

Expanding of Excimer Laser Photoablation's Functionality in Ophthalmology

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Abstract

One of the significant weaknesses of excimer laser-based vision correction devices is the difficulty of achieving a required change in the refractive properties of the cornea to sharply focus the image on the retina with distance from the working area (ablation zone) center to the periphery due to a change in the laser beam incidence angle. The study is aimed at improving the quality of laser action on the eye cornea by introducing an optical corrective system into the existing excimer laser vision correction equipment, ensuring the coincidence of the direction of the laser beam incidence on the corneal surface with the normal.

It has been shown that the greater the reflection coefficient, the lower the absorbed energy, and the shallower the laser radiation penetration and ablation depths, which reduces the laser action opportunities and quality. When using excimer laser vision correction devices, it has been proposed to change the angle of the laser beam incidence on the cornea with a distance from the working area (ablation zone) center to the periphery during the surgery by introducing an optical corrective system based on a lightweight controllable and movable mirror, which allows achieving the coincidence of the direction of the laser beam incidence on the corneal surface with the normal.

The studies have shown that the coincidence of the laser beam incidence on the corneal surface at any point with the normal when using a priori data on the specifics of the patient's eye allows expanding the functional opportunities of excimer laser photoablation, i. e., expand the ablation zone by 30 % and eliminate the possibility of errors caused by the human factor. The technique proposed can be used for excimer laser vision correction according to PRK, LASIK, Femto-LASIK, and other methods. To implement this approach, a patented excimer laser vision correction unit has been proposed with a PC-controlled optical shaping system comprising galvo motor platforms and galvo mirrors installed on them.

Keywords: photoablation, optical correction system, excimer-laser vision correction, angle of incidence of the laser beam on the cornea.

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Расширение функциональных возможностей фотоабляции эксимерным лазером в офтальмологии

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Одним из существенных недостатков устройств для коррекции зрения на основе эксимерных лазеров является трудность достижения заданного изменения преломляющих свойств роговицы для чёткой фокусировки изображения на сетчатке с удалением от центра рабочей зоны (зоны абляции) к периферии в связи с изменением угла падения лазерного луча. Целью исследования являлось повышение качества лазерного воздействия на роговицу глаза за счёт введения в существующую аппаратуру для эксимер-лазерной коррекции зрения оптической корректирующей системы, обеспечивающей совпадение направления лазерного луча, падающего на поверхность роговицы, с нормалью.

Показано, что чем больше коэффициент отражения, тем меньше поглощённая энергия, тем меньше глубина проникновения лазерного излучения и меньше глубина абляции, что снижает возможности и качество лазерного воздействия. Предложено при использовании устройств для эксимер-лазерной коррекции зрения изменять в процессе операции угол падения лазерного луча на роговицу с удалением от центра рабочей зоны (зоны абляции) к периферии за счёт введения оптической корректирующей системы на основе управляемого, лёгкого подвижного зеркала, что позволяет добиться совпадения направления лазерного луча, падающего на поверхность роговицы, с нормалью.

Проведённые исследования показали, что совпадение лазерного луча, падающего на поверхность роговицы в любой точке с нормалью, при использовании априорной информации об индивидуальных особенностях глаза пациента, позволяет расширить функциональные возможности фотоабляции эксимерным лазером, а именно, увеличить зону абляции на 30 % и исключить вероятности ошибок из-за человеческого фактора. Предложенная методика может быть использована для эксимер-лазерной коррекции зрения по методикам PRK, LASIK, Femto-LASIK и др. Для реализации данного подхода предложена защищённая патентом установка для эксимер-лазерной коррекции зрения с управляемой от компьютера оптической формирующей системы, включающей платформы с гальвоприводом и установленными на них гальвозеркалами.

Ключевые слова: фотоабляция, оптическая корректирующая система, эксимер-лазерная коррекция зрения, угол падения лазерного луча на роговицу.

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Introduction

Ophthalmology was the first medicine branch to use lasers [1–4]. Various lasers with wavelengths from 193 nm to 10.6 μm are used to treat eye diseases. The nature of laser radiation impact differs for various biomaterials with specific properties. Accordingly, in each case, specific parameters are chosen: wavelength, duration of exposure, power, pulse repetition rate, etc. [5]. The laser radiation wavelength determines the application area of the laser in ophthalmology. Excimer lasers emit energy in the UV range (193–351 nm wavelength). These lasers allow removing specific surface layers of tissue with an accuracy of 500 nm using photoablation (evaporation).

Vision correction technology is based on profiling the cornea's outer surface. Removing tissue in the central area corrects myopia [6], evaporation of the cornea peripheral part allows correcting hyperopia, and dosed removal in different cornea meridians allow eliminating astigmatism [7]. Despite the widespread use of excimer lasers for vision correction, such devices have a significant drawback, i. e., the difficulty of achieving a required change in the refractive cornea properties (upward or downward) to accurately focus the image on the retina with a distance from the working area (ablation zone) center to the periphery due to a change in the laser beam incidence angle. This limits side vision; peripheral, binocular vision deteriorates; in the dark, problems occur, associated with a contrast decay, nocturnal myopia, glare, and halos. Higher-order aberrations are also difficult to correct.

In this regard, the study is aimed at improving the quality of laser action on the eye cornea by introducing an optical corrective system into the existing excimer laser vision correction equipment, ensuring the coincidence of the direction of the laser beam incidence on the corneal surface with the normal.

Approaches used

Like any optical system, the human eye features optical defects – aberrations deteriorating the vision quality by distorting the image on the retina. Aberration is any angular deviation of a narrow parallel light beam from the point of ideal intersection with the retina as it passes through the entire optical system of the eye. In technical

optics, the optical system quality is determined by the aberrations of a plane or spherical front of a light wave passing through this system. Thus, an eye without aberrations has a flat wavefront and ensures the most accurate point source image on the retina (the so-called Airy Disk, the size of which depends only on the pupil diameter). But normally, even with 100 % visual acuity, optical defects of the light-refracting eye surfaces distort the beam path and form an incorrect wavefront distorting the image on the retina. The quantitative characteristics of the image's optical quality are the root-mean-square errors in the real wavefront deviation from the ideal one. German mathematician Zernike suggested using a series of polynomials to describe wavefront aberrations. An optical system is considered good if the Zernike coefficients are close to zero and, therefore, the wavefront root-mean-square error is less than 1/14 of the light wavelength (Marechal criterion). This coefficient allows forecasting visual acuity by simulating the image of any optotypes on the retina.

There are excimer laser-based vision correction devices, using the following laser methods and technologies to correct vision:

- Flying Spot technology. Its distinctive feature is the flying spot system – the excimer laser beam “flies” all over the treatment area surface and polishes the cornea by shooting a large number of laser pulses. The damage is minimal due to splitting the energy into mini-pulses;

- Eye Tracking technology. The vision correction excimer laser is equipped with a control system pointing the laser beam at the area to be treated with micrometer precision. This laser technology compensates for the patient's all involuntary eye movements. Its precision allows using it to treat patients with eye twitching syndrome (nystagmus);

- Topographic Laser Treatment technology. The topographic excimer laser system allows using it, considering the specifics of each eye. This means that only certain cornea areas will be evaporated, while the rest are saved. Topographic technology is especially widely used for postoperative correction (e. g., scars, irregular astigmatism).

All the absorbed laser radiation energy E is spent to heat the biological tissue volume V_0 to the boiling point $T_b - (E_1)$ and evaporate this biological tissue volume (E_2) (with the widespread assumption of identification of biological tissue with water). The E energy is determined by the equation:

$$E = E_1 + E_2 = P_a t = C_p m \Delta T + \chi m = C_p \rho h_0 \Delta T d_0^2 / 4A + \rho \chi d_0^2 / 4A = \rho h_0 (C_p \Delta T + \chi) d_0^2 / 4A, \quad (1)$$

where P_a is the absorbed radiation power, W; t is the time of the biological tissue exposure to laser radiation, s; C_p is the specific heat capacity of biological tissue, kJ/deg·kg; m is the mass of heated and evaporated biological tissue, kg; ρ is the biological tissue density, kg/m³; d_0 is the Gaussian beam diameter, m; h_0 is the radiation penetration depth at the $1/e^2$ level; ΔT is the increment of the biological tissue temperature when heating, °C ($\Delta T = T - 36.6$ °C); χ is the specific energy of water evaporation, kJ/kg.

Considering the calculated value of the coefficient $A = 2.31$, equation (1) will take the form:

$$E = 0.34 \rho d_0^2 h_0 (C_p \Delta T + \chi). \quad (2)$$

According to equation (2), the energy spent on heating and evaporating biological tissue is proportional to the radiation penetration depth h and the temperature T required to achieve any thermal and, hence, surgical effect (ablation temperature $T = 250\text{--}300$ °C).

Ablation (from Late Latin *ablatio* – taking away) is removing material from a solid surface with a stream of hot gas. Laser ablation is removing material from a surface with a laser pulse. At low laser power, materials evaporate or sublime in the form of free molecules, atoms, and ions, forming a weak non-luminous plasma, usually dark, over the irradiated surface. When the laser pulse power density exceeds the ablation regime threshold, a micro explosion occurs, forming a crater on the material surface and a luminous plasma.

The absorbed energy E is less than the incident energy and depends on the reflection coefficient (K_{ref}):

$$E = [1 - (K_{ref} + K_{tr})] P t / S, \quad (3)$$

where P is the radiation power, W; t is the exposure time, s; S is the irradiation area, m²; K_{ref} is the laser beam reflection coefficient; K_{tr} is the transmittance of the irradiated biological tissue.

For wavelengths of 0.63 and 0.89 μm, the biological tissue transmittance is 0.12 and 0.41, respectively.

According to equation (3), the higher the reflection coefficient, the lower the absorbed energy, and the shallower the laser radiation penetration and ablation depths.

Figure 1 plots the dependence of the reflection coefficients for the *TM*-wave (the light polarization state, where the electric vector is perpendicular to the incidence plane) and the *TE*-wave (the polarization state, where the electric vector lies in the polarized light incidence plane) on the incidence angle. For unpolarized light, the curve will pass in the middle.

As the plot shows, with an increase in the incidence angle over 10°, the reflection coefficient starts increasing, and with an angle over 60°, it starts growing sharply.

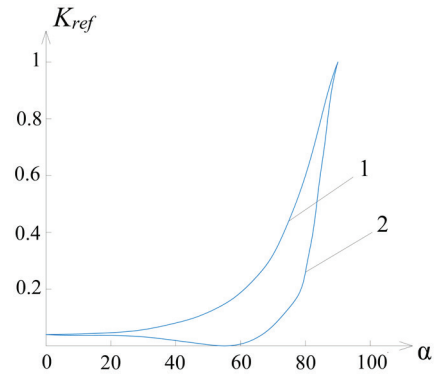


Figure 1 – The dependence of the reflection coefficients K_{ref} for the polarized light *TE*-wave (curve 1) and *TM*-wave (curve 2) on the incidence angle

When the laser beam deviates from the normal, the reflection coefficient increases and can reach unity when the laser beam is fully reflected. Considering that the incidence angle is the angle between the laser beam incident on the cornea surface and the normal to the surface at the incidence point (Figure 2), in the working area center, the laser beam incidence angle OAO is zero, and with a maximum working area diameter of 8.2 mm, depending on the distance from the optical shaping system to the cornea, can reach 60° (OBC angle).

The correction system operating principle and the study results

To reduce the laser beam deviation from the normal and, accordingly, the beam reflection coefficient, an optical corrective system is required. Directing a laser beam OB with a given laser radiation wavelength using this system onto a reflective surface, i. e., a relatively lightweight control-lable movable mirror with a coating capable of reflecting the laser beam at a relatively high speed and located appropriately, the coincidence of the direction of the laser beam incidence on the corneal surface with the normal can be achieved (OCB angle in Figure 3).

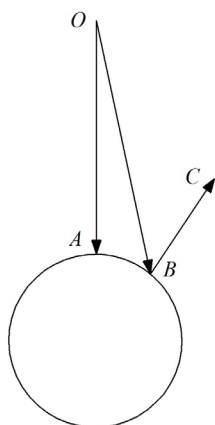


Figure 2 – The angle of the laser beam incidence on the cornea

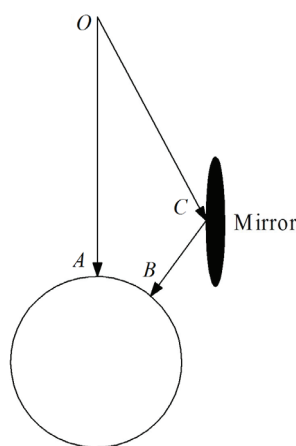


Figure 3 – The angle of the laser beam incidence on the cornea with a mirror

The proposed approach allows expanding the device functionality by changing the laser beam incidence angle on the cornea with distance from the working area (ablation zone) center to the periphery. It also allows changing the laser operating modes directly during the surgery, while eliminating the likelihood of errors caused by the human factor.

The technical result obtained in this case is achieved by introducing an optical correcting system comprising platforms with a galvo drive and galvo mirrors installed on them into the excimer laser vision correction device consisting of an excimer laser, a laser operating mode control unit, an optical shaping system, a computer, and an algorithm controller [8].

The proposed technique can be used for excimer-laser vision correction according to PRK.

The studies have shown that the coincidence of the laser beam incidence on the corneal surface at any point with the normal when using a priori data on the specifics of the patient's eye allows

expanding the functional opportunities of excimer laser photoablation. The technique proposed can be used for excimer laser vision correction according to PRK (Photorefractive Keratectomy), LASIK (Laser Keratomileusis), Femto-LASIK, and LASEK [9–12]).

Along with obtaining a required corneal profile, the corneal surface quality in the ablation zone is of great importance [13–15].

For the stable operation of the complex proposed, the mirror rotation should be controlled until the laser beam coincides with the normal. To do this, the mirrors are made semitransparent, and a reflected light flux sensor is installed in the center of the mirrors. By the reflected light flux energy, the beam coincidence with the cornea normal is controlled. The sensor is installed on the reverse side of the mirror does not interfere with the mirror operation in directing the light flux to a given area of the cornea. The sensor is connected to a digital measuring system transmitting data to a computer, which estimates the beam coincidence with the normal and generates control signals to move (rotate) the mirrors.

The problem of adjusting the mirrors to achieve the laser beam coincidence with the normal is reduced to that of finding an extremum on the reflected radiation energy curve. Adjustment takes a certain time and is performed under the condition of the minimum laser beam energy not affecting the cornea. After the adjustment, with the chosen mirror positions, a therapeutic or surgical procedure can start with an increase in the laser energy.

However, there is an issue with the cornea surface irregularity. If the beam aperture is less than the corneal surface irregularities, then the beam tuning will be complicated since the beam reflection will depend on the shape and size of the surface irregularities.

When the laser beam probes the cornea, the reflection of the beam from the surface, associated with the corneal irregularity, will depend on the corneal surface irregularity (Figure 4), where d_1 is the expanded beam aperture, d_2 is the beam aperture less than the irregularity element size h . In this case, if the beam aperture is less than the irregularity size ($d_2 \leq h$), then the beam reflection will depend on the irregularity element geometry. If the beam aperture is much more than all the irregularities ($d_1 \gg h$), then the maximum reflection will be achieved when the beam coincides with the normal. It is also known that according to Rayleigh law, the irregularity size

should be less than the probing radiation wavelength to talk about the corneal surface smoothness.

Therefore, the beam tuning aperture should be several times larger than the size of irregularities.

In this case, there are two approaches to choosing the aperture:

1. The tuning aperture is the same as that the treatment one.
2. The tuning aperture is larger than the treatment one.

To compare different approaches, statistics on the nature (irregularities) of the cornea in different patients should be obtained.

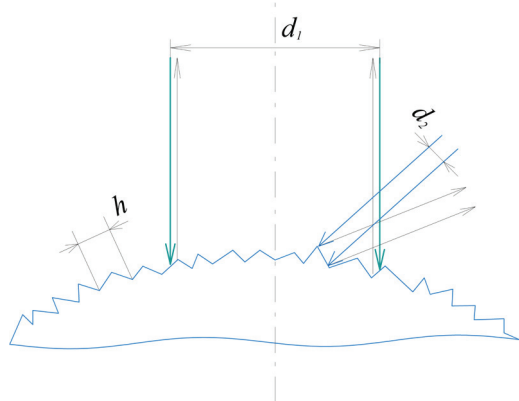


Figure 4 – The laser beam reflection from the cornea surface

A different laser radiation wavelength can be used for tuning, which may improve the tuning accuracy, but in this case, the optical transmission scheme should coincide with that of the main laser. To do this, fiber-optic lines and schemes for converting radiation from two lasers to a common one for probing the cornea can be used.

The created complex has two operating modes:

1 – adjusting the complex on a patient at low radiation energy with an enlarged aperture using one or two lasers.

2 – a working situation when the main laser beam aperture reduces with an increase in the radiation energy to that required for the specific treatment.

To check the correctness of using the proposed technique to set the laser radiation exposure modes, a step wedge has been reproduced¹ when changing the direction of the laser beam incidence on the material (plexiglass). For the experiment, PMMA acrylic glass has been used to adjust and set the Laser Scan unit modes from zero to 30°. To measure micro

¹ GOST 24930–81. Facsimile Equipment Gray Scale. Moscow: Publishing House of Standards, 1981, 7 p.

irregularities on the sample outer surface, an MII-4 interference microscope was used².

According to the scientific and technical requirements for the surface roughness, the arithmetic mean deviation of the profile and the height of the profile irregularities taken at 10 points at the same step have been determined and calculated. The random value of the profile irregularities x_i has a discrete random distribution; then the arithmetic mean profile deviation is determined by the formula:

$$M(x) = \frac{\sum_{i=1}^N x_i}{N}, \quad (4)$$

where N is the number of surface micro irregularity measurements for one wedge step.

The results of the calculation by equation (4) are shown in Figure 5.

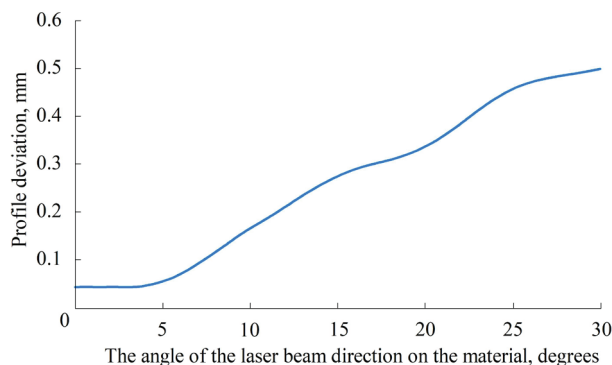


Figure 5 – The arithmetic mean deviation of the surface micro irregularities

The central limit theorem allows asserting that whenever a random variable is a result of adding a large number of independent random variables, the variances of which are small compared to that of the sum, this random variable distribution law turns out to be virtually a normal law. Since random variables are always generated by an infinite number of reasons, and most often none of them has a variance comparable to that of the random variable itself, then most of the random variables occurring in practice are subject to the normal distribution law. The literature data do not contradict this. According to the law of large numbers, the random micro irregularity mean values have a normal distribution. Therefore, according to the three-sigma rule (3σ), almost

² Interference Microscope MII – 4 [Electronic resource]. Microscopes and Accessories [Site]. URL: <http://www.mbs10.ru/mii-4.html> (date of access: 03.17.2021).

all values of a normally distributed random variable lie within the interval $(M(x) - 3\sigma; M(x) + 3\sigma)$ with a probability of 0.997, where $M(x)$ is the mathematical expectation. For clarity of data presentation, the variance has been calculated. The calculation results are shown in Figure 6.

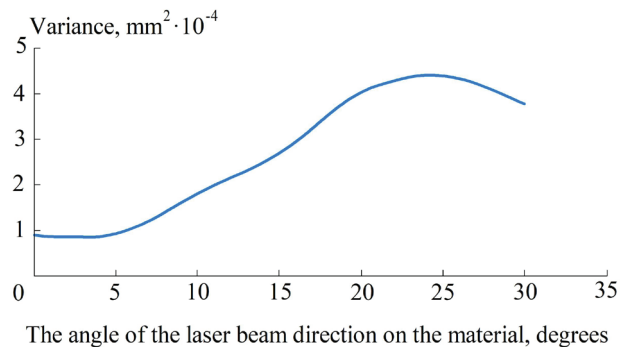


Figure 6 – Dispersion of the surface profile deviation

From a visual point of view, dispersion is an indicator of the plexiglass surface micro irregularity. Dispersion is a measure characterizing the spread of values of a random micro irregularity variable x_i relative to its mathematical expectation $M(x)$. If the variance is small, then the random variable values x_i are close to each other. If it is large, the values x_i are far from each other. The random variable x_i variance is calculated by the following formula:

$$D(x) = \frac{1}{n-1} \sum_{i=1}^n (x_i - M(x))^2,$$

where n is the random variable x_i measurement number.

Conclusion

The analysis of the optical corrective system characteristics has shown that changing the laser operating modes directly during the surgery is promising for expanding its functionality by changing the laser beam incidence angle on the cornea with distance from the working area (ablation zone) center to the periphery, thereby eliminating errors caused by the human factor.

The changes to the system design allow controlling the beam aperture and radiation energy. Depending on the algorithm chosen, two operating modes are possible: tuning and treatment. Thereat, in the tuning mode, a laser with a different radiation wavelength can be additionally used. These procedures can be controlled by a

computer. Improving the system functionality allows for an effective treatment. The calculation and experimental results show that the ablation zone can be increased by 30 %.

The scientific and technical solutions provided herein can be used in both creating new treatment complexes in ophthalmology and improving existing ones.

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