

The prediction of urinary calculi fragmentation duration under the holmium laser pulses

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Abstract. The results of settlement-experimental definition (prediction) of urinary stones fragmentation duration by the holmium laser impulses with the wavelength of 2.1 microns and energy from 0.8 to 1.6 J are presented in the paper. The obtained analytical expressions allow to estimate the duration of urinary stone complete fraction on the basis of its volume and radiological density as well as on its location, comprising the auxiliary manipulations time, and to predict lithotripsy operation duration regarding this data.

1 Introduction

In modern medicine, practically in all its specialties, in urology, in particular, laser technologies are widely spread. Lasers of various types are used in urology for the treatment of a hyperplasia and a prostatectomy, treatment of malignancies in an urinogenital system, of a transurethral ureterotomy, etc. [1].

The urolithiasis being characterized by firm mineral calculus formation (urolites) in various areas of an urinary system: kidneys, ureters, bladder is one of the common types of urological diseases. Patients suffering from the urolithiasis form 30 — 40% of all stationary urological patients in hospitals. If it is not possible to cure the patient with conservative methods, doctors are forced to perform surgery. Today, open operations regarding the removal of urinary stones are carried out seldom. They were succeeded by a low-invasive lithotripsy – a way of crushing of stones under the influence of ultrasonic shock waves or laser radiation.

Contact laser lithotripsy with use of a lithotripter on the basis of the holmium laser to be "a gold standard" of a contact lithotripsy, is the most perspective way of urinary calculus fragmentation. Under this surgery the optical probe is carried out through a natural physiological foramen: through an urethra, a bladder and an ureter till its direct contact with a stone. Then, laser impulses are given through the optical fiber, thus producing an urinary calculus fragmentation.

Operations of a laser lithotripsy are concerned to be high-tech surgeries, characterized by the high cost which is compensated by compulsory medical insurance system. Therefore, health facility is interested in increasing the number of such surgeries to be realized on the basis of rational planning of operations promoting the maximum loading of

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the operational room and the high-tech equipment [2,3]. For realization of such planning it is necessary to have an opportunity to estimate the expected duration of operation of a lithotripsy on the basis of results of preoperative inspections of the patient. As for now domestic and foreign references do not present the ways of lithotripsy surgery duration assessment in general and by means of the holmium laser in particular. In [4] an attempt to estimate time spent only for actually fragmentation of a stone without the necessary additional manipulations which are carried out during lithotripsy surgery time is made.

The paper aims to hold the analysis of physical processes of urinary stones fragmentation under the influence of laser impulses and to receive the settlement ratios allowing to estimate fulltime of the contact lithotripsy procedure carried out by the holmium laser taking into account the necessary auxiliary technology manipulations time.

2 Study objects and experimental technique

Urinary stones from 0.019 cm³ to 4.98 cm³ are the study objects. The maximum radiological density of the studied stones fluctuated from 500 to 2250 units of Hounsfield, and average from 322 to 1125 units of Hounsfield. Urinary calculus location: various parts of the left and right ureters, pelvis and cups of both kidneys. Access to urinary calculus was provided through a natural foramen (urethra) to the stone located in an ureter by means of rigid ureteroskop, and to the stone located in the pyelocaliceal system of a kidney by means of semi-rigid or flexible ureteroskop. Domestically produced holmium laser (Ho: YAG) of the «Triple» type which generated impulses lasting 500 μs with energy from 0.8 to 1.8 J and with a frequency from 8 to 12 Hz was used as a litotripter. Optical fibers with a diameter from 270 to 600 microns were used for impulses` transfer from the radiator to a stone. The fragmentation process was tracked with an endocamera of the 1CCD HD ENDOCAM Performance HD type, and displayed on a surgical monitor, and at the same time the entire operation was recorded on electronic device. Matlab`s Statistics and Machine Learning Toolbox was used for experimental data processing.

3 Physical and chemical properties of urolites and their fragmentation features under the influence of laser radiation

Urinary stones` (urolites) fragmentation time depends on their physicochemical properties and location in a human body. Urolites can be found in any area of an urinary system. Predominantly, they are located in the pyelocaliceal system of kidneys and various sites of an ureter (≈ 90%), a bladder (≈ 8.5%) and are much more rare in an urethra (≈1.5%).

On chemical composition urinary stones approximately for 80% consist of calcic (Ca) salts oxalic (oxalates), urinary (urates) or phosphoric (phosphates) of acids [5]. Oxalic stones are to be met most often: calcium oxalate monohydrate (CaC₂O₄·H₂O) — the mineralogical name vevelit, as well as calcium oxalate dihydrate (CaC₂O₄·2H₂O) — mineral vedelit. Urates, i.e. the stones consisting of salts of uric acid (C₅H₄N₄O₃) are the second highest type (about 15%). Phosphates (the mineralogical name struvites) consisting of magnesium, ammonium phosphate and calcium carbonate (MgNH₄PO₄·6H₂O) are the least met in urological practice. Except the mentioned types of urolites there are some other types representing a combination of various salts.

Hardness, structure, form and the size of urolites belongs to physical properties of urinary stones. The urolites` radiological density depending on its mineral composition is used as a characteristic of hardness. The radiological density of urinary stones is defined when carrying out a computer tomography and measured in relative units of Hounsfield (HU). The experiment held established that density of urinary stones can change from 50

HU (a dihydrate of uric acid) up to 3450 HU (apatites). Urinary stones usually represent multicomponent formations which all range of density is divided into 4 groups.

- Stones of high density (more than 1200 HU), the main component of these urolites is mineral vevelit ($\approx 50\%$).
- Stones of average density (800-1200 HU) - major components are struvite of 10-30%, apatite of 30-40% and vevelit 20-30%.
- Stones of low density (400-800 HU) – the main components are struvite and whitlockite and also apatite and struvite.
- Stones of density lower than 400 HU composed with salts of uric acid.

In urology for stone sizing the less informative one or two sizes set in millimeters are still used. By the size stones are divided into groups: <5 mm; 5-10 mm; 10-20 mm and > 20 mm [6]. However urinary stones have the wrong various configuration: in the form of small grains of sand, cone-shaped, cylindrical or oval forms, branched or coral. The surface can be smooth, hilly with ledges and thorns of various form. The form of stones is often defined by its location in an urinary system. It is obvious that under these conditions one or two sizes do not characterize the volume of a stone which depends significantly on its form.

Due to the fact that the fragmentation of a stone depends on its volume and density, it is offered to use the mass of a stone calculated as the multiplication of an urolite volume on its volume density, instead of one or two sizes of a stone and radiological density [4]. Stone volume is defined when performing a computer tomography during the preoperative inspection now. The dependence of volume density of an urolite ρ from its radiological density, gained by authors of the paper [7] as a result of processing of experimental data, is used for calculation of physical volume density:

$$\rho (\pm 0.07) = 1,539 \ 0,000485HU \ [g/cm^3], \quad (1)$$

where HU – the radiological density of a stone, in Hounsfield's units.

According to its structure the majority of stones have the kernel surrounded with a shell of other density. In most cases a stone kernel is formed by oxalate or phosphate, and a shell – by urate or oxalate. The existence in stones up to 10% of water is common for all types of stones which are formed in a human body. Due to this fact it is possible to apply the laser radiation having property of significant absorption in water to urolites' fragmentation process.

The most important target of a laser lithotripsy is a full fragmentation of a stone at the minimum negative impact on the soft tissues surrounding it. This problem is solved only at full absorption of energy of laser radiation in stone material at the minimum absorption by its surrounding soft tissues.

The physics of fragmentation of urinary calculus under the influence of laser radiation differs when using impulses of the laser of various length. This process is schematically represented in fig. 1 and in details analysed in [8]. Calculus fragmentation begins with absorption of photons. Therefore the most important factor is laser energy density or optical energy absorbed by a calculus. The stone fragmentation under the impulses lasting about 10 μs is carried out owing to photoacoustic effect under which the energy of optical radiation transforms to acoustic (mechanical) energy with the formation of a shock wave. Besides, absorption by a stone for very short period of energy causes instant boiling up of the water which is contained in it and the emergence of big internal tension. Thereof, relatively large fragments (splinters) are pulled out from a surface of a stone, and in material of a stone cracks which facilitate its further fragmentation (Fig. 1a) are formed.

The stone fragmentation under the impulses lasting about 100-200 μs is carried out due to photothermal ablation (evaporation) of material of a stone. Between the laser fiber ending and a surface of a stone there is an optical breakdown of a layer of liquid with formation of a steam-gas torch (bubble). Forming and collapse of this bubble promotes

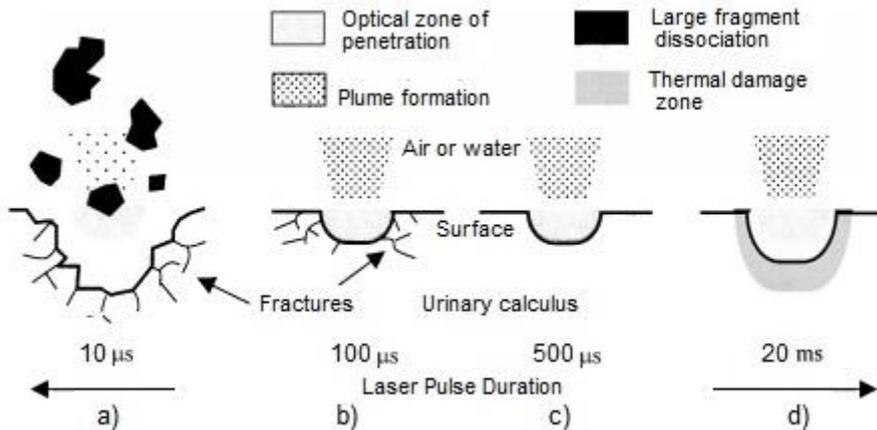


Fig. 1. An illustration of fragmentation or ablation of an urinary stone under the influence of laser impulses of various duration: a) 10 μ s; b) 100-200 μ s; c) 400-600 μ s; d) 20 ms.

formation of the acoustic shock waves leading to cracking of walls of the formed crater (Fig. 1b). At increase in duration of laser impulses up to 400-600 μ s the photothermal mechanism at which the calculus material ablation takes place still operates, however cracks of walls of a crater are not observed (Fig. 1c). Further increase in duration of laser impulses up to tens of milliseconds leads to penetration of overheating zone deep into the material due to long photothermal influence that can damage surrounding tissue (Fig. 1d).

4 Surgery duration assessment of a laser contact lithotripsy

The general time of fragmentation (lithotripsy) of an urinary stone TLT can be presented in the following form:

$$T_{LT} = T_{fc} + T_{dz} = T_{fc} (1 + K_{dz}), \quad (2)$$

where T_{fc} – "net" time of fragmentation of a stone under the influence of impulses of a laser lithotripter; T_{dz} – additional time for performance of necessary technology manipulations; K_{dz} – the additional time coefficient.

Additional manipulations include: fragmentation field washing; movement of fiber on which laser impulses, because of stone shift under influence of laser impulses or because of a chest rise; viewing of an ureter regarding various anomalies, repeated passes through an urethra, a bladder and the mouth of MT, etc.

The expected time of "net" stone fragmentation, at the set energy and frequency of impulses of a holmium lithotripter, can be calculated on the basis of the formula given in [4]:

$$T_{fc} = m / (\gamma \times F_i \times E_i), \quad (3)$$

where m – the mass of a stone in milligrams; E_i – value of energy of an impulse in joules (J), F_i – the frequency of impulses of the laser with E_i energy in hertz (Hz); γ – the specific size of loss of mass of a stone on energy unit. This size is determined by authors experimentally and is equal 0.402 ± 0.11 mg/J.

For calculation of additional time coefficient K_{dz} the actual total general time of a lithotripsy T_{LL} counted from the beginning of fragmentation to its end and the actual time during which there was actually a fragmentation of a calculus ("net" time of fragmentation) T_{dz} was measured. The additional time coefficient was calculated by a formula:

$$K_{dz} = (T_{LTF} - T_{dca}) / T_{dca}.$$

The exact actual value of "net" time of fragmentation T_{def} was determined on the basis of quantity of impulses of Ni spent for stone fragmentation of a certain weight (or the size) and frequencies of impulses of F_i of a laser lithotripter by a formula $T_{dca} = N_i/F_i$.

During the real-life practice (in vivo) of measurement of time intervals of final stone fracture and of necessary additional manipulations it is established that the value of coefficient of additional expenses is random variable with the density of probability following the beta distribution. Beta distribution, as well as widely used normal distribution, is set by two parameters — $\alpha > 0$ and $\beta > 0$. However unlike the normal, always having the bell form, beta distribution has much bigger flexibility. Depending on parameters α and β it can take the hypodispersion form, a concave form (well) or convex, close to normal distribution.

Beta distribution parameters α and β are determined on the basis of the average value of additional time coefficient K_{dz} calculated on experimental data and a standard deviation as well as on the minimum K_{min} and the maximum K_{max} value of this coefficient.

During this research it is established that beta distribution parameters are various when crushing the stones located in an ureter or the pyelocaliceal system (PS) of a kidney. It is experimentally shown that the average value of additional time coefficients for stones' fragmentation located in pyelocaliceal system by means of a semi-rigid ureteroscope (URS) and additional washing (microdrainage), was 1.32 at a standard deviation 0.57, and when crushing stones by means of a semi-rigid ureteroscope without additional washing the average value of additional time coefficient was significantly higher and was 5.44 at a standard deviation equal 2.42. Beta distribution coefficients for the additional drainage are $\alpha = 1.2238$, $\beta = 3.2489$ and without drainage are $\alpha = 1.5020$, $\beta = 3.2668$ respectively. The provided data confirm decrease in additional time for technology manipulations and reduction of laser lithotripsy surgery duration in general due to introduction of additional washing of fragmentation field for the stones located in the pyelocaliceal system of a kidney.

Fig. 2a shows the type of distribution of standardized additional time coefficient during the fragmentation by means of a semi-rigid ureteroscope and additional microdrainage of field of fragmentation. Transition from standardized values of parameter x to the present value of additional time coefficient is carried out on a formula

$$K_{dz} = x (K_{max} - K_{min}) + K_{min}.$$

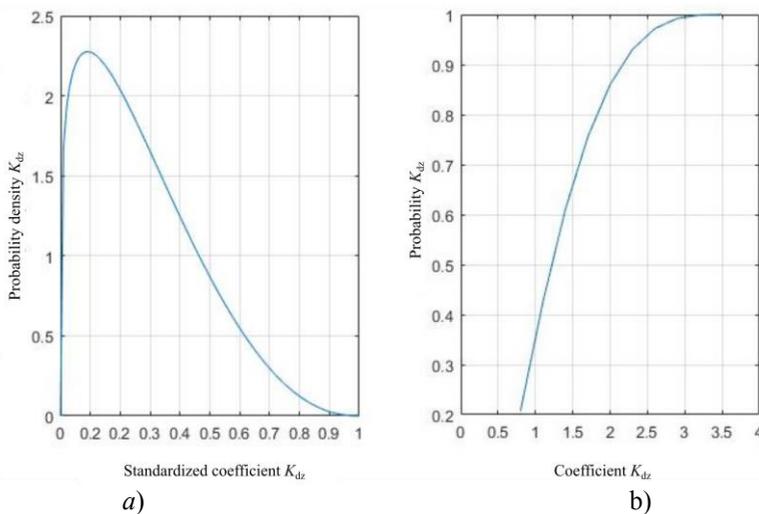


Fig. 2. The plot of the dependence of probability density of additional time coefficient K_{dz} for standardized values (a) and probability that absolute value K_{dz} will not exceed a preset value (b) during the fragmentation by semi-rigid URS in pyelocaliceal system with additional drainage.

For forecasting of duration of the procedure of a laser lithotripsy the following formula of pair linear regression is offered

$$T_{LL} = T_{dz} + K_{dz}T_{dz}.$$

Net calculus fragmentation time T_{dch} is estimated on a formula (1) on the basis of data of preoperative inspection of the patient and experience of the previous operations of the surgeon. The additional time coefficient K_{dz} is a random variable and can change from minimum to the maximum value. For a guarantee that duration of operation of a laser lithotripsy with the set probability will not exceed the predicted value, the dependence of probability of not excess by additional time coefficient of the set value on an absolute value K_{dz} is constructed. In fig. 2b such dependence for the procedure of calculus fragmentation, located in a pyelocaliceal system by a semi-rigid ureteroskop with additional drainage is shown. According to the figure when choosing $K_{dz} = 2.4$ in 95 of 100 cases the current K_{dz} value will not exceed this value.

During the research held, authors have received parameters of distributions of additional time coefficients for all types of a transurethral holmium laser lithotripsy that allows to predict duration of stages of such surgeries.

The alternative network model of a laser contact lithotripsy [9] which allows to estimate the expected time of carrying out surgery on the basis of experimentally received parameters of distribution of separate stages is developed for forecasting of duration of performance of all operation from the moment of arrival of the patient to the operational room before its evacuation.

5 Conclusion

The settlement-experimental method of forecasting of duration of an interval of time of fragmentation itself of an urinary stone under the influence of the holmium laser impulses as well as a time interval of performance of necessary auxiliary manipulations is offered. It is shown that for assessment of duration of fragmentation it is expedient to use the parameter of specific speed of loss of mass of a stone offered by authors representing the stone lump attitude towards the total energy of laser radiation spent for its final fracture, and for decrease in the total time spending for a lithotripsy it is necessary to apply additional microdrainage of field of fragmentation.

It is shown that the general time of a lithotripsy depends on net time of fragmentation and additional time coefficient which is a random variable distributed under the beta law. Quantitative estimates of parameters of distribution of additional time coefficient for the urinary calculus location in various parts of an urinary system are received.

The received analytical expressions allow to estimate the stone fragmentation proper time and lithotripsy surgery time in general on the basis of patients' preoperative inspection results and additional time coefficients' data.

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