined UV (213 nm) and IR radiation cornea ablation treatment in the nanosecond technology consists in organizing conditions of "dry" or "dehydrated" ablation of human tissues (e.g. cornea) in naturally wet environment by taking a special succession of used laser beams of different wavelengths, in which at the first stage of cornea treatment a surface of cornea tissue is treated with IR radiation, which falls in one of IR strong bands of water absorption and dehydrates a superficial layer of tissue, and at the second stage a thin (about 1-3 μm) layer of cornea collagen is ablated with UV (for example, 213 nm) radiation. As a sequence, an improvement of medical results of cornea ablation treatment should take place, as it goes under controlled superficial cornea layer wetness conditions.

The present study is focused on comparing the ablation efficiency and reproducibility of 213 nm and combined 213 nm + 1444 nm laser radiation treatment of cornea. 1444 nm laser radiation is taken as an example to show a positive potential of the combined UV-IR laser treatment.

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

Water represents about 80 % of cornea content, as additional measurements show. For the physiological solution (0.9 % NaCl in water) and water, in the 1360–1600 nm spectral range absorptance reaches 31 cm^{-1} at 1444 nm, which is an effective laser line for the Nd:YAG laser, and well complies to the idea of a combined laser wavelengths cornea treatment. Usage of 1444 nm laser line allows one to increase a temperature of a surface corneal layer due to water absorptance and to dehydrate the corneal surface.

In fig. 1 the scheme for combined cornea treatment with UV 213 nm and IR 1444 nm radiation is shown. The optical scheme of the 213 nm laser setup is detailed in [9]. The 1444 nm laser is described in [10].

The approximate laser ablation pits topology for an eye is shown in fig. 2. Ablation pits were regularly done on the periphery of the round flat surface to guarantee identical cornea ablation properties.

At the flat surface of each eye, an even number of pits, treated only with 213 nm and with combination of 213 nm and 1444 nm, were done. Each pit was treated in air at room temperature (20–25 ºC) by *N* focused pulses on one spot of the fifth-harmonic Nd:YAG laser (213 nm, pulse duration of about 10 ns) or with a combination of 213 nm and 1444 nm at a 1 Hz repetition rate.

To guarantee safe conditions of 1444 nm laser treatment, it was preliminarily controlled in the real experimental condition of no cornea coagulation. At a 1 Hz repetition rate of 1444 nm radiation, which was used during the experimental investigation, the appearance of small pits, without some damage of cornea, which disappeared in several minutes after finishing the experiment, was tolerated. The appearance

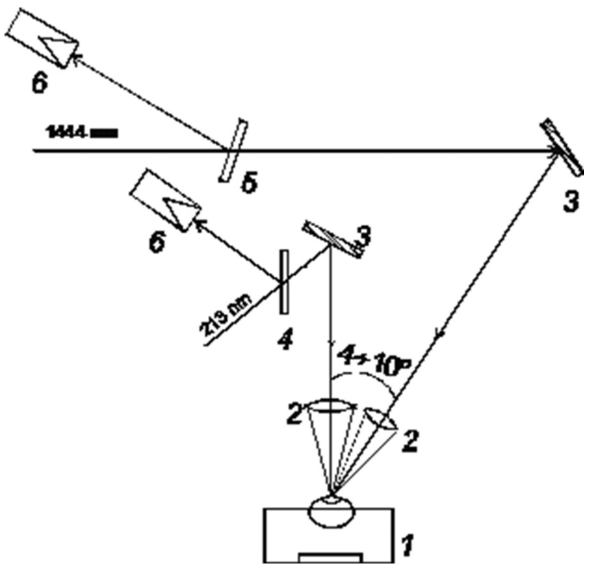

Fig. 1. Optical scheme of the laser ablation research setup:
1 – eye in a holder; *2* – focusing lens; *3* – deflecting mirrors; *4, 5* – reflecting glass (quartz) plates; *6* – energy meters

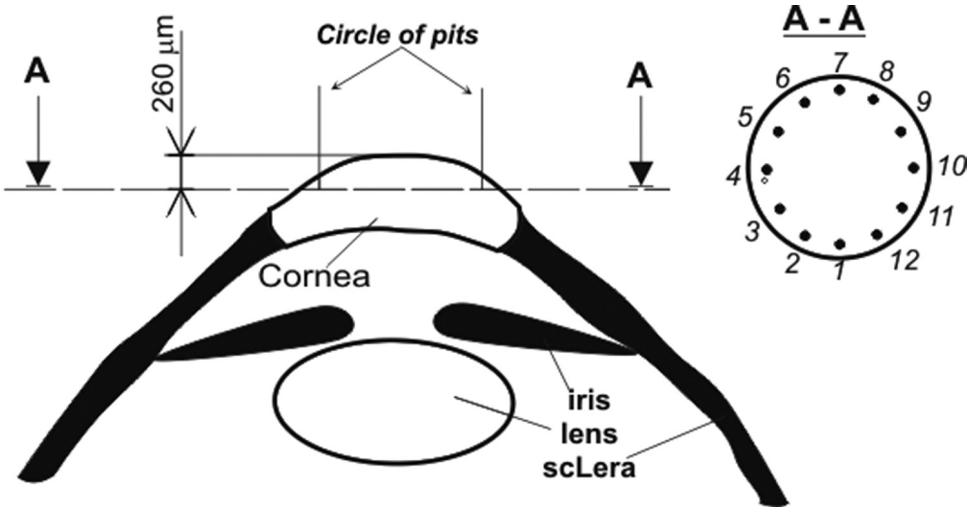

Fig. 2. Approximate pits topology for an eye

of such pits signalizes the dehydration of the corneal layer due to 1444 laser radiation heating. It is necessary to emphasize that the mechanism of dehydration may be rather complicated and include, for example, direct water vaporization from corneal surface and/or water micro circulation in inner heated corneal layers. The establishment of an exact mechanism of cornea dehydration requires further study.

A confocal Zeiss LSM 510 laser scanning microscope was used to determine the maximum pit depth H. A laser depth ablation rate $h = H/N$.

At each pit center, the 213 nm laser pulse fluence $F_{213,\max}$ and 1444 nm laser pulse fluence $F_{1444,\max}$ were determined from the experimentally measured energies E_{213} and E_{1444} and the real laser beam distributions that were close to Gaussian distributions. In the experiment, the Gaussian radius $w_0 = 347$ μm for the 213 nm laser beam. (For w_0 $F(w_0) = 1/e^2$). Cross-sectional fluence distributions for laser beams were made in such a manner that the 1444 nm cross-sectional fluence distribution well overlapped the 213 nm one.

At the pit center, the 213 nm laser pulse fluence $F_{213,\max} = 0.65$ J/cm^2 and the 1444 nm laser pulse fluence $F_{1444,\max} = 4$ J/cm^2. The 1444 nm pulse duration was about 70 microseconds (“pike” regime of generation). During a combined 213 nm + 1444 nm treatment, first, 1444 nm radiation occurs and then, with a delay of about 100 μs 213 nm radiation.

For reproducibility, the enucleated eye was kept pressed at 26 mmHg in a special holder, which allowed the flat corneal surface to be practically normal to the 213 nm laser beam (at an angle of not more than 5°).

A number of eyes were investigated under various conditions.

For a combined 213 nm + 1444 nm laser radiation treatment of the cornea, the cornea temperature rise ΔT_L at a depth L for 1444 nm radiation was approximately estimated using the Bouger law for laser fluencies and neglecting thermal conductivity during a short laser pulse by the expression:

$$\Delta T_L = kF_{1444,\max}\cdot\Delta t\exp(-kL)/\rho C,$$

where $F_{1444,\max}$ is the laser fluence at the corneal surface; Δt the laser pulse duration; k the corneal absorptance for IR (1444 nm) radiation; c the specific heat of the cornea taken approximately equal to that of water 4.18 J/g °C, ρ the cornea density taken approximately equal to that of water, 1 g/cm^3.

Estimations show that ΔT_L reaches approximately 30 °C at the corneal surface and 90 % of 1444 nm radiation energy is absorbed at a depth of 700 μm, and at a depth of 220 μm the laser fluence decreases approximately by 50 %. It is necessary to keep in mind that the IR (1444 nm) radiation fluence yields a corneal surface temperature of about 50–55 °C, which is lower than the cornea proteins temperature coagulation threshold. Experimental investigations of the cornea coagulation threshold showed that for 1444 nm radiation single pulses with an approximately 70 μs duration the coagulation threshold corresponds to about 7–9 J/cm^2.

Results and discussion. Table contains the data for 213 nm and combined 213 nm + 1440 nm treatment. For each eye, 4–6 pits were done with 213 nm and the same number of pits was done with combined 213 nm + 1440 nm. Statistics was investigated at approximately constant 213 nm ($F_{213,max}$ = 0.65 J/cm^2, which is close to optimal) and at 1444 nm ($F_{1444,max}$ = 4 J/cm^2, which does not provide cornea coagulation during the treatment) pulse energy and N = 50. Table contains the experimental and calculated data only for a group of 8 eyes that were treated in one day.

Experimental and calculated data for 213 nm and combined 213 nm + 1440 nm laser treatment

Number	*h-ave*, μm	*h-std*, %	$F_{1444,max}$, J/cm^2
eye 1	1.43 1.29	6.3 10.7	4 0
eye 2	1.90 1.75	10.9 9.4	4 0
eye 3	1.94 1.54	4.6 25.2	4 0
eye 4	1.90 1.42	14.4 11.4	4 0
eye 5	1.56 1.55	12.4 12.2	4 0
eye 6	1.53 1.51	7.5 14.3	4 0
eye 7	1.92 1.79	11.3 11.8	4 0
eye 8	1.93 1.57	9.1 10.1	4 0

Separately, for the 213 nm and 213+1444 nm treatment, for each eye, the simple mean for *h, h-ave* and the standard deviation *h-std* are calculated and are shown in Table.

In all cases, for the average depth *h-ave,* the combined 213 nm + 1444 nm treatment gives a more productive removal of the cornea than the pure 213 nm treatment, which is, most of all, connected with less specific heat of the dehydrated cornea. It is supposed that it would be rather difficult to substantially increase *h-ave* due to additional dehydration at higher $F_{1444,max}$ over a risk of cornea coagulation. A standard deviation *h-std* for the combined 213 nm + 1444 nm treatment substantially decreases in most of the cases. In some cases, the standard deviation *h-std* is the same or a little higher than the one the for 213 nm treatment.

Investigations showed that the IR-UV combination, when, at the first stage of cornea treatment, an IR laser pulse at 1444 nm, falling into a water absorption band with an absorption coefficient of about 31 cm^{-1}, dehydrates the superficial layer of cornea and at the second stage, in about 100 μs, a UV laser pulse at 213 nm ablates a thin (about 1–3 μm) layer of collagen, gives promising results. Due to the controlled dehydration of the corneal surface, the process of 213 nm laser ablation ensures a better reproducibility of results and a higher productivity.

It is safe to assume that the effect is much more pronounced for the combination of UV and IR laser radiation at 1930 nm corresponding to a water absorptance of 130 cm^{-1}. And most interesting and intriguing would be the combination of UV and IR laser radiation taken from the 2750–3000 nm range where the water absorption coefficient reaches 10 000 cm^{-1}.

Conclusions. The laser ablation efficiency of the cornea for UV (213 nm) and combined IR+UV (213 nm + 1444 nm) ablation treatment in safe conditions, preventing the laser coagulation at 1444 nm, was investigated. Investigations showed that the IR-UV combination, when, at the first stage of cornea treatment, an IR laser pulse at 1444 nm, falling into a water absorption band with an absorption coefficient of about 31 cm^{-1}, dehydrates the superficial layer of the cornea and at the second stage, in about 100 μs, a UV laser pulse at 213 nm ablates a thin (about 1-3 μm) layer of collagen, gives promising results. Due to the controlled dehydration of the corneal surface, the process of 213 nm + 1444 nm laser ablation ensures a better reproducibility and a higher productivity. It is shown that in the case of combined 213 nm + 1444 nm treatment the reproducibility of results is better twice or more than in the case of 213 nm ablation for some eyes.

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Поступила в редакцию 01.10.2015