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Correction of eye refraction by nonablative laser action on thermomechanical properties of cornea and sclera

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***Abstract*. A new approach is proposed for correcting the eye refraction by controlled variation of the mechanical properties of the sclera and cornea upon nondestructive laser heating. Experimental *ex vivo* studies of rabbit and pig eyes show that laser-induced local denaturation of the sclera changes the refraction of the cornea by 3 diopters on the average, and the subsequent nondestructive irradiation of the cornea increases its plasticity, which leads to a further increase in its radius of curvature and a decrease in refraction by 7 diopters.**

Keywords: *eye refraction, laser thermoplastics, cornea, sclera, mechanical properties of a biological tissue.*

1. Introduction

Lasers have been used widely for many years now for correcting the anomalies of vision. Excimer lasers, which are used for a high-precision ablation and shaping of the cornea, have received wide recognition in ophthalmology during the last two decades [1 – 3]. However, considerable post-operational complications are encountered in some cases, because the object of direct laser irradiation is the optical region of the cornea [3 – 7]. In this context, the development of new noninvasive and efficient technologies for laser refractive surgery seems to be a very important problem.

Attempts to change the eye refraction by nonablative local denaturation of the cornea by IR laser radiation [8 – 12] showed that it is possible to decrease to some extent the radius of curvature of the cornea, but the magnitude of this effect could not be controlled; in addition, denaturation of the cornea also led to post-operative complications. The logic of the development of new techniques called for a rejection of harmful irradiation of the cornea. The changes in the eye refraction caused by exposing the sclera to CO_2 laser radiation were mentioned in Ref. [13], but serious damage to the eye tissues was observed in this case.

Our earlier studies showed that local modification of the sclera caused by 1.56-μm cw laser irradiation resulting in a change in the eye refraction by several diopters [14 – 15]. An analysis of the morphological changes in the sclera during nonablative laser action revealed that the structure of the sclera in the region adjoining the cornea could be modified by low-traumatic laser radiation, which can deform the corneal surface without damaging it [16]. The aim of this work is to study the laser-induced variations in the thermomechanical properties of cornea and sclera using the techniques developed for nonablative laser correction of the eye refraction.

2. Materials and methods

Experiments were performed *ex vivo* with the eyes of pigs, rabbits and human donors, as well as *in vitro* with isolated samples of sclera and cornea tissues. Radiation from a 1.56-μm, 0.3 – 3.0-W erbium-doped fibre laser (IRE – 'Polyus' group, Russia) was used. The effect of laser radiation on the mechanical properties of cornea and sclera (experiments were performed with pig's eyes) was estimated from a change in the elastic modulus (Young's modulus). The surface deformation produced by a spherical indenter of diameter 1.5 mm pressed in the tissue before laser irradiation, during irradiation, and after irradiation was determined by measuring the diameter $d = 2r$ of the indentation and its depth h for a constant applied force F (Fig. 1). The elastic modulus E was calculated from the known dependence of the indentation radius r on the force F,

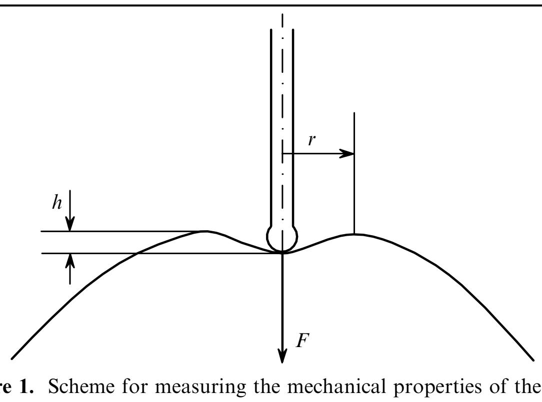

Figure 1. Scheme for measuring the mechanical properties of the sclera and cornea during laser irradiation.

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$$r \approx \frac{2R}{3h}\left(\frac{F}{E}\right)^{1/2}, \tag{1}$$

where E is the compression modulus and R is the radius of the eyeball. The diameter of the indentation was measured from the geometrical parameters of the optical flash observed upon an oblique illumination of the indentation. The kinetics of variations was recorded with a video camera.

The plastic properties of the cornea and the sclera during traditional (nonlaser) heating were studied by using a TMA METTLER TA4000 thermomechanical analyser. The tissue sample in the form of a circular plate of thickness 0.8 mm and diameter 4 mm was heated at the rate of 10 °C min^{-1} under a load 0.005 N.

The deformation (variation in the radius of curvature of the surface) of the cornea was studied by exposing the sclera and cornea of rabbit and human donor eyes to laser radiation. The eye being tested was mounted on a horizontal platform with the pupil facing upwards. The cornea was moistened occasionally by a physiological saline solution with the help of a pipet. Irradiation was performed in two stages: a point-to-point irradiation of the sclera at a distance of 1 – 2 mm from the limb by 1.5-W radiation (75 W cm^{-2}), followed by 0.3-W irradiation (15 W cm^{-2}) of the corneal region adjoining the limb (Fig. 2a). The radius of curvature of the cornea was determined by the geometrical optics methods (Fig. 2b). A grid with spacing $a_1 = 0.75$ mm, illuminated by a parallel beam from a diode laser, was mounted at the input plane of the optical system. The magnified image of the grid at the output of the optical system was recorded in the plane of the screen with a digital camera. After image processing by superimposition of a calibrated ruler, the enlarged grid spacing a_2, and consequently, the magnification of the optical system in which the cornea of the eye served as a convex spherical mirror, was determined. A positive lens in the optical scheme formed a light spot of size 2.5×1.2 mm on the surface of the cornea confined within the pupil (the central region of diameter 3 – 4 mm in the cornea is known to be a spherical surface). All these measures made it possible to perform calculations in the geometrical optics approximation to a high degree of accuracy.

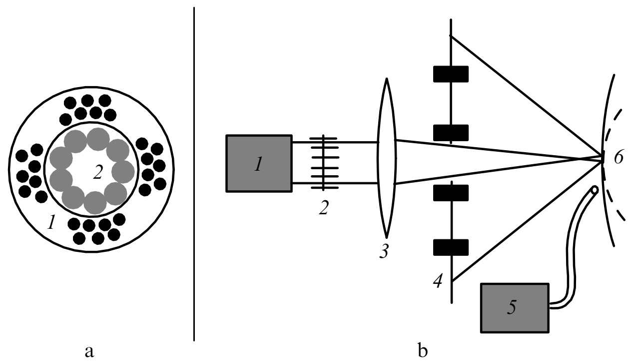

Figure 2. Variation in the curvature of the eye cornea upon successive laser irradiation of sclera and cornea; (a) scheme of irradiation of the eye: [(*1*) sclera; (*2*) cornea; the irradiated areas are marked by circles]; (b) scheme of measurements: (*1*) light source; (*2*) grid with a step 0.75 mm; (*3*) lens; (*4*) magnified image of the grid on the screen; (*5*) erbium-doped fibre laser; (*6*) corneal surface, the dashed curve shows the initial shape of the corneal surface.

3. Results and discussion

3.1 Thermomechanical properties of sclera and cornea irradiated by a laser

Our study showed that for $R \approx 1.5$ cm, $h \approx 0.5$ mm, and $F = 6$ G, the Young modulus $E \approx 2.4$ MPa of the cornea agrees with the available value [17] and does not vary upon 10-W laser irradiation for 0.2 s (power density 25 W cm^{-2}), which did not cause any appreciable damage of the eye tissues. However, laser heating may lead to short-term variations in the mechanical properties of the eye, which can be observed only during laser irradiation.

Short-term variations in the mechanical properties of the cornea during laser irradiation were analysed by measuring the diameter of the indentation under a constant force. The results of our measurements showed that for a moderate intensity of laser radiation (60 W cm^{-2}), the diameter of the indentation decreased after 10 s, probably due to denaturation of the components of the biological tissue. For a low intensity of laser radiation (7.5 W cm^{-2}), the diameter of the indentation increased (Fig. 3), suggesting an increase in the plasticity of the cornea. An analogous increase in the plasticity of the biological tissue caused by a brief heating of cartilage was used earlier in a new method of laser reshaping of the deformed cartilage [18]. The indentation diameter in the sclera decreased for all laser radiation powers used (from 0.2 to 3.0 W), i.e., the sclera tissue was hardened.

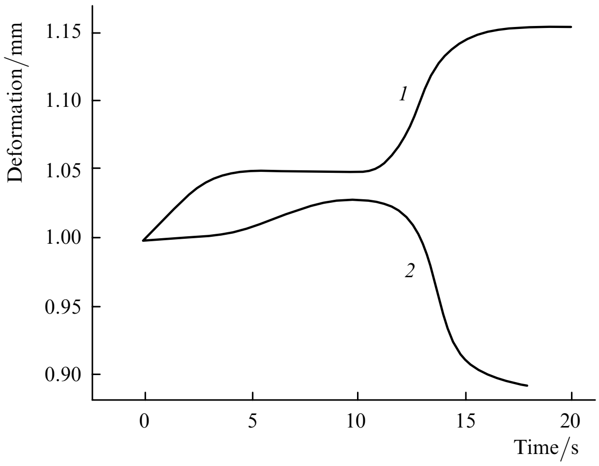

Figure 3. Dependence of the diameter of an indentation, formed on the cornea surface by the indenter, on the laser irradiation time: laser radiation intensity is (*1*) 7.5 W cm^{-2}; and (*2*) – 60 W cm^{-2}.

The change in the position z of the surface observed during conventional heating of the cornea and sclera to 66 °C suggests that the plasticity of the tissue increases in this temperature range. The sign of the derivative dz/dT changes at a temperature about 60 °C, which corresponds to the temperature at which the indentation radius increased (Fig. 3). A sharp increase of z was observed at temperatures about 70 °C, indicating a decrease in the plasticity of the cornea due to its denaturation (Fig. 4). The study of the eyes of pigs, rabbits and human donors showed that the thermomechanical properties of the eye tissues are universal (the difference in the characteristic temperatures does not exceed 15%).

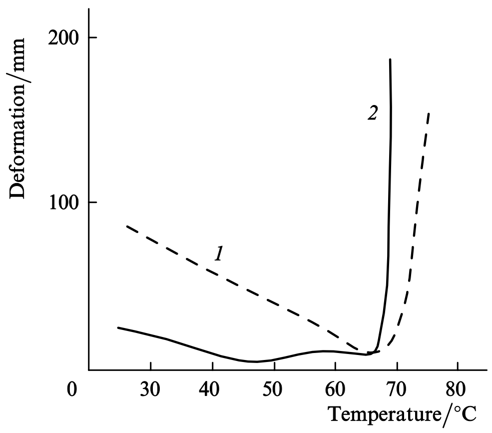

Figure 4. Temperature dependence of the indentation depth z in the cornea (*1*) and sclera (*2*) upon conventional (non-laser) heating.

Thus, a moderate heating of the cornea increases its plasticity, while a more intense heating leads to its hardening. The plasticity of the sclera does not change after laser irradiation. Heating of the sclera causes its shrinking resulting in additional tensions in the eye structures. The difference in thermomechanical properties of the sclera and the cornea can be explained by the peculiarities of their macroscopic and microscopic structures, which is manifested not only in a significant difference in the diameters of collagen fibrils, but also in their spatial organisation [19]. The appearance of tensile forces in the sclera accompanied by an increase in the plasticity of the cornea can be used to control changes in the corneal curvature.

3.2 Variation of the radius of curvature of the cornea by successive laser irradiation of sclera and cornea

Images of the grid mesh in the screen plane obtained before and after laser irradiation (Fig. 5) show the variation of the mesh spacing in the grid during laser irradiation of the eyes of rabbits and human donors. The radius of curvature R_c of the central region of cornea was calculated from the mesh spacing (Fig. 5) by the expression

$$A = (1 + L_2 P_c)(1 - L_1 P_{len}) - L_2 P_{len}, \quad (2)$$

where $A = a_2/a_1$ is the magnification of the system; $P_c = 2/R_c$ is the optical power of the cornea; $P_{len} = 1/f$ is the optical power of the lens; L_1 and L_2 are the distances between the lens and the corneal surface and between the corneal surface and the screen, respectively.

Our experiments showed that the radius of curvature of the eye cornea increased on the average by 0.4 mm after irradiation of the sclera, and by another 0.7 mm after subsequent irradiation of the cornea (when the cornea plasticity increased). As a result, the overall variation in the radius of curvature of the cornea amounts to 1.1 mm, which corresponds to a variation in the eye refraction by 7 diopters (in ophthalmology, the curvature of the cornea surface is expressed in keratometric diopters $K = 337.5/R_c$, where the radius of curvature of the cornea is measured in mm).

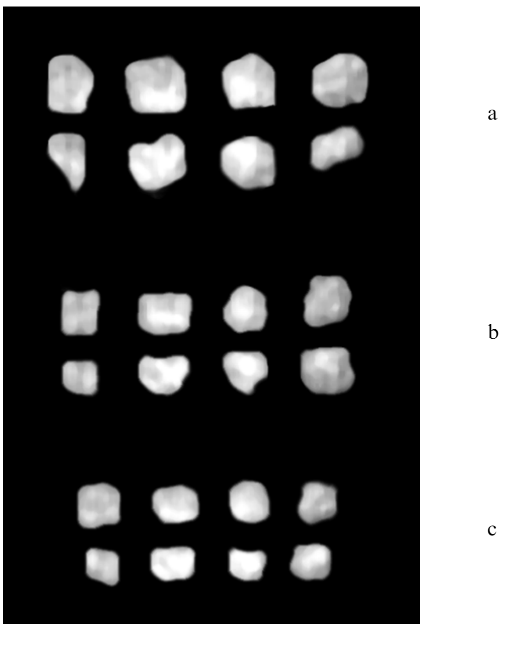

Figure 5. Images of the grid mesh (a) before and (b) after irradiation of the sclera; as well as (c) after successive irradiation of sclera and cornea.

4. Conclusions

An analysis of the change in the mechanical properties of the sclera and the cornea after conventional and laser heating has shown that the plasticity of the cornea increases upon a slight heating, while heating to a higher temperature (over 70 °C) leads to a sharp hardening of the cornea due to its denaturation. We have determined laser irradiation regimes for which the variations in the mechanical properties of the cornea are reversible (the elastic modulus reverts to its initial value after cooling of the tissue). We have shown that the plasticity of the sclera does not increase after traditional or laser heating. Based on these properties, we have proposed a new method for changing the eye refraction by stretching the cornea due to laser-induced local contraction of the sclera and subsequent nondestructive laser heating of the corneal surface, which increases its plasticity and, hence, its radius of curvature.

The efficiency of this approach was demonstrated experimentally for the first time by successive irradiation of the sclera and cornea. We shown that exposure of sclera to laser radiation changes the refraction by 3 diopters, while subsequent irradiation of the cornea decreases the refraction by 7 diopters.

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