Pulsed UV laser technologies for ophthalmic surgery

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Abstract. The paper provides an overview of the results of multiyear joint researches of team of collaborators of Institute of Laser Physics SB RAS together with NF IRTC "Eye Microsurgery" for the period from 1988 to the present, in which were first proposed and experimentally realized laser medical technologies for correction of refractive errors of known today as LASIK, the treatment of ophthalmic herpes and open-angle glaucoma. It is proposed to carry out operations for the correction of refractive errors the use of UV excimer KrCl laser with a wavelength of 222 nm. The same laser emission is the most suitable for the treatment of ophthalmic herpes, because it has a high clinical effect, combined with many years of absence of recrudescence. A minimally invasive technique of glaucoma operations using excimer XeCl laser (\(\lambda=308\) nm) is developed. Its wavelength allows perform all stages of glaucoma operations, while the laser head itself has high stability and lifetime, will significantly reduce operating costs, compared with other types of lasers.

1. Introduction

Today, the use of UV lasers for eye surgery has become an integral part of ophthalmic surgery. This area is one of the most important for the Institute of Laser Physics SB RAS and SF IRTC "Eye Microsurgery", the experience of successful cooperation which has more than 30 years. Joint studies on the possibility of using high-power short-pulse UV laser radiation in medicine and development of laser medical technologies began by collaborators of these organizations in the 1980s. By the time the team has had a complete set of pulsed excimer laser sources, most of which were created at the Institute for the first time in the world [1, 2]. Then in 1986 the world's first operation of laser correction of refractive errors were made. In order to keep the Bowman's membrane with epithelial layer, which would inevitably evaporate when exposed to and to hold direct ablation of the corneal stroma, the authors have been proposed and practiced separation of the corneal stroma, thus, the corneal flap is folded to one side. Results of clinical trials for the correction of high myopia in a number of patients were reported in [3]. The famous ophthalmologist professor at Columbia University (New York, USA) S. Trokel, noting a significant contribution to Russian researchers called the first operation "proto-LASIK" [4]. Later, with the introduction of mechanical microkeratome for corneal bundle, this method of correction was finally formed as a Laser-Assisted in Situ Keratomileusis - LASIK, which to date remains the most popular method of laser correction of refractive errors.

Then, in the late 1980s one began researches on the possibility of laser treatment of viral and other eye diseases, based on the bactericidal effect of UV short-pulse laser radiation. On the first positive
results of the use of short-pulse UV laser radiation for the treatment of various eye diseases: glaucoma, herpes simplex virus, corneal ulceration was reported in [3].

The results of the researches were first developed UV laser ophthalmic medical devices for the treatment of refractive error correction eye surgery and the treatment of ophthalmic otrkrytougolnoy glaucoma. At the beginning of 2000 in the Institute of Laser Physics SB RAS is created ophthalmic system under trademark Medilex™ at a wavelength of 193 nm and 222 nm.

In the course of further joint researches ILP SB RAS and NF IRTC "Eye Microsurgery" continues the continuous improvement of existing and development of new laser medical technologies for ophthalmic surgery, creating new laser medical devices.

2. The perspectives of using the wavelength of 222 nm of the KrCl excimer laser for refractive surgery and for the treatment of some eye’s diseases

For years there has been a growing interest to the refractive surgery of the human eye by the emission of the excimer lasers surgical means rather than the use of spectacles or contact lenses [5].

Excimer lasers are capable of emitting different wavelengths in the ultraviolet region, including 193, 222, 248, 308 and 351 nm. For corneal surgery, 193 nm is the wavelength of choice because it produces the most precise cuts with the minimum amount of thermal distortion of the surface of the tissue [6]. Therefore surgeons usually use the excimer ArF laser with radiation wavelength of 193 nm [7-9].

However a different research groups study the possibility of the application another laser wavelengths for the refractive surgery [10-12].

This paper describes a new UV ophthalmic laser system Medilex™ based on excimer ArF (193 nm) or KrCl (222 nm) lasers. We have shown that the use of the wavelength of 222 nm for photorefractive surgery has several medical and technical advantages compared with typical wavelength of 193 nm and we propose that the emission of the wavelength of 222 nm of the KrCl excimer laser is preferable for refractive surgery than traditionally used wavelength of 193 nm [13, 14].

2.1. Features of excimer laser system

UV ophthalmic laser system Medilex™ can be used for the correction of the myopia, hyperopia, astigmatism and myopic or hyperopic astigmatism by the Photorefractive Keratectomy (PRK) or Laser in Situ Keratomileusis (LASIK) procedures and for Phototerapeutic Keratectomy (PTK) to treat corneal pathologies. All procedures mentioned above can be realized using either the wavelength of 193 nm of ArF excimer laser or the wavelength of 222 nm of KrCl excimer laser.

The UV ophthalmic laser system Medilex™ consists of a laser subsystem, an optical subsystem, an alignment subsystem, a measurement and a control subsystem. The laser subsystem generates the pulsed coherent UV radiation of suitable wavelength and energy level. The optical subsystem provides a means for conditioning the beam and delivering it to the patient’s eye. The alignment subsystem provides a microscope coaxial with the laser beam alignment to the center of patient’s eye. The measurement and control subsystem provides the computer and electronics circuitry required for monitoring and controlling to all systems of the set-up via a microprocessor device.

The laser system is built as a cabinet. In the cabinet, the excimer laser, the gas subsystem, the high voltage power supply, the vacuum pump, the control units and other auxiliary aggregates are included. The unit measures 1500×800×1300 mm and the weight is about 400 kg. Electric power lines needed for the excimer laser systems are: single phase 220V, 50Hz, 5 A.

In addition the system is supplied by XYZ patient’s bed with fluently changing speed of movement and video camera with monitor to observe the patient’s eye during process of treatment. A video recorder or computer can be connected to the video camera for archiving. All surgical procedures can be documented using the computer system connected to a printer.

2.2. The excimer laser

For UV ophthalmic system we use the simple, reliable and efficient excimer ArF and KrCl lasers which were designed in Institute of Laser Physics SD RAS [15]. The technical parameters of these lasers using in UV ophthalmic system are shown in the Table 1.
Table 1. The technical parameters of the excimer lasers.

| Parameter          | Value                        |
|--------------------|------------------------------|
| Laser medium       | ArF or KrCl                  |
| Wavelength         | 193 nm or 222 nm             |
| Fluence            | up to 250 mJ/cm²             |
| Pulse durations    | 12±2 ns (FWHM)               |
| Pulse repetition   | up to 20 Hz                 |

2.2. Beam delivery system

The beam delivery system has been developed to permit precise thickness of tissue to be ablated at exact locations on the anterior corneal surface without involving normal adjacent or deeper corneal tissue. Optical scheme allowed the laser beam to be projected onto the cornea either as a fairly uniform beam of 0.2-5 mm diameter or as a radially symmetric nonuniform pattern for the correction of the refraction anomalies over 4-7 mm diameter areas. Beam delivery system operates under total computer control.

Figure 1 is a functional schematic diagram of the major parts in the beam delivery system Medilex™. The entering laser beam is rectangular with dimensions of approximately 10×22 mm. The intensity profiles in the short and long directions are essentially Gaussian and “top-hat”. Since there are significant “hot spots” at the edges of this beam, firstly it is passed through a 7×20 mm aperture mask to “scrape-off” these edges. Then it turns by mirror and passes through cylindrical telescope. As the compressed by cylindrical telescope the laser beam still has different intensity profiles in the principal directions it next passes through a beam homogenizer. In this article we describe the optical delivery system with beam homogenizer – the Dove prism. In other our optical delivery systems we used the special waveguide or diffractive homogenizers.

The rotating beam having time-averaged axially-symmetric intensity profiles is next passed through an expandable rotating slit and patented special masks [16]. Expandable rotating slit is used for treatment of astigmatism and has two computer-controlled motors, with one of them being controlled the expansion of slit and the second one controlled the angle of inclination. When the PRK, LASIK or PTK procedures are realized the slit is opened at a maximum dimension. The using of the special masks for refractive surgery and PTK procedures enables us to achieve very smooth surface of the cornea and good quality of central reprofiling form figures 2 and 3 illustrate schematically the form of masks (a), distribution of laser emission intensity during process of ablation (b) and the ablation profiles achieved with the use of masks in the myopia (figure 2) and hyperopia (figure 3).
cases (c), respectively. The diameter of masks depends on the degree of anomaly of refraction and it is changed within 4 - 7 mm. The rotation of the masks with a variable velocity under the special law allows to correct the myopic or hyperopic astigmatism.

After the mask the laser beam is delivered to the cornea of patient’s eye via spherical lenses and mirror. The photodiode provides the measurements of radiation energy before and during process of the operation allowing to make the ablation with great accuracy. Fixation green light diode provides the alignment of laser beam with the center of the patient’s eye. The observation of the patient’s eye during process of operation by a video system is possible using beam splitter, beam-bender and video camera.

2.3. Discussion

2.3.1. The comparative analysis of the interaction of excimer lasers radiation with the tissue of the human eye cornea. For determination of the possibility of using different radiation wavelengths of the excimer lasers for refractive surgery we have performed the comparative analysis of the interaction of those ones with the tissue of human eye cornea. The first stage of our investigations was the deriving of the transmission spectrum of the human cornea in ultraviolet region of the spectra. The results are given in[13]. The curve of transmission of the cornea illustrates that three wavelength 193 nm, 222 nm and 248 nm of ArF, KrCl and KrF lasers is found in the region of strong absorption (from 2700 up to 210 cm⁻¹) of cornea and only two wavelength 193 nm and 222 nm have the total absorption in thin layers of cornea [14]. The laser radiation with a longer wavelength cannot be used for microsurgery of the cornea as it will penetrate inside on eye.

The determination of the ablation rate of the cornea using wavelength 193, 222 and 248 nm was the next stage of our investigations. We have obtained that the highest rate of ablation process is achieved at 248 nm up to 3 um/p, and the lowest rate is achieved at 193 nm-up to 0,8 um/p for maximal energy density. When 222 nm is used the ablation of corneal tissue is twice as quick as that (2 um/p) at 193 nm and only by 30% slower that at 248 nm [13].
2.3.2. The effect of the UV laser radiation wavelength on the cornea tissue damage. The experiments on determination of thickness of the zone of damage at the cut surface of corneal stroma following laser ablation at three different wavelengths were performed [14].

In exposing the cornea of an isolated rabbit or human eye to laser radiation a tissue defect was formed, its depth being dependent on the number of pulses. Along the defect margin, an opaque eosinophilic (damaged) layer was observed, its thickness being 0.3 μm after radiation at wavelength of 193 nm, about 0.6 μm at wavelength of 222 nm and about 10 μm at wavelength of 248 nm. The examination of the eosinophilic layer on the floor of the lesion demonstrated its homogeneity and the eosinophilic layer thickness did not change depending on the number of pulses. In all cases the epithelium along the wound margin was practically not damaged. At the power density approaching the threshold values which depend on the radiation wavelength the epithelium may be damaged, collagen fibres remaining intact. It should be emphasized that when non-penetrating corneal defects were formed close to the Descemets membrane and endothelium the latter remained intact.

Experiment in vivo. The laser beam on the rabbit cornea produced lesions of a given configuration. No visible thermal coagulation was observed following laser radiation (λ =193; 222; 248 nm). After laser radiation a normal response in the form of moderate pericorneal injection, pupil narrowing and mild irritation was observed during 7 days. Epithelization of the lesions took three days. Inflammatory phenomena disappeared completely in 10 days. Histologic examination in the areas exposed to laser radiation revealed thickening of the epithelial layer, vacuolization of the epithelium, appearance of compact and contracted nuclei and formation of keratiesquamas. In the connective tissue underlying the new epithelium bands of collagen fibers were located chaotically, there appeared accumulations of fibroblasts and fibrocytes. The extent of such changes depended on focusing the laser beam. The histologic examination of the areas of the cornea exposed with the energy density lower than the threshold levels irrespective of the wavelength revealed as a rule no changes of the connective tissue. The epithelium was normal opacification of the cornea after the repair of the tissue lesions caused by radiation (energy density 0.2·0.5 J/(cm²·pulse). No damage of the deep eye media was noted.

2.3.3. The study the chromosome rearrangement in the eye cornea. The study of the chromosome rearrangement was made upon the cornea and the bone marrow of 1-1.5 months old female nonline mice. The animals were divided into two groups. In the first group, one eye of the animal was exposed to laser radiation, the other being used as a control. The mice of the second group were not subjected to any special effect and were used as an intact control group. In the course of the experiments the energy density of the radiation was changed in the range of 0.015-1.5 J/(cm²·pulse) for the wavelength of 248 nm, 0.027-0.04 J/(cm²·pulse) for 222 nm and 0.3-0.9 J/(cm²·pulse) for 193 nm. The area of the spot with the maximum energy density was 0.001 cm². To characterize the process of mutation, the dose of exposure equal to the product of the energy density in one pulse and the number of pulses was determined. The cornea were fixed in ethanol-acetous mixture (3:1) 10 and 72 hours after exposure, stained according to Erlich and stable specimens were made.

It was shown that in this case the concentration of the cells with mutation does not differ from the control over the whole range of doses [20]. Thus, the exposure of the corneal tissue to powerful UV short-pulse radiation does not present any danger from the point of view of the mutation appearance in the epithelial cells at the parameters being used.

All these results mentioned above allowed us to turn to the clinical tests of ophthalmic devices. The correction of anomalies of refraction (myopia, hyperopia and astigmatism) and healing some diseases of the eye (herpetic keratities and glaucoma) were performed together with Eye Microsurgery Intersectoral Research and Technology Complex (Novosibirsk).

There were performed 82 refractive treatments. There were 18 men and 23 women of 18 to 42 years of the age old. Photorefractive keratectomy (PRK) was performed for 20 patients, LASIK for 21 patients. 15 patients had the myopia degree up to 6.0 D, 26 patients had the myopia degree over 6.0 D. Preoperative and postoperative examination involved visual acuity, refractometry, keratometry, pachimetry and computerized topography. The analysis of PRK efficiency in-group of patients with the myopia degree up to 6.0 D revealed that desired effect (visual acuity 0.8-1.0) was achieved in
72%. Refractive effect was stable throughout 5-months follow-up period. The result, close to emmetropy, was achieved in 92% in the case of the myopia degree over 6.0 D. 21 patients with myopia over 6.0 D, were operated by LASIK technology. There were no intraoperative complications. 94% of patients, 7 days after surgery, had refractive closed to emmetropy. Refractive effect was stable throughout 3-months follow-up period.

3. The choice of the laser wavelength for a herpetic keratitis treatment
Recently the utilizing the 193 nm radiation wavelength of an ArF excimer laser took a world-wide extension as more simple and efficient method of the refraction anomalies correction such as myopia, hyperopia, astigmatism and as an instrument for therapeutic procedures on the surface of a cornea [5, 18]. However there was a question unexplored on an opportunity of use UV radiation of excimer lasers for treatment of other superficial diseases of an eye. There are communications on use of ArF laser at treatment of the open-angle glaucoma [19]. But laser treatment method is not known to have some advantages over the existing traditional non-laser ones. At the same time the question about the possibility of using the UV excimer lasers radiation for the treating the virus eye diseases such as herpetic keratitis and also ulcers of a cornea is interesting. This task arises from that fact, that one of the most widespread virus infections on today is herpetic one. The main aim of our work was the investigation of the possibility of a herpetic keratitis laser treatment.

3.1. Materials and methods
The three ophthalmic laser system based on ArF (193 nm), KrCl (222 nm) and KrF (248 nm) excimer lasers were developed and created for making the investigations. The constructions of these systems were almost the same as for the ophthalmic system Medilex were described in detail in [20]. To implement the purpose of the investigation the trial of 75 patients with herpetic keratitis manifests by a surface arborescent keratitis before and after treatment has been carried out. All patients undergoing surgery were volunteer and only one eye was operated on in each individual. The clinical diagnosis was determined on the base of a complex of ophthalmologic methods. Depending upon a laser radiation wavelength used (193 nm, 222 nm or 248 nm) all patients were allocated to 3 groups (25 patients in each group), where lacrymal fluid was obtained on day 7-10 after laser exposure and testing a changes of the parameters studied was performed. Additionally a group of 28 healthy individuals was used for intact control. The choice of a time point for investigation was determined by literature findings that indicated a necessity of such time period for antibody production and its pronounced utilisation or formation of circulating immune complexes (CIC).

Certainly, it is interesting to determine a herpes simplex virus (HSV) effect and laser treatment of HSV on some integral immunobiochemical parameters of lacrimal fluid. We have chosen testing of antibodies to native DNA-antigens CIC and lactoferrin in the capacity of the parameters. The choice of these parameters was determined by the following factors:
1. At present one may ascertain that inflammation of any etiology and localization as well as some pronounced degenerative-destructive processes follow herpetic keratitis, a destruction of cell membranes, DNA-antigens elimination.
2. A pathogenic significance of CIC in the arising and forming of the immune response, an interrelation of this parameter with inflammation and immunologic homeostasis maintenance is beyond doubt.

3.2. Results and discussion
3.2.1. The 193nm laser radiation treatment. The 1st group of the patients (25 patients) was treated by 193 nm laser radiation wavelength. During laboratory investigations in this group of patients with herpetic keratitis the autoantibody (AAB) levels to native DNA-antigens in lacrimal fluid was 0.46±0.03 a.u. (arbitrary units) and was not significantly different from normal value.

The level of CIC was 42.6±6.3 a.u. that is significantly (p<0.02) higher than normal value (25.1±3.9 a.u.) and is at the level of the parameter studied in patients with herpetic keratitis before treatment (42.9±6.9 a.u.). A positive clinical effect of the laser treatment with 193nm radiation
wavelength was obtained in 9 of 25 patients treated that was equal 36%. A clinical effect appears as a decrease of the pain characterised for patients with herpetic keratitis, reduction of photophobia, epiphora, and eyelid edema. However, a positive clinical effect was not obtained in 16 patients (64% of this patient group) after laser ablation of the herpes inflammation area by 193 nm radiation wavelength.

As a result one may ascertain that laser therapy by 193 nm laser radiation wavelength does not produce a destructive effect on cornea tissues in an irradiated area that is confirmed by a reduction of antibody levels to native DNA-antigens. However, the absence of such effect can indicate inefficiency in treatment as to an effect upon HSV. The laser with the given wavelength has an inefficient energy for coagulation of HSV on the surface of the cornea and does not cease an inflammation formation. The further formation of an inflammation is confirmed by CIC high levels that indicate a continued humoral response to antigen stimulation. Thus, the use of the 193-nm radiation wavelength is low effective to treat herpetic keratitis manifested with a surface arborescent keratitis.

3.2.2. The 222 nm laser radiation treatment. The 2\textsuperscript{nd} group of the patients (25 patients) was treated by 222 nm laser radiation wavelength. In the result of treatment by 222 nm radiation wavelength there is a significant increasing the lacrimal fluid antibodies level to native DNA-antigens that are equal 0.76±0.11 a.u. compared with the results obtained in control group 0.47±0.03 a.u. (p<0.008) as well with the results obtained before treatment - 0.54±0.02 a.u. (p<0.04). Comparing these results with those obtained by 193 nm wavelength treatment a reliable increase (p<0.006) of a parameter studied was also revealed. After exposure by 222 nm wavelength the level of CIC (figure 8) was 35.6±3.5 a.u. that reliable exceeded (p<0.05) a normal value (25.1±3.9 a.u.). An unreliable tendency to the decrease of a studied parameter compared with 1\textsuperscript{st} group and this group before treatment (35.6±3.5 a.u. versus 42.6±6.3 a.u. and 42.9±6.9 a.u. respectively) is also revealed.

As a result of clinical trials the data were obtained that allowed to evaluate the efficiency of the treatment by 222 nm radiation wavelength. 22 patients of 25 treated ones (88%) showed a positive clinical results. But it is necessary to note that the treatment of a herpetic inflammation area by 222 nm radiation wavelength results to the absence of a complete clinical effect in 12% patients (3 persons) though the area damaged was entirely ablated.

3.2.3 The 248 nm laser radiation treatment. The 3\textsuperscript{rd} group of the patients (25 patients) was treated by 248 nm radiation wavelength laser therapy. In this group of the patients autoantibody levels to native DNA-antigens (figure 7) was equal 0.95±0.12 a.u. that reliable exceeded (p<0.004) the normal values 0.47±0.03 a.u. and as well parameter levels obtained in the group of patients with herpetic keratitis before the treatment 0.54±0.02 a.u. (p<0.001). When compared the results obtained in this group with ones of the groups of patients treated by 193 nm and 222 nm radiation wavelengths the reliable tendency to increasing the autoantibody levels to normal DNA-antigens (p<0.002 and p<0.04 respectively) has been revealed.

CIC level after exposure by 248 nm radiation wavelength (figure 8) was equal 27.8±8.5 a.u. that was not significantly differed from normal value 25.1±3.9 a.u. The tendency to the decrease of a CIC levels in comparing with those of the 1\textsuperscript{st}, 2\textsuperscript{nd} groups and the data obtained in 3\textsuperscript{rd} groups before treatment (42.6±6.3 a.u., 35.6±3.5 a.u. and 42.9±6.9 a.u. respectively) has been also revealed.

The clinical results obtained in this group of patient were the same as for the patients of the 2\textsuperscript{nd} group treated by 222 nm radiation wavelength. A positive clinical effect was obtained in 22 patients of 25 ones (88%). However, in patients with a positive clinical dynamics in given group a number of negative accessory effects after laser exposure were found. When determined a visual acuity level did not exceed 0.5 and was in the range of 0.2-0.5. This fact is explained by a high level of a thermal effect of 248 nm radiation wavelength upon affected cornea area that manifested as a semitransparent epithelium formation and in further formation of cloud-like opacity in the exposure area.

The results obtained indicate that with increasing the wavelength from 193 nm to 248 nm the autoantibody levels to native DNA-antigens are raising and the CIC levels decrease that indicated by reduction of antigen-antibody intensity reaction and antigen stimulation.
The data obtained indicate that 248 nm radiation wavelength possesses the maximal thermal effect from all wavelengths used in our experiments. It is confirmed by higher autantibody levels to native DNA-antigens in lacrimal fluid. This wavelength has a high level of a destructive effect upon the eye cornea, which results to cornea opacity in some cases.

4. Ab-externo glaucoma surgery with UV laser radiation

Today glaucoma called chronic eye disease characterized by constant or periodic increase in intraocular pressure (IOP) with the development of trophic disorders in the outflow tracts, in the retina and the optic nerve, causing the appearance of typical defects in the field of view and the development of the edge of excavation (groove punching) of the optic nerve. Glaucoma mainly affects people over 40 years, but is also found youth glaucoma and even congenital glaucoma (newborns). Thus, the frequency of congenital glaucoma was 1 per 10-20 thousand infants aged 40-45 years. Primary glaucoma occurs in about 0.1% of the population. In the age group 50-60 years have glaucoma occurs in 1.5% of cases and in persons over 75 years - more than 3%.

The aim of our work was to development of a safe, clinically effective and convenient way to practice laser treatment of glaucoma and implement the methodology of the operation on the treatment of patients with open-angle glaucoma (ab-externo) using a short-pulse excimer laser radiation.

Main tasks of our investigation were:

- to determine the transmission spectrum of the sclera in the range of 190-400 nm;
- to investigate the effects of KrF, XeCl, XeF excimer lasers to the tissue of the sclera, which are capable of producing ablation of sclera amid filtration intraocular fluid, without causing damage of the scleral tissue;
- to determine the threshold energy for ablation and ablation rate for these wavelengths;
- to find out a convenient, effective way to deliver UV radiation to the area of operation;
- to carry out of a clinical testing.

Studies were carried out using two UV laser systems. The typical laser chamber design with high-voltage excitation system and view of Medilex™ excimer lasers are presented in figure 4.

![Figure 4](image)

**Figure 4.** The laser chamber design and HV excitation system(left) and view of excimer laser system Medilex™ design (right), based on the gas-discharge pumped ArF /KrCl excimer laser.

4.1. Experiment and discussion

Experimental part was carried out with scleral tissue of isolated human eye using 3 wavelengths: 248, 308 and 353 nm - specially designed excimer laser systems were created. Ablation threshold and ablation speed for studied wavelengths were investigated. Dependence of thickness of an isolated human eye's sclera layer removed per pulse on the energy density of radiation for different wavelengths is presented on the figure 6. It was shown that in terms of the maximum rate of ablation,
the XeCl (308 nm) and XeF (353 nm) laser radiation is the most acceptable for practical use, as it allows to provide higher speed of operations.

![Graph](image)

**Figure 6.** The dependence of thickness of an isolated human eye’s sclera layer removed per pulse on the energy density of radiation for different wavelengths.

Histological examination of the sclera preparations subjected to radiation with a wavelength of 308 and 353 nm, edge grooves have been presented structured collagen fibers without evidence of damage, and coagulation of visible lesions (figure 7). The walls of the arteries and veins around the zone of ablation and at the edges of the flap all over were not damaged; foci of hemorrhage and hemosiderosis were absent. At the same time, research of the transmission spectrum of UV radiation of human scleral tissue in the 190 - 500 nm showed that the maximum absorption of the UV radiation in tissue is shorter than 300 nm (figure 8). At longer wavelengths, the absorption becomes less, and the laser light starts to penetrate deep into the scleral tissue.

![Histology images](image)

**Figure 7.** The histological test of sclera tissue.

At wavelengths over 310 nm radiation can penetrate through the entire thickness of the sclera, reaching the underlying tissues. This could lead to possible damage to the internal parts of the eye with unpredictable consequences, therefore safer when exposed sclera is radiation having a wavelength less than 310 nm. In this case, such is a XeCl laser with a wavelength of 308 nm. As a result, the basis for the establishment of a medical device for the treatment of open-angle glaucoma was chosen XeCl excimer laser.
Based on experimental results, a new method for ab-externo open-angle glaucoma surgery with excimer laser radiation ($\lambda = 308$ nm) is suggested and clinically realized. The UV laser ophthalmological medical system Medilex™ was developed on the XeCl excimer laser (see on the figure 17). The basic ab-externo method of laser irradiation is the maximum thinning of trabeculae and Descemet's membrane while maintaining the integrity of these tissues in order to achieve the maximum antihypertensive effect by restoring the ocular fluid filtration. The procedure for the intensification of filtering properties is layered evaporation (ablation) trabeculae and Descemet membrane. Duration of exposure is determined by the ophthalmologist in each individual case as the current intensification of aqueous humor. The main advantage of using the excimer laser surgery for this is the high precision tissue removal and surface quality without thermal injury.

To thinning was necessary to develop an optical system that allows the delivery form and focus the UV laser radiation on the surface of the biological tissue. To deliver 308 nm to the surgical field, flexible fiber light guide with easy-to-use handle was made (figure 9). The optical system of the laser system is designed for the transport of laser radiation, transforming geometrical dimensions of the
laser beam is focused to a diameter of about 0.05 cm and, subsequently, the transmission of a focused radiation on the surface of Descemet's membrane.

The basis of the future medical system has been taken previously developed UV excimer laser system Medilex\textsuperscript{TM} based on the gas-discharge pumped excimer laser (see figure 10). Energy characteristics of the laser system are provided by gas mixtures which do not involve the usage of expensive buffer gases, such as helium grade "60" and neon (see figure 15).

![Figure 10](image.png)

**Figure 10.** The pulse energy $E$ and total efficiency $\eta$ of XeCl (308 nm) excimer laser as the function of charging voltage $U_{\text{charg}}$ (left) and the XeCl-laser radiation print on the thermofilling paper (right).

The usage of a pulsed gas-discharge XeCl excimer laser, the active medium which is a mixture of gaseous components without the buffer gas is first proposed. The source of intense UV laser radiation is able to compete effectively on a combination of factors with an excimer laser, the active medium which is a mixture of gaseous components with helium buffer gas (grade "B").

The long standing studies were carried out in cooperation with the Novosibirsk ophthalmologists.

5. Conclusion
On the base of investigations carried out and results obtained we have choose the 222 nm KrCl laser for the photorefractive keratectomy. The use of the KrCl laser has several advantages over the ArF (193 nm) laser as the ablation rate is about one-and-a-half times higher than that of the ArF laser, allowing shorter laser treatment times and less chance of eye movement during the process of treatment. Tissue damage adjacent to the area of ablation is histologically about the same as and clinically indistinguishable from that of the ArF laser and little or no mutagenic potential has been attributed to the 193 nm wavelength, it is possible that mutagenesis is even less with the 222 nm wavelength, as it does not penetrate the nuclear membrane as well as the 193 nm wavelength. There are technical advantages as well. Importantly, there is no toxic fluoride gas to deal with because in gas active media of KrCl laser the HCl is used as halogen gas. The lifetime of the KrCl gas mixture is higher than that of ArF gas mixture and the wavelength of 222 nm is better transmitted through the optical system, allowing increased efficiency and prolonged life of the optics.
In ophthalmic devices for photorefractive keratectomy the using of the radiation of the KrCl excimer laser was suggested and realized. Using the results of investigations the new surgical UV ophthalmic laser systems Medilex™ based on ArF and KrCl excimer lasers for the photorefractive keratectomy were created and the first trial utilizing the KrCl laser to produce a photorefractive keratectomy in human eyes has been performed. The process of KrCl laser superficial keratectomy has proved to be one of the promising areas of surgical intervention for photorefractive keratectomy in the future. Intensive investigations need to be undertaken on the corneal wound healing process following laser ablation as well as the nature, and long-term stability of the corneal excisions or induced refractive corrections.

For the first time the effect of the UV laser radiation to human eye cornea with herpetic keratitis was experimentally investigated. On the base of results obtained we consider that the use of 222nm laser radiation wavelength is most efficient to treat the herpetic keratitis that manifests by a surface arborescent keratitis. As it allows treating the herpetic keratitis with sufficient curative and low traumatic effects.

A new method for ab-externo excimer laser surgical treatment of open angle glaucoma is developed. For the first time, the technology allows for the operation incisions and scleral ablation trabeculae and Descemet's membrane UV laser radiation with a small footprint and traumatic surgery. As a consequence, informed choice of laser wavelength is noted that the procedure for thinning of trabeculae does not stop even when a filtering aqueous humor. The result is a higher clinical effect – a significant reduction in postoperative complications related to inflammation and scarring. Established trabeculae does not stop even when a filtering aqueous humor. The result is a higher clinical effect – a significant reduction in postoperative complications related to inflammation and scarring. Established installation reduces trauma and increase the hypotensive effect of the operation due to the possibility to carry out cuts and dosed separation sclera ablation of trabeculae and Descemet's membrane.

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