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Use of bursts of 1.54-μm microsecond laser pulses for cataract destruction

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Abstract. **The possibility of using bursts of microsecond pulses of an Yb,Er : glass laser (λ = 1.54 μm) for cataract destruction was investigated experimentally *in vitro* for the first time. The energy in a laser pulse was limited from below by the eye lens destruction threshold and from above by the radiation resistance of the input end face of the radiation-supplying fibre. The energy of a burst consisting of three microsecond laser pulses, separated by time intervals of 850 μs, was 255 ± 15 mJ, and the burst repetition rate was 15 Hz. The hydroacoustic signal, generated after each burst pulse in the water around the lens, contained two components. The first occurred immediately after the laser pulse transmission, and the second was delayed by 250 to 350 μs. The amplitude of the second component of the hydroacoustic signal exceeded the amplitude of the first component and was maximum (50.0 ± 8.0 MPa) for the signal induced by the second pulse in the burst. The efficiency of cataract destruction by microsecond-pulse bursts generated by an Yb,Er : glass laser was found to depend on the lens nucleus density, to exceed significantly the efficiency of cataract destruction by single microsecond pulses of this laser, and to be comparable with the efficiency of eye lens destruction by a 1.44-μm Nd : YAG laser.**

Keywords: *laser, microsecond pulse, pulse burst, hydroacoustic signal, cataract, extraction, destruction efficiency.*

1. Introduction

Cataract is one of the most widespread eye diseases, which manifests itself in eye lens opacification [1, 2]. Cataract treatment implies surgical removal (extraction) of a turbid lens and its replacement with an artificial one. Currently, several methods are applied for cataract destruction: manual fragmentation of a turbid lens, cryoextraction, ultrasonic phacoemulsification accompanied by simultaneous irradiation with femtosecond laser pulses, ultrasonic phacoemulsification without laser irradiation, and laser cataract extraction (LCE) without manual and ultrasonic impacts. Manual fragmentation and cryodestruction are methods of large incision surgery; the others are assigned to small incision surgery. In the former case, the eyeball is subjected to wide opening, whereas in the latter case the operation is performed through a small surgical incision. The small incision surgery if free of many drawbacks inherent in large incision surgery, because it allows one to stabilise the intraocular pressure during the operation and reduce the risk of complications caused by eye decompression during large incision surgery, such as detachment of choroid and expulsive haemorrhage, leading to loss of eye. In addition, small incision surgery allows one to reduce the probability of exogenous penetration of infection into the eye cavity, decrease the degree of surgically induced astigmatism, increase the quality of sight, and shorten the period of visual rehabilitation for patients [3]. Currently, large incision surgery is applied only in exceptional cases.

The most popular method of small incision surgery is ultrasonic phacoemulsification [4], in which femtosecond laser radiation is applied in some operation stages (cornea cuts, capsulorrhexis, preliminary lens dissection) [5, 6]. However, ultrasound is used in both techniques for complete cataract destruction. This is their main drawback. The energy of ultrasound used for lens destruction affects simultaneously all other eye tissues and is even dissipated beyond the eyeball. As a result, some complications arise: subclinical forms of retina edema; increased loss of corneal posterior epithelial cells, and possible thermal damage of cornea in the corneal incision region because of the ultrasonic tip overheating at the instant of aspiration hole occlusion by lenticular masses. When working with an ultrasonic tip, pressure is exerted on the posterior lens capsule and the fibres of the zonule of Zinn, which may cause their trauma [7, 8]. A serious hazard is the acoustic vibrations caused by the collapse of cavitation bubbles arising during ultrasonic phacoemulsification [9]. To a great extent, this is the reason for the higher risk of eye tissue damage after ultrasonic destruction of dense cataracts, whose removal calls for a longer total ultrasonic exposure as compared with soft lenses [10].

The first and up-to-date single technology of efficient laser destruction of cataracts of any degree of density without manual handling and ultrasonic impacts was developed in Russia in the 1994s – 1997s under the guidance of S.N. Fyodorov using a 1.44-μm Nd : YAG laser [11, 12] (which had not been previously applied in ophthalmology). A laser surgical complex Rakot was developed (Nela, Ltd.; the Russian Federation). This technology, which has successfully been used in clinical practice [13 – 15], reduces to minimum the aforementioned drawbacks of ultrasonic phacoemulsification and makes shorter the total operation time due to the high output of the laser destruction of lens [16]. The laser used for LCE operates

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in the free-running mode with the following parameters: the pulse duration (at $\lambda = 1.44$ μm) is ~250 μs, the pulse energy is up to 300 mJ, and the pulse repetition rate is up to 30 Hz [17, 18]. The laser radiation is supplied through a quartz optical fibre with a core diameter of 450 ± 10 μm. The LCE technology is being continuously developed and upgraded, in particular, due to the high potential of combined application of Nd : YAG (1.44 μm) and He–Ne (0.63 μm) lasers in cataract surgery [19]. A drawback of the aforementioned laser complex is its large weight and sizes, which are determined to a great extent by the use of lamps for pumping.

Obviously, one of the directions of development of laser cataract surgery is the design of portable mobile complexes based on diode-pumped solid-state lasers. However, the replacement of pump lamps with diodes having a working wavelength of 1.44 μm increases significantly the cost of the laser system. The reason is as follows: since the gain cross section on the Stark sublevels of the secondary laser transition $^4F_{3/2} - {}^4I_{13/2}$ in neodymium ions [20] is low at this wavelength, one needs a high pulsed pump power. A possible alternative is a diode-pumped Yb,Er : glass laser [21] with a working wavelength of 1.54 μm, which lies within the resonance absorption line of water with a maximum in the vicinity of 1.44 μm [22]. In this case, one does not need a high power of pump diodes to obtain high pulsed lasing energies because of the long lifetime of the upper laser level of working Er^{3+} ions (about 8.5 ms) [23]. In addition, the wide absorption band of Yb^{3+} ions in the wavelength range of 920–950 nm provides stable output characteristics during the entire laser operating cycle without any additional measures for thermal stabilisation of pump diodes. However, a significant drawback of Yb,Er : glass lasers is the low thermal conductivity of glass and the corresponding restriction on the average laser power. This drawback can be minimised using the useful loss modulation mode in a cavity formed by three highly reflective mirrors with radiation output through a shutter based on frustrated total internal reflection (FTIR) [24]. The average laser power can additionally be increased when one pump pulse leads to generation of a burst consisting of several microsecond laser pulses, which is obtained due to the more efficient use of residual population inversion (characteristic of three-level media). Each microsecond laser pulse may be a set of submicrosecond pulses. This operation mode allows one to increase significantly the number of pulses generated per second (effective frequency) and, therefore, the average radiation power at a relatively small thermal load on the active element. In the regime of efficient-loss modulation in the Yb,Er : glass laser cavity, under conditions of generation of microsecond-pulse bursts, the following parameters may be achieved: energy of each burst pulse of 100 mJ, effective repetition rate of 60 Hz, efficiency with respect to the embedded optical power of pump diodes of 5.2%, and differential efficiency of 11% [21, 25]. Thus, the average power of an Yb,Er : glass laser (λ = 1.54 μm) becomes comparable with that of a free-running Nd : YAG laser at $\lambda = 1.44$ μm.

Studies of the interaction between the human eye lens and single microsecond pulses of an Yb,Er : glass laser [25–28] showed that a lens exposed to 1.54-μm laser radiation undergoes destruction due to the combined impact of the laser beam and laser-induced acoustic waves arising in the collapse-and-recovery phase of vapour cavities formed in the water around the lens. The efficiency of cataract destruction by single microsecond pulses of an Yb,Er : glass laser depends on the lens density. For lenses with degrees of density of I–II (according to Buratto's classification [29]), III–IV, and V, the destruction efficiency is, respectively, 213 ± 23, 55 ± 8, and 22 ± 3 mm^3 kJ^{-1} [25].

However, the lens destruction by bursts of microsecond laser pulses with λ = 1.54 μm has not been investigated previously. The hydroacoustic (HA) effects accompanying this impact on water have neither been described in the literature. At the same time, the result of the impact of laser-pulse bursts on water and eye lens may differ from the action of a single laser pulse due to the accumulation of thermal and HA perturbations caused by each burst pulse in the lens and surrounding water. In this context, it is urgent to study the effect of bursts of microsecond pulses of an Yb,Er : glass laser on water and eye lens.

The purpose of this work was to investigate *in vitro* the HA signal induced in water by bursts of microsecond pulses of an Yb,Er : glass laser and the efficiency of destruction of human eye lenses with cataracts of different density using this laser.

2. Yb,Er : glass laser generating microsecond-pulse bursts

The principle of operation and characteristics of an Yb,Er : glass laser in the regime of efficient-loss modulation

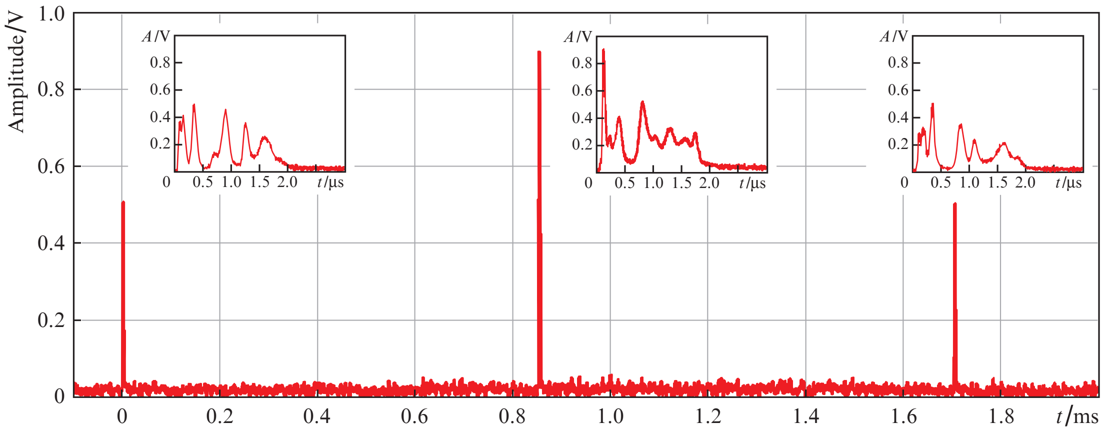

Figure 1. Typical oscillograms of a pulse burst emitted by an Yb,Er : glass laser operating in the regime of efficient-loss modulation with an FTIR shutter.

with an FTIR shutter were discussed in detail in [21, 25]. In our experiments, this laser generated bursts consisting of three microsecond pulses separated by a time interval of 850 µs (Fig. 1).

Each microsecond pulse consisted of several spikes ∼100 ns long. The pulse repetition rate in the burst was chosen so as to obtain a pulse energy in the range of 70 – 110 mJ, with an energy deviation between pulses within a burst of no more than 30%. In this case, the main factor determining the pulse repetition rate is the acquisition time of inverse population in the active element that is sufficient to generate pulses with a desired output energy at a limited power of the pump diode modules in use. The pulse energy was limited from below by the lens threshold destruction and from above by the radiation resistance of the input end face of the feeding fibre [25].

The burst repetition rate (15 Hz) was limited by the thermomechanical strength of an active laser medium; the effective pulse repetition rate was 45 Hz. The energy E in burst reached 255 ± 15 mJ in our experiments; the energies of the first, second, and third pulses were 82 ± 5, 99 ± 5, and 74 ± 5 mJ, respectively.

3. Hydroacoustic signal induced in water by microsecond pulses of an Yb,Er : glass laser

A schematic of the experimental bench for studying the laser-induced HA signals in water is presented in Fig. 2.

Bursts of laser pulses were introduced into the bulk of distilled water in a cell via a quartz fibre with a core diameter of 450 ± 10 µm and a numerical aperture of 0.18. The fibre end face was located at a distance of 15 ± 1 mm from the cell bottom and at a distance of 45 ± 5 mm from the cell walls. HA signals were measured using an HGL-0200 hydrophone (ONDA Corp., the United States) equipped with a preamplifier. The hydrophone was oriented at an angle of 45° with respect to the laser beam axis, and its receiving end face was placed at a distance of 2.6 ± 0.2 mm from the fibre distal end face. The hydrophone signal was detected and recorded using two TDS 2022B oscilloscopes (Tektronix Inc., the United States). The HA signal obtained by irradiating water with microsecond laser pulses may contain several components

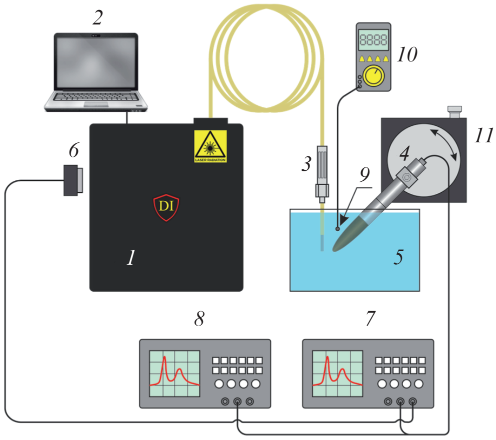

Figure 2. Schematic of an experimental bench for studying laser-induced hydroacoustic signals: (*1*) Yb,Er : glass laser operating in the regime of efficient-loss modulation with an FTIR shutter; (*2*) computer for controlling the laser power supply and FTIR shutter operation; (*3*) optical fibre with an SMA adapter; (*4*) hydrophone; (*5*) cell filled with water (100 × 100 × 40 mm); (*6*) InGaAs photodetector; (*7*,*8*) oscilloscopes; (*9*) thermocouple; (*10*) device for monitoring thermocouple readings; (*11*) mechanical translator.

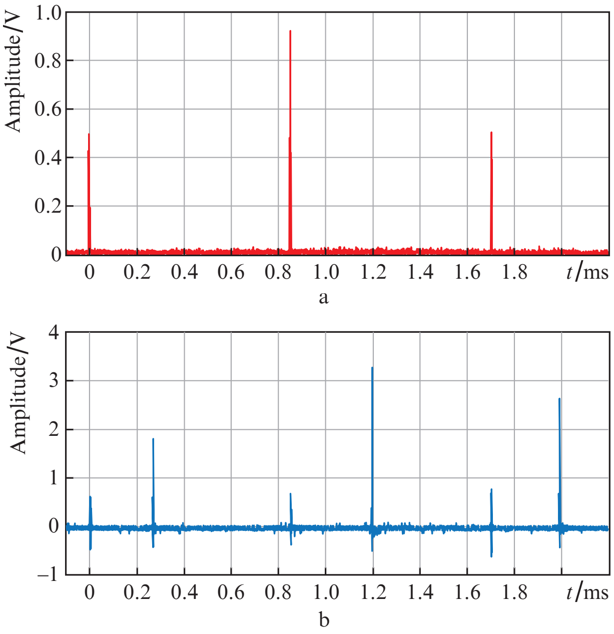

Figure 3. Oscillograms of (a) laser pulse burst (E = 255 ± 15 mJ) and (b) hydroacoustic signal excited in water by this burst.

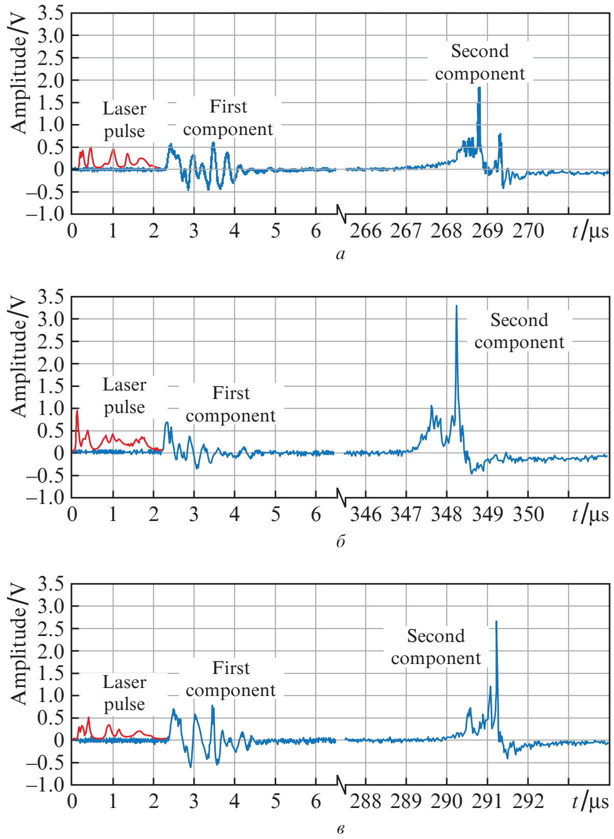

Figure 4. Typical oscillograms of the (a) first, (b) second, and (c) third laser pulses (E = 255 ± 15 mJ) and components of the HA signal excited in water by these pulses.

[30]. In our experiments, the HA signal excited in water by each laser pulse from the burst contained two components (Fig. 3). Oscilloscope *7* recorded laser pulses and the first component of HA signal, while oscilloscope *8* recorded the second HA component. The influence of liquid heating in the cell during experiments was disregarded, because the irradiation was switched on for only a short time (sufficient to detect signals).

We recorded the amplitudes of the first HA component, which is due to the thermoelastic effect (arising as a result of very rapid thermal expansion of the liquid exposed to a laser pulse), and the second HA component, related to the process of vapour cavity collapse and recovery.

Typical oscillograms of HA components are shown in Fig. 4. Measurements of the HA signal excited in water by each laser pulse from the burst were performed successively for the first, second, and third pulses with an interval of 5–7 min (the time for which the laser was switched off to let the water in the cell be cooled to room temperature.

The histograms illustrating the amplitude ratio A for the first and second HA components and delay times t_{d} between these components for each laser pulse from the burst are presented in Fig. 5.

For all laser pulses from the burst, the amplitude of the second HA component was more than twice as large as that of the first component. The maximum amplitude of the second component was observed for the second laser pulse in the burst (Fig. 5b), its average value during the working cycle amounted to 3.35 ± 0.53 V, which corresponds (at a hydrophone sensitivity of 6.7×10^{-8} V Pa^{-1}) to a pressure drop of 6.7×10^{-8} MPa. Taking into account that the second laser pulse had the highest energy among the burst pulses, this result was quite expectable. The delay time between the first and second HA components (i. e., the vapour cavity lifetime) for the second pulse in the burst turned out to be 50 μs longer than the impact time of single pulses with the same energy, which was recorded in [25]. Therefore, the maximum volume of the vapour cavity was larger in our case. Since the pressure drop in the collapse-and-recovery phase increases with an increase in the maximum volume of the vapour cavity, the HA effects in the regime of pulse burst generation are more intense in comparison with the single laser pulse impact.

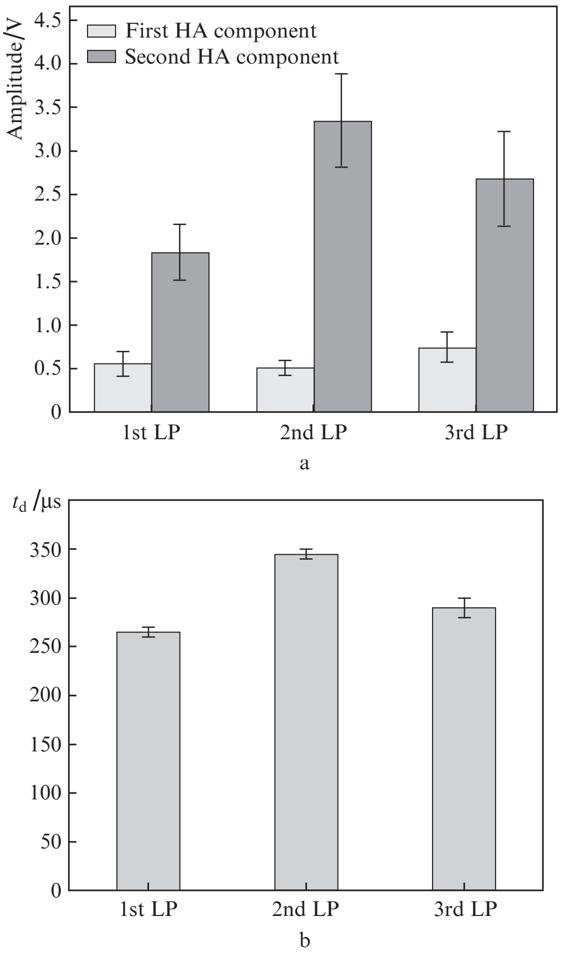

Figure 5. (a) Amplitudes of the components of the HA signal excited in water and (b) delay times t_{d} between the first and second components for each laser pulse (LP) from a burst.

It is noteworthy that the amplitude of both HA components for the third laser pulse in the burst exceeded the amplitude of the corresponding components for the first pulse, despite the fact that this pulse had the least energy in the burst. This may be related to the heating of the irradiated volume by two previous laser pulses and accumulation of nuclei in the form of microbubbles in this volume. Under these conditions, a vapour cavity of larger volume is formed, as indicated by the longer cavity lifetime (see Figs 5 and 6). As a consequence, the pressure drop in the collapse-and-recovery phase for the third pulse exceeds that for the first pulse.

4. Destruction of human eye lenses with cataracts of different density by a Yb,Er : glass laser in the regime of generation of microsecond-pulse bursts

An *in vitro* study was performed on six human eye lenses with cataracts of different density: three groups (two lenses in each), characterised by degrees of density of I–II, III–IV, and V (Fig. 6). The lenses were obtained in the course of planned cataract surgery by intracapsular extraction. The extracted samples were placed in viscoelastic Viziton-PEG (OOO NEP 'Eye Microsurgery', Russia) and kept in it for no more than 24–48 h at a temperature of 4–6 °C above zero. Before carrying out experiments, the lenses were washed in a physiological solution (to remove viscoelastic residues) and then placed in a Petri dish filled with a physiological solution.

An irrigation–aspiration system Skat (a component of the Rakot complex) was used to hold a lens during laser irradiation and dispose products of biological tissue destruction. The maximum rarefaction during aspiration was 150 Torr, and the maximum pressure during irrigation was also 150 Torr. The operation was performed by an experienced ophthalmic surgeon; it began with destruction of the densest part of the lens (i. e., nucleus), after which its peripheral regions were processed.

The energy E of a three-pulse burst generated by the Yb,Er : glass laser amounted to 255 ± 15 mJ, and the burst repetition rate was f = 15 Hz. The lens was fractured into fragments with sizes sufficiently small to be transported through the aspiration channel of the irrigation–aspiration tip. Video recording was performed during destruction. The lens destruction time t was found using frame-by-frame analysis of video recording. The average lens volume V in the experiment was 250 mm^3. The cataract destruction efficiency η was estimated as

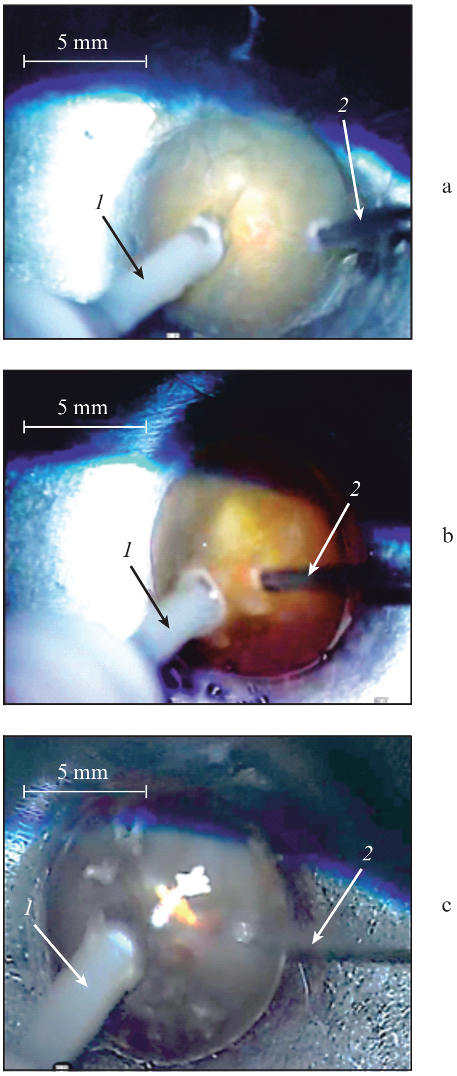

Figure 6. (Colour online) Photographs of human eye lenses with degrees of cataract density of (a) I–II, (b) III–IV, and (c) V during their laser destruction: (*1*) working part of the tip of irrigation–aspiration system and (*2*) working part of the laser tip.

$$\eta = \frac{V}{Eft}. \qquad (1)$$

The experimentally found times and efficiencies of destruction of lenses with cataracts of different degrees of density by an Yb,Er : glass laser generating microsecond-pulse bursts ($E = 255 \pm 15$ mJ) are listed in Table 1. Note that the presented values of time and efficiency are comparable with those obtained using an Nd : YAG laser (1.44 μm) in the free-running mode [17].

Table 1. Destruction time and efficiency for lenses with cataracts of different degree of cataract density, averaged over two samples with the same degree of density.

Degree of cataract density	Lens destruction time/s	Lens destruction efficiency/mm^3 kJ^{-1}
I–II	80 ± 10	2100 ± 250
III–IV	140 ± 20	1200 ± 150
V	130 ± 20	1280 ± 200

The destruction time for a cataract with a degree of density I–II was the shortest. The destruction of lenses with a degree density of III–V took a longer time. The result obtained is in agreement with the data of [25], which indicate that the efficiency of lens destruction by single laser pulses decreases with an increase in the lens density. In addition, it should be noted that the irradiation by microsecond-pulse bursts led to a significant (by an order of magnitude or even more) rise in the efficiency of laser destruction of the eye lens in comparison with the case of a single microsecond laser pulse.

Thus, our experiment revealed that, using 1.54-μm radiation of an Yb,Er : glass laser, generating bursts with an energy $E = 255 \pm 15$ mJ (consisting of three microsecond pulses) with a repetition rate $f = 15$ Hz, one can implement destruction of cataracts of any degree of density; the destruction efficiency and time are comparable with the corresponding values obtained using 1.44-μm radiation of Nd : YAG laser with a free-running pulse energy up to 300 mJ. This result, being undoubtedly positive, may be related both to the effect of heat accumulation in the treatment region and to the specific features of hydroacoustic processes occurring under impact of microsecond-pulse bursts.

5. Conclusions

The hydroacoustic signal arising in water exposed to microsecond-pulse bursts generated by an Yb,Er : glass laser was experimentally investigated. It is shown that, for all microsecond pulses from a burst, the amplitude of the second component of HA signal is more than twice as large as the first-component amplitude. The second-component amplitude is maximal for the second pulse in a burst, and the pressure drop reaches 50.0 ± 8.0 MPa in this case.

The potential of this laser in the mode of generation of microsecond-pulse bursts for cataract extraction was investigated. The time and efficiency of destruction of human eye lenses with cataracts of different density by radiation of this laser were determined *in vitro*. It was shown that the efficiency of turbid lens destruction by microsecond-pulse bursts exceeds greatly the efficiency of cataract destruction by single microsecond pulses. The results obtained were compared with the data of long-term clinical observations of cataract removal using Nd : YAG laser radiation ($\lambda = 1.44$ μm) and the Rakot system. The efficiency of destruction of human eye cataract by bursts of microsecond laser pulses with a wavelength of 1.54 μm was found to be close to the efficiency of cataract destruction by a Nd : YAG laser ($\lambda = 1.44$ μm) operating in the free-running mode; their radiation energies and average powers are comparable.

Thus, the object of this study – the diode-pumped laser with a wavelength of 1.54 μm, generating bursts of microsecond pulses – can be considered as an adequate alternative of lamp-pumped laser with a wavelength of 1.44 μm, operating in the free-running mode, with allowance for the much smaller weight and sizes of a laser system in the former case. There is a potential for increasing the average output power of Yb,Er : glass laser in the mode of generation of microsecond-pulse bursts by optimising the thermomechanical characteristics of glass, parameters of the optical scheme, introduction of radiation into a fibre, and modulation characteristic of the shutter; correspondingly, the rate of cataract extraction using this laser can be significantly increased in future.

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