ENDOUROLOGY

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COMPARATIVE STUDY OF THE EFFICIENCY OF ELECTRIC PULSE AND LASER LITHOTRIPTORS IN VITRO

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The paper presents a comparative study of nanosecond electropulse and holmium laser lithotripters in vitro. Two types of specimens were used, simulating "hard" and "soft" urinary stones, for the preparation of which BegoYone dental heavy-duty gypsum was used. For testing, four standard sizes of stone samples in the form of a rectangular parallelepiped were made. At the same time, the sizes of the probes and stones to a certain extent simulated the real clinical situation. In experiments, probes of three sizes were used for the Ho:YAG laser lithotripter (LL): 230, 365, and 600 µm; Comparison of the efficiency of lithotripters in experiments was carried out for pairs of probes, which corresponded to a certain stone size. Comparative studies were carried out in an aqueous medium at room temperature. "Stones" of the specified size for each type of lithotripter probe were placed on a stainless steel grid with a cell size of 2x2 mm, immersed in water. The distal part of the probe (tip) was placed at an angle of 90° to the horizontal surface of the "stone" and brought into contact with the sample. The experiment was terminated when no particles of the destroyed "stone" remained on the grid surface. Each experiment with a given type and size of the "stone" and probe was repeated at least 5 times. The results of the studies showed that for the destruction of all types of "stone" samples, nanosecond EPL requires much lower energy and time costs than LL, i.e., it is more efficient in terms of physical parameters. For the destruction of "soft stones", EPL always required noticeably less energy than for the destruction of "hard stones". At the same time, when working with LL, approximately the same energy, and sometimes even more, was expended than for the destruction of a "hard stone". Different dependences on the pulse energy and the properties of "stones" during their destruction for the two considered methods of contact lithotripsy were confirmed experimentally.

Key words: urinary stones; contact lithotripsy; lithotriptor; holmium laser lithotripter

Introduction. Urolithiasis is a common disease and accounts for more than 30% of all urological diseases in different countries [1]. At the same time, for the treatment of the most complex forms of nephroureterolithiasis (large, multiple and staghorn kidney stones, "impacted" and large ureteral stones, etc.), endourological methods are increasingly being used, in particular percutaneous and transurethral contact lithotripsy, which can reduce the perioperative risks of remote shock wave lithotripsy and open lithotomy, as well as to reduce the duration of inpatient and outpatient treatment [2].

In the field of contact lithotripsy, several main methods are currently used: ultrasonic, pneumatic, electrokinetic, laser and electrohydraulic. Each lithotripter has its own advantages and disadvantages. For ultrasonic lithotripsy, only rigid probes and rigid endoscopes are used, and its scope is currently limited mainly to kidney stones. Impact lithotripsy (pneumatic or electrokinetic methods) is considered one of the most effective and safe methods of contact destruction of "stones". However, the use of such lithotripters is also limited by the capabilities of rigid endoscopes, and retrograde stone propulsion during transurethral - ureterolithotripsy is considered a disadvantage of the method. Electrohydraulic and laser methods of lithotripsy, being an effective method of contact crushing, can be used with both rigid and flexible endoscopes, which significantly expands the scope of their use in modern urology. However, electrohydraulic crushing is associated with a higher complication rate than other methods, since the electrical discharge, which results in a shock wave, causes tissue damage when it occurs too close to the walls of the urinary tract. Laser fragmentation is safer, but requires more time and more expensive equipment. In addition, frequent damage to the flexible urethropyeloscope due to breakage of the laser fiber in the curved endoscope is a major disadvantage of this method [3–7].

As an alternative to existing methods of lithotripsy, the company “Lithtech Medical Ltd.” (Israel) developed a new method and a contact lithotripter that allows safe destruction of "stones" in all parts of the human urinary system, having probes of various diameters that can be used with both rigid and flexible endoscopes. This method of lithotripsy essentially differs from the existing ones in its principle of operation and uses short nanosecond electric pulses to destroy “stones” [8–11].

A new technology for the destruction of solid biological stones is based on the following phenomenon: when very short electrical pulses of a certain voltage are applied to a solid body in a liquid medium, the solid dielectric has a lower breakdown voltage than the liquid medium. When a nanosecond high-voltage pulse acts on a urinary stone, which is basically a solid inorganic dielectric, it breaks down and an electric current flows through the plasma channels formed in the volume of the dielectric. In this case, tensile thermomechanical stresses arise in the “stone”, which lead to its cracking and, ultimately, to destruction [8]. With the electropulse method of destruction of “stones”, in contrast to the electrohydraulic method, the energy of the electric impulse is released directly in the volume of the body being destroyed, which requires much less energy for its disintegration.

On fig. Figure 1 schematically compares the volt-second breakdown characteristics for the same discharge gap for a solid and a liquid medium. The point of intersection of the volt-second characteristics Ak corresponds to the equality of the strengths and the probability of electrical breakdown of the compared media. When the pulsed voltage is exposed to less than 2–3×10-7, the solid body becomes electrically weaker than such a liquid dielectric as industrial water, and in the area of the diagram to the left of Ak, the electrical breakdown of the solid body prevails.

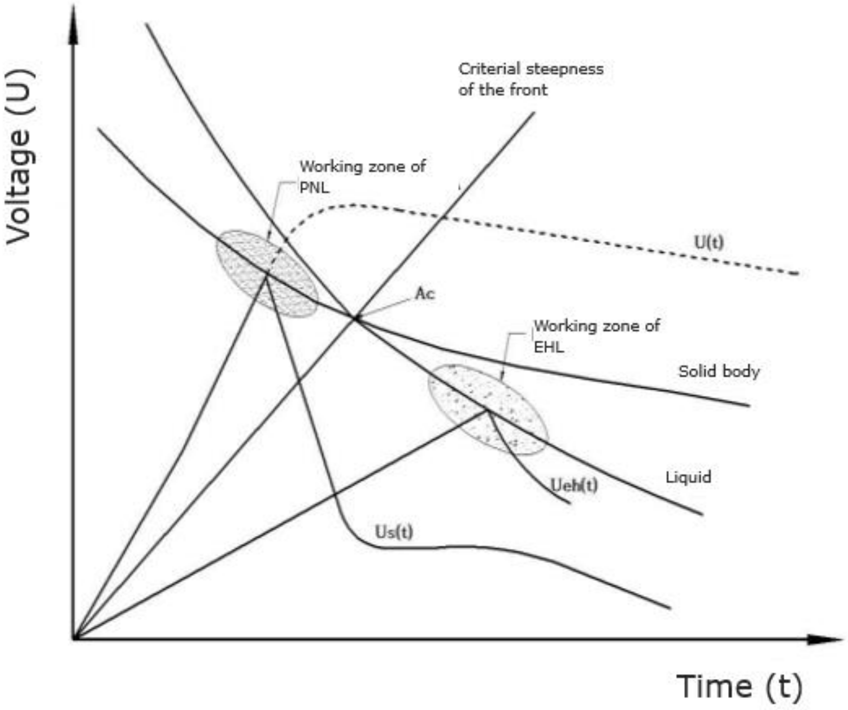


Figure 1. The principle of electrical impulse destruction: comparison of the volt-second characteristics of various media. Explanations in the text. Ak is the point where the liquid and solid breakdown probabilities are equal. U (t) is the voltage pulse, Us (t) is the voltage pulse during breakdown.

The implementation of the noted effect of the inversion of the electric strength of dielectrics as applied to the destruction of a solid body is illustrated in Fig. 2. A voltage pulse U(t) with parameters corresponding to the left side of the graph is applied to the electrodes installed on the surface of a solid body from a point equal to the probability (Fig. 2a). Breakdown in the gap with a probability of more than 50 % occurs inside the solid, and not along the shortest path on the surface of the solid. This phenomenon is called the introduction of a discharge into a solid. The breakdown stage of the process is characterized by current pulse I(t) flowing in the discharge channel and energy release (Fig. 2b). In this case, if the necessary amount of energy is released in the discharge channel quickly enough, the impact of the discharge channel on a solid body will be similar in appearance to a microexplosion in a solid body with the formation of a funnel and separation of a part of the material from the array (Fig. 2, c). The environment surrounding the destructible array of material with current-carrying electrodes plays the role of an agent that promotes electrical breakdown of the solid.

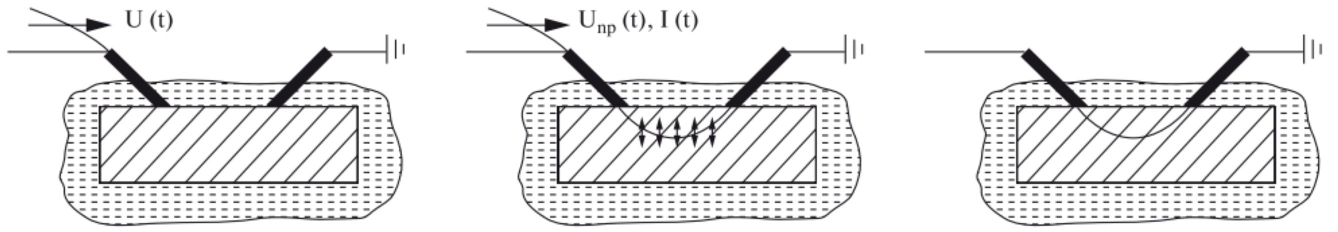


Figure 2. The sequence of processes of breakdown and destruction of a solid body in a system with one free surface. Explanations in the text. U(t) is the voltage pulse applied to the solid body. U_{np} (t) is the voltage pulse during breakdown, I(t) is the current pulse.

This variety of the method of destroying solids by electric breakdown is called the electric pulse method of destroying materials. The main prerequisite for the destruction of materials in this way is their tendency to electrical breakdown and brittle fracture under conditions of pulsed force loading. This method was used as the basis for the operation of a new, unparalleled nanosecond electric pulse lithotripter (EIL), which makes it possible to create an electrical breakdown in urinary "stones" with their subsequent fragmentation. Currently, EIL is used in clinical practice in dozens of Russian clinics and has proven to be an effective and safe lithotripter [9–11].

The basic characteristics of the developed device are the creation of a nanosecond pulse with a rise time of less than 50 ns, a duration of 250–500 ns, and a voltage of up to 9.6 kV at an energy applied to the object from 0.3 to 1 J.

The mechanism of destruction of urinary "stones" with the help of EIL, based on the theory of the process itself, can be represented by the following interrelated stages. Initially, the surface of the “stone” is destroyed, which is located between the electrodes under the action of an electric arc, which creates the effect of a microexplosion with the formation of an explosive thermal and mechanical shock wave, leading to the creation of a spall hole in the zone of the electrodes (see Fig. 2, a–c). Then there is an accumulation of microdamages in the volume of the “stone” due to the propagation of shock waves in it, caused by electrical breakdown. Consolidation of damages into a main crack, which is connected with the initial hole, i.e., the fracture zone between the electrodes, causes the subsequent splitting of the stone (Fig. 3).

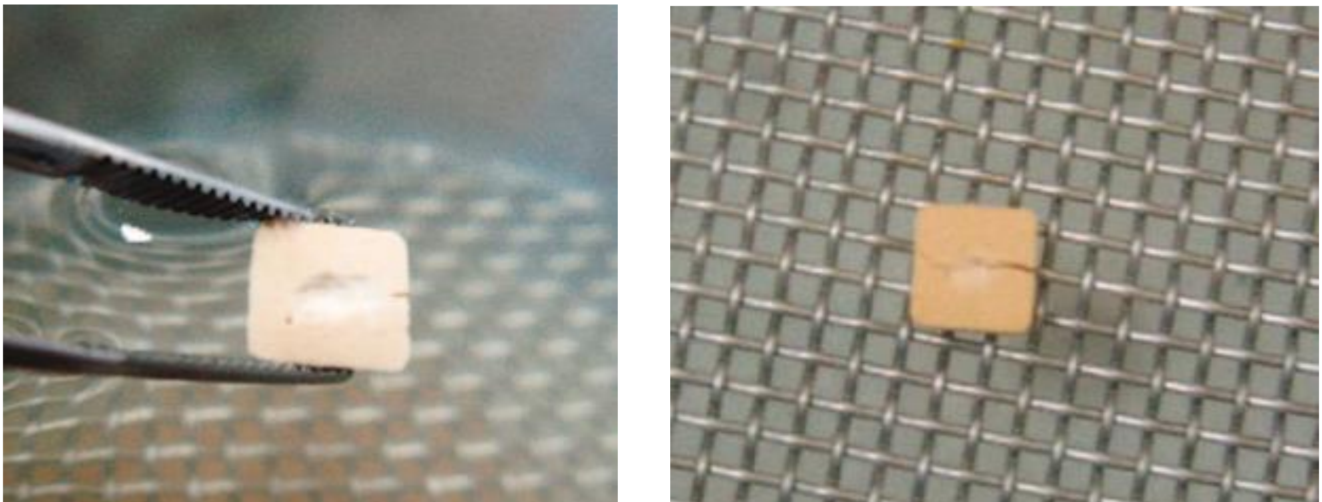


Figure 3. The initial stage of the destruction of an artificial "urinary cameo" sample during the operation of a nanosecond EPL.

The aim of this work was to compare, under laboratory conditions, the efficiency of fragmentation of artificial urinary "calculi" by nanosecond EPL and standard holmium (Ho:YAG) laser lithotripter (LL), which is widely used in clinical practice.

Materials and methods. The studies were carried out on samples of two types, simulating "hard" and "soft" urinary stones, for the preparation of which BegoStone heavy-duty dental gypsum (BegoStone plusTM, Bego, USA), which has a very low coefficient of expansion, was used. The sample preparation procedure was followed in accordance with the manufacturer's recommendations [12]. The difference in the density and hardness of the materials was achieved by changing the proportion of the initial powder of the material to water during their mixing. The "hard" samples had a powder:water weight ratio of 15:3, and the "soft " ones, 15:6, respectively. The density of the obtained samples was evaluated on the Hounsfield scale (HU), hardness - according to the Vickers method (HV). The Vickers hardness measurement was carried out with a load of 100 g and a holding time of 10 s. The average density of the "hard " samples was 2530 HU, the "soft" ones, about 1400 HU, and the microhardness indices were about 90 and 60 HV, respectively.

rectangular parallelepiped were fabricated for testing. Each "stone" size corresponded to a certain probe size of the compared lithotripters. At the same time, the sizes of the probes and "stones" to a certain extent simulated the real clinical situation. In the experiments for Ho:YAG LL, we used Genuine StarMedTec fibers (StarMedTec, Germany) probes of three sizes: 230, 365, and 600 µm. For EPL, 2.7, 3.6, 4.5, and 6 Fr probes were used. The efficiency of lithotripters in experiments was compared for pairs of probes, which corresponded to a certain size of the "stone" (Table 1). In table. 1 also shows the main clinical application of the compared probes.

Table 1

Selecting the size of probes and "stones" to compare the effectiveness of lithotripters

EPL probe size, Fr	Probe size Ho : Yag LL, µm	Stone size, mm	Main clinical application (stone localization)
2.7	230	5x5x4	Ureter, kidney (t.a.)
3.6	365	6x6x4	Ureter
4.5	600	8x8x4	Ureter, urinary bladder
6	600	8x8x5	Bladder, kidney (p.a.)

Note. T.a. – transurethral access, p.a. - percutaneous access

When working with EPL, one probe was used to destroy one stone of a certain size. In LL, reusable probes were used until the probe stopped working. The tip of the laser probe was cut with a special tool both during the experiment, if required (according to the visual inspection of the probe), and before each new experiment to update the working surface of the probe.

Experimental technique. Comparative studies were carried out in an aqueous medium at room temperature. "Stones" of the specified size for each type of lithotripter probe were placed on a stainless steel grid with a cell size of 2x2 mm, immersed in water. The distal part of the probe (tip) was placed at an angle of 90° to the horizontal surface of the "stone" and brought into contact with the sample. The experiment was terminated when no particles of the destroyed "stone" remained on the grid surface, i.e., when the fragmented sample was crushed into parts smaller than 2 mm. Thus, the criterion for the success of the experiment was the fragmentation of the stone sample into pieces less than 2 mm in size. Each experiment with a given type and size of the "stone" and probe was repeated at least 5 times.

At a given energy and pulse frequency, the number of pulses (for EPL) or the accumulated energy (for LL) needed to destroy a certain "stone" with a given type of probe was recorded. The efficiency of EPL and LL was compared at similar energy levels for both devices, using the same types of stones and the corresponding - probe diameters. Subsequently, the recorded data were recalculated for both cases into the number of pulses and accumulated energy, as well as the "net" time required for the complete fragmentation of the stone into the corresponding parts 2 mm or less in size.

In the experiments we used:

- nanosecond EPL Urolit-105M (Litëch Medical Ltd. and Medline Ltd., Israel) (Fig. 4, a); maximum pulse energy 1 J, maximum frequency 5 Hz, maximum output power 5 W;
- Ho:YAG LL Auriga (StarMedTech, Germany) (Fig. 4, b), operating in the frequency mode (up to 20 Hz) with a wavelength of 2080 nm and allowing the transmission of pulse energy to the "stone" up to 3 J. The output power of the system up to 30 W.

Figure 4. Instruments used in the experiments. Left - nanosecond EPL Urolit-105 M, right - Ho:YAG laser lithoriptor Auriga.

The operating parameters of the equipment for performing basic comparative tests, where devices were compared at the same levels of pulse energy, were as follows: for EPL, the minimum applied pulse energy was 0.8 J, the maximum was 1 J, for LL - 0.8 and 1, 2 J, respectively; the number of pulses in a burst for EPL was 5, for LL it was unlimited; the pulse repetition rate for both lithotripters was 5, as was the frequency mode, which was multimodal.

In addition to the main (basic) experiment, the LL efficiency was evaluated under laboratory conditions at higher pulse energies than in the basic experiment. A laser lithotripter with a 365 µm probe was studied during the destruction of artificial "stones" at a pulse energy of 1.6 J ("stone" 6x6x4 mm). In addition, tests were also carried out with the largest 600 µm laser probe studied in this work for pulse energies of 1.6, 2, and 2.5 J on samples of “stones” 8x8x4 and 8x8x5 mm. For these tests, "hard" and "soft" stones were used. In addition, the efficiency of LL was studied at different powers (we changed the pulse energy and frequency). A laser lithotripter with the largest 600 µm laser probe in this study was examined at 14.4, 24 and 30 W applied power on 8x8x4 and 8x8x5 mm stone samples. Only “hard stones” were used in the experiments.

After the tests, a statistical analysis of the measurement results was performed. The criterion for evaluating a significant difference in the results obtained for the two devices under study was the criterion p at a significance level of at least 0.05. The calculation was carried out using statistical program IBM SPSS Statistics.

Results and discussion. It should be noted that the number of successfully fragmented “stones” in this work is 100%; in all the experiments performed, the samples were destroyed into parts less than 2 mm in size.

The total energy (Esum) and the number of pulses required to destroy the “stone”, as well as the “pure” time spent on the fragmentation of a “stone” of a certain type and size, for the two compared types of lithotripters in the basic experiment are given in Table. 2.

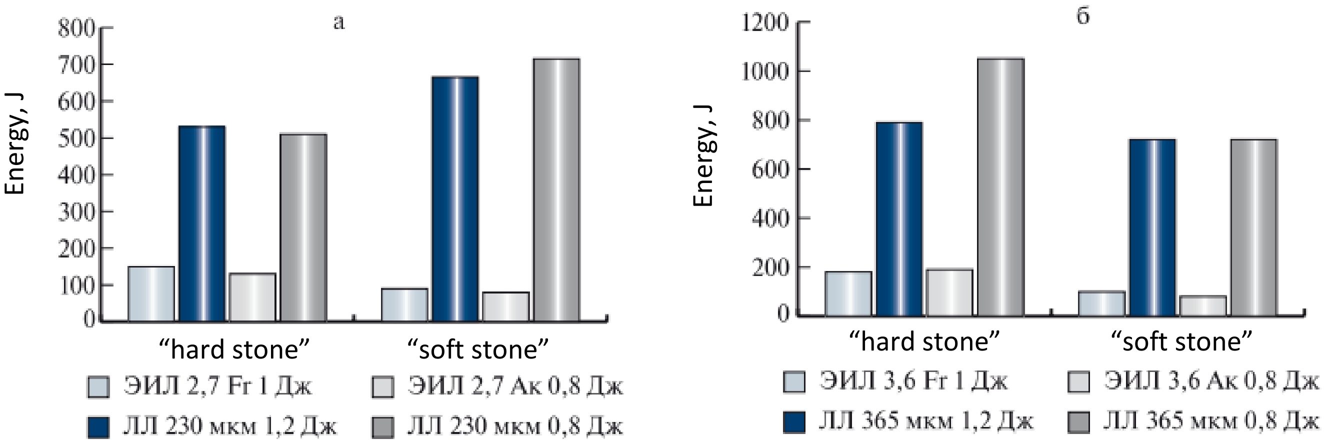
table 2

Test results

Parameter	**Esum, J**	**Number of pulses**	**Time, s**
“Hard stone”, EPL, impulse energy Emin=0.8 J			
Probe 2.7 Fr, sample 5x5x4 mm	137±54	171±68	34±14
Probe 3.6 Fr, sample 6x6x4 mm	171±21	214±68	43±5
Probe 4.5 Fr, sample 8x8x4 mm	288±69	360±87	72±17
Probe 6 Fr, sample 8x8x5 mm	290±67	363±84	73±17

Hard “stone”, LL, impulse energy Emin=0.8 J			
Probe 230 µm, sample 5x5x4 mm	524±75	655±94	131±19
Probe 365 µm, sample 6x6x4 mm	1010±121	1263±151	253±30
Probe 600 µm, sample 8x8x4 mm	1718±364	2147±455	429±91
Probe 600 µm, sample 8x8x5 mm	1984±86	2480±108	496±22
Soft “stone”, EPL, impulse energy Emin=0.8 J			
Probe 2.7 Fr, sample 5x5x4 mm	79±29	655±94	131±19
Probe 3.6 Fr, sample 6x6x4 mm	77±10	1263±151	253±30
Probe 4.5 Fr, sample 8x8x4 mm	119±34	2147±455	429±91
Probe 6 Fr, sample 8x8x5 mm	97±16	2480±108	496±22
Soft “stone”, LL, impulse energy Emin=0.8 J			
Probe 230 µm, sample 5x5x4 mm	726±31	908±38	182±8
Probe 365 µm, sample 6x6x4 mm	724±111	905±139	181±28
Probe 600 µm, sample 8x8x4 mm	1117±197	1396±246	279±44
Probe 600 µm, sample 8x8x5 mm	1407±94	1758±117	356±21
“Hard stone”, EPL, impulse energy Em ax =1 J			
Probe 2.7 Fr, sample 5x5x4 mm	151±43	151±43	30±9
Probe 3.6 Fr, sample 6x6x4 mm	30±9	154±32	31±7
Probe 4.5 Fr, sample 8x8x4 mm	285±70	285±70	57±14
Probe 6 Fr, sample 8x8x5 mm	236±43	236±43	47±9
“Hard stone”, LL, impulse energy Em ax =1 J			
Probe 230 µm, sample 5x5x4 mm	539±102	449±85	90±17
Probe 365 µm, sample 6x6x4 mm	787±71	656±59	131±12
Probe 600 µm, sample 8x8x4 mm	1510±350	1258±292	252±58
Probe 600 µm, sample 8x8x5 mm	1858±204	1548±170	310±34
Soft “stone”, EPL, impulse energy Em ax =1 J			
Probe 2.7 Fr, sample 5x5x4 mm	87±8	87±8	18±2
Probe 3.6 Fr, sample 6x6x4 mm	95±13	95±13	19±3
Probe 4.5 Fr, sample 8x8x4 mm	160±29	160±29	32±6
Probe 6 Fr, sample 8x8x5 mm	129±16	129±16	26±3
Soft “stone”, LL, impulse energy E max =1 J			
Probe 230 µm, sample 5x5x4 mm	664±83	553±69	111±14
Probe 365 µm, sample 6x6x4 mm	722±109	601±91	120±18
Probe 600 µm, sample 8x8x4 mm	1256±173	1047±144	209±29
Probe 600 µm, sample 8x8x5 mm	1592±267	1328±233	265±46

The main criterion for comparing the efficiency of devices was the total energy spent on the destruction of the "stone" and leading to its required fragmentation. For clarity, the Esum indices of the considered pairs of probes are shown in Figs. 5.



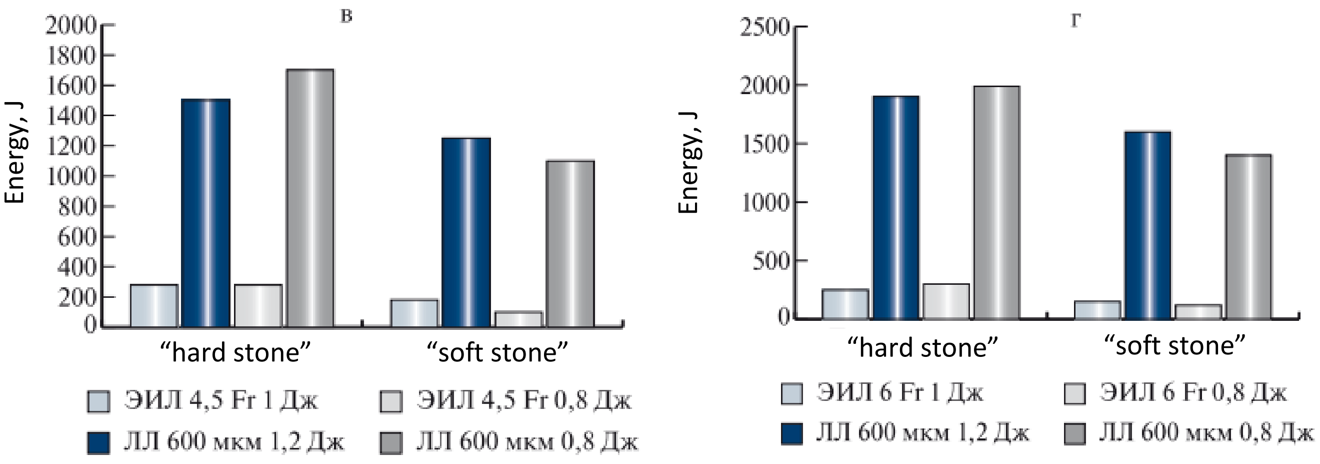


Figure 5. Comparison of the total energy spent on the fragmentation of "stones" for the selected pairs of probes.

The results of experimental studies on the study of the efficiency of an LL operating at higher pulse energies than in the base experiment are presented in Table 1. 3. The results of experimental studies of the efficiency of LL operating at different powers are given in Table. 4. Of the given in table. 2–4 and in fig. It follows from Table 5 that, for all tested types of rock samples, nanosecond EPL requires a significantly lower total energy and less time than LL for the destruction of artificial rocks. The total energy of destruction, the number of pulses, and the operating time of the device in many cases differed by almost an order of magnitude ($p<0.05$). At the same time, when working with both lithotriptors, it was possible to fragment all samples of "stones" into parts less than 2 mm.

Table 4

The results of LL tests on the destruction of "hard stone" with increasing power (probe 600 µm)

Parameter	Yesum, J	Number of pulses	Time, s
Pulse energy 0.8 J, sample 8x8x4 mm, frequency 18 Hz, power 14.4 W	2379±138	2974±173	165±10
Pulse energy 3 J, sample 8x8x5 mm, frequency 8 Hz, power 24 W	2418±294	806±98	101±12
Pulse energy 2.5 J, sample 8x8x5 mm, frequency 12 Hz, power 30 W	2922±318	1169±127	97±11

For the destruction of "soft stones", EPL always required significantly less energy than for the destruction of "hard stones" ($p<0.05$). At the same time, when working with LL, approximately the same energy, and sometimes even more, was expended than for the destruction of a "hard stone". It is clear that the actions of the compared lithotripters differ in the mechanism of destruction of samples with different density α8.0 (hardness), which, in our opinion, explains the significant difference in the data obtained [8, 13]. Statistical analysis confirmed the existence of a fundamental difference between the samples of the results obtained. In addition to a significant difference in the recorded indicators themselves, the spread of their values was also much smaller for EIL than for LL.

Taking into account the obtained results, it seemed interesting to consider the given characteristic of the total energy expended for the destruction of the "stone" to the volume of its sample (specific energy of fragmentation) and its dependence on the size of the lithotriptor probe (Fig. 6).

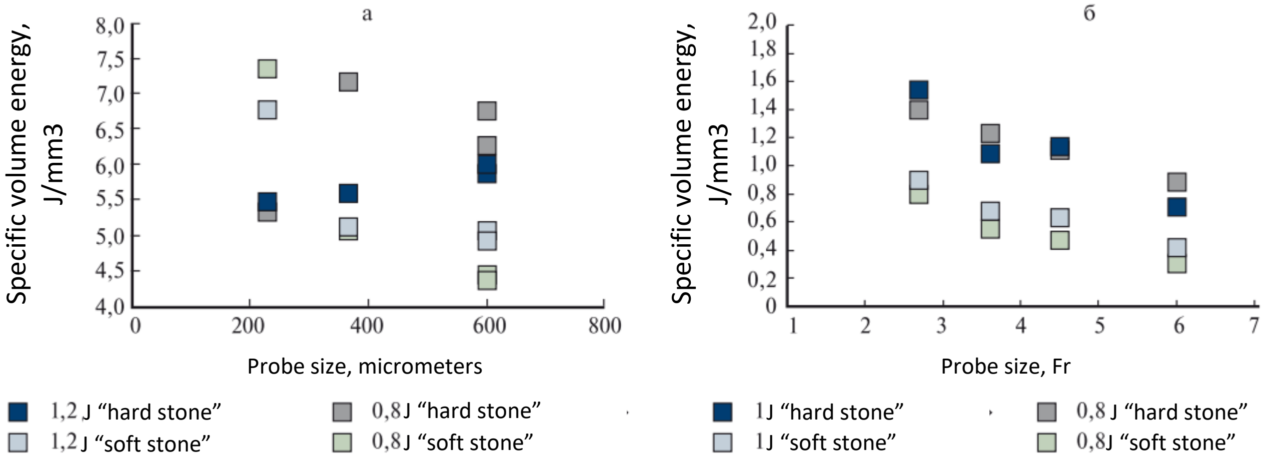


Figure 6. Dependence of the specific energy of "stone" fragmentation on its density and the size of the lithotriptor probe for LL (a) and EPL (b).

It is shown that LL is not characterized by an explicit dependence of the specific energy of the pulse applied to the stone, on the density of the sample material and on the probe diameter ($p < 0.05$), which, apparently, confirms the well-known opinion about the relative "indifference" of the laser to the properties of the fragmented material. At the same time, when working with EPL, a clear dependence of the specific energy on the density of the destroyed material was demonstrated: a decrease in the specific energy required to destroy the "stone" is noted with an increase in the probe size ($p<0.05$). At the same time, the total average - level of the required specific energy of fragmentation of "stones" for all the results obtained for EPL is more than 6 times lower than for LL (Fig. 7). Thus, the EPL requires significantly lower values of Esum for the destruction of the "stone" and, accordingly, the time spent for this, with comparable pulse parameters.

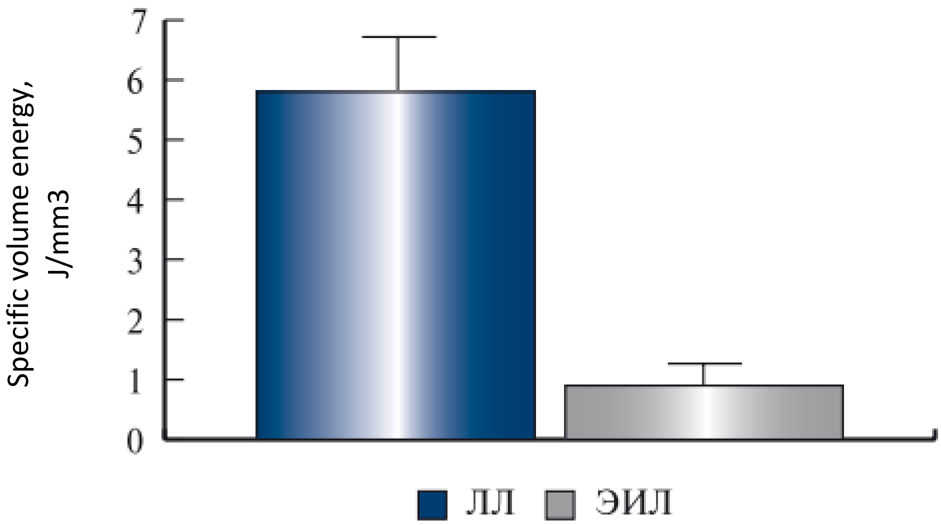


Figure 7. Total specific energy required for the destruction of experimental samples.

In this regard, we made an attempt to determine the parameters of the LL pulse, at which it is possible to obtain results similar to those of the EPL. For this purpose, additional tests were carried out (see Table 3). As seen in fig. 8, an increase in the energy of the LL pulse by more than a factor of 3 led to only insignificant changes in the total energy required for the destruction of "stones," and even a tendency was observed for an increase in the total energy required for fragmentation, with an increase in the energy of the LL pulse. On this basis, the following clinical conclusion can be drawn: with holmium laser lithotripsy, if there is a need to crush the "stone" to sand (transurethral pyelocalicolithotripsy, "impacted" "stone" of the ureter, etc.), one should not strive to start crushing at high energies.

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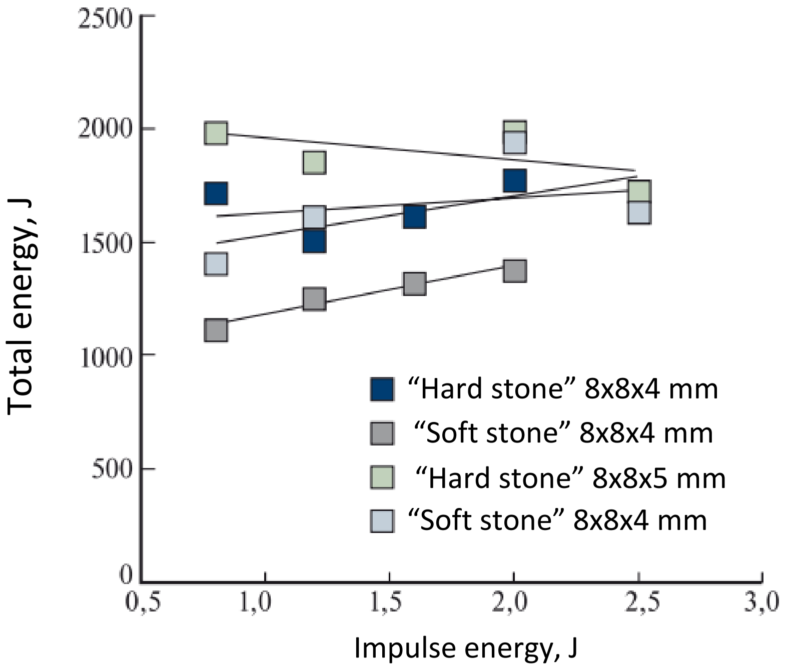

Figure 8. Dependence of the total energy required to destroy the "stone" on the energy of the LL pulse.

Additionally, the operation of the LL was studied with an increase in the power of the transmitted signal due to a change in the pulse energy and its frequency (see Table 4). The results obtained are shown in fig. 9. As in the previous case, increasing the applied momentum backfired and resulted in an increase in the energy required to fragment the samples ($p<0.05$).

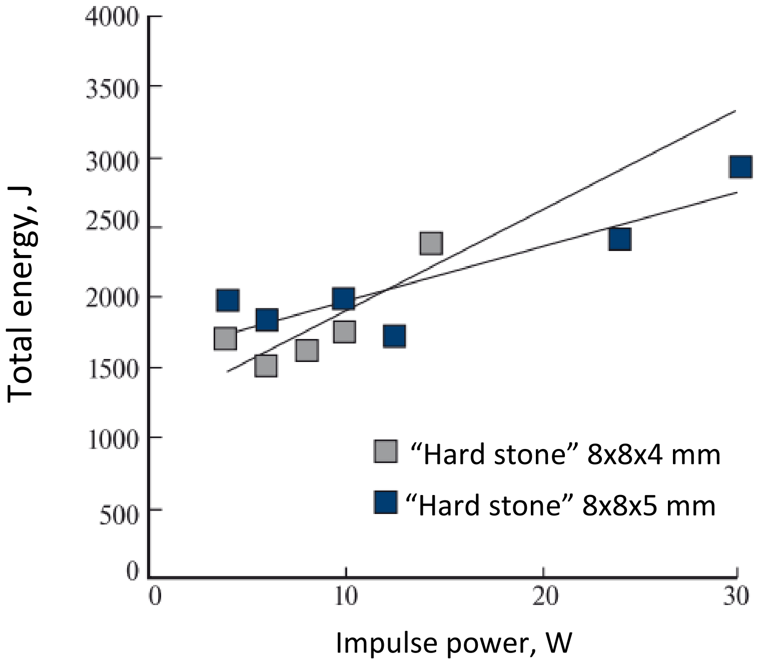

Figure 9 Dependence of the total energy required to destroy the "stone" on the power of the LL pulse.

Conclusion. Thus, the results of the studies performed showed that, for all types of stone samples in this experiment, nanosecond EPL requires significantly lower energy and less time to destroy “stones” than LL, i.e., in terms of physical parameters, it is more efficient for their crushing.

The actions of the compared lithotripters differ in the mechanism of destruction of “stone” samples, which explains the different influence of the density and hardness of their samples on the results obtained. For example, during the destruction of soft “stones”, for nanosecond EPL, it was always required to expend much less energy compared to “hard stones”. At the same time, the laser lithotriptor often required the same energy to destroy both hard and soft “stones,” and sometimes even more energy was required for a “soft stone” than for a “hard” one.

Thus, in this experimental study, various variants of the dependence of the pulse energy and the properties of “stones” during their destruction for the two considered methods of contact lithotripsy were confirmed.

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