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OPTIMIZATION OF HOLMIUM FIBER LITHOTRIPSY PARAMETERS IN UROLOGY

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Abstract: This article reviews current approaches to optimizing the parameters of holmium (Ho:YAG) contact fiber lithotripsy in urology. It analyzes the physical basis of the method, including the 2.1 μm wavelength, water absorption, and the photothermal mechanism, as well as the relationship among the main adjustable parameters: pulse energy, repetition frequency, power, pulse duration and shape, and fiber diameter. Stone disintegration strategies, including fragmentation, dusting, and pop-dusting, are comparatively described. Methods for reducing retropulsion, including long-pulse modes and Moses technology, are discussed together with thermal effects, safety issues, and the role of irrigation. The influence of stone composition and density, expressed in Hounsfield units, on parameter selection is also considered. The article substantiates that rational parameter selection can increase the stone-free rate, shorten operative time, and reduce the risk of complications. The practical relevance of the topic is emphasized for regions with a high prevalence of urolithiasis.

Keywords: urolithiasis, holmium laser, Ho:YAG, contact lithotripsy, laser parameters, fragmentation, dusting, retropulsion, Moses technology, endourology, RIRS.

Introduction

Urolithiasis is one of the most common urological diseases. In recent decades, its incidence has increased, while the recurrence rate has remained high. Advances in endoscopic technology have substantially changed treatment strategies: open surgery and predominantly extracorporeal lithotripsy have increasingly been replaced by minimally invasive contact techniques, including ureteroscopy, retrograde intrarenal surgery (RIRS), and percutaneous nephrolithotripsy [1].

Today, the key instrument for contact stone fragmentation is the holmium:yttrium-aluminum-garnet (Ho:YAG) laser, which, owing to its versatility and applicability to stones of any composition, is regarded as the gold standard for endoscopic lithotripsy [2; 3]. At the same time, the efficacy and safety of the intervention are determined not only by the surgeon's technique but also, to a considerable extent, by the correct selection and optimization of laser parameters. The aim of this review is to systematize current concepts regarding the parameters of holmium fiber lithotripsy and the principles of their optimization in order to improve the efficacy and safety of treatment.

Physical Basis of Holmium Laser Lithotripsy

The Ho:YAG laser is a pulsed solid-state laser with a wavelength of approximately 2100 nm (2.1 μm). Radiation at this wavelength is strongly absorbed by water; therefore, its depth of penetration into biological tissues is limited and is approximately 0.4 mm. This feature provides a pronounced local effect while limiting damage to surrounding structures [2]. Stone disintegration is predominantly photothermal: absorbed energy causes local heating, evaporation of water contained in the stone, and thermal destruction of its structure. The formation of a vapor bubble in the fluid also contributes to the process.

Energy is delivered to the stone by direct contact through a flexible quartz fiber passed through the working channel of the endoscope. This allows the method to be used in both rigid and flexible ureteroscopy, including procedures performed within the renal collecting system. Understanding the physical mechanism is essential for deliberate adjustment of the generator, because the interaction between laser radiation, the stone, and the surrounding fluid underlies all subsequent parameter-related decisions.

Main Parameters of Laser Exposure and Their Interrelationship

The main adjustable parameters of holmium lithotripsy include pulse energy, pulse repetition frequency, resulting power, pulse duration and, in modern devices, pulse shape, as well as the diameter of the laser fiber used. It is fundamentally important to understand that these parameters are not independent: resulting power is the product of pulse energy and frequency; therefore, any change in one indicator inevitably affects the others [4; 5].

Pulse energy, measured in joules, generally varies in clinical practice from 0.2 to 2.0 J or more. Higher energy provides a pronounced fragmentation effect and produces larger fragments, whereas lower energy promotes superficial ablation of material and the formation of fine dust. Pulse repetition frequency, measured in hertz, traditionally ranged within several tens of hertz, whereas the emergence of high-power systems has expanded this range to 80 Hz and above, enabling the implementation of high-frequency fragmentation techniques [4].

Pulse duration and pulse shape have a substantial effect on the outcome. Lengthening the pulse while maintaining the same energy reduces the peak intensity of exposure and decreases backward displacement, or retropulsion, of the stone, which is particularly important during ureteral procedures. Fiber diameter, most commonly 200, 272, 365, and 550 μm, is also a significant parameter. Thinner fibers are preferable in flexible ureteroscopy because they restrict deflection of the distal end of the endoscope less and leave a larger lumen for irrigation; however, they undergo tip degradation, or burnback, more rapidly. Thicker fibers are more durable and are used mainly in percutaneous procedures [4; 8].

Fragmentation Strategies: Fragmentation, Dusting, and Pop-Dusting

Modern endourology offers several stone disintegration strategies, and choosing among them is largely the essence of parameter optimization. Classical fragmentation involves the use of relatively high pulse energy at a low frequency. Its purpose is to divide the stone into larger fragments, which are then removed using a basket extractor. This strategy is effective when histological assessment or analysis of stone composition is required; however, it requires repeated instrument insertion and increases the duration of the intervention [3].

An alternative is the dusting technique, in which low energy and high frequency are applied. The stone is converted into fine dust and small fragments that can pass spontaneously through the natural urinary tract, allowing routine extraction to be avoided [3; 10]. Pop-dusting occupies an intermediate position: the fiber is held at a short distance from a cluster of fragments, and high energy and high frequency are used to further disintegrate the already formed fragments. The choice of strategy depends on the size and location of the stone, the type of access and endoscope, the availability of consumables, and the clinical objective of the intervention.

Retropulsion and Methods for Its Reduction

Retropulsion, defined as backward displacement of the stone under the action of a laser pulse, is one of the main technical problems of lithotripsy, especially in the ureter. Proximal migration of the stone may require additional manipulations and increase the risk of incomplete removal. The severity of retropulsion increases when high energy and short pulses are used [4].

Several approaches are used to reduce retropulsion: reduction of pulse energy, pulse lengthening through long-pulse modes, and special pulse modulation technologies. The most extensively studied among them is Moses technology, which is based on dividing the pulse into two parts: the first part creates a vapor channel in the liquid, while the second delivers energy to the stone through the formed channel with lower energy loss. Preclinical studies have shown that this technology promotes more effective energy transmission and reduces retropulsion compared with standard modes [5]. Rational use of these capabilities helps shorten fragmentation time and reduce fragment loss.

Thermal Effects and Safety Issues

Increasing laser power predictably accelerates stone fragmentation; however, it is also associated with increased heat generation and warming of the irrigation fluid in the confined space of the urinary tract. Experimental and clinical studies have demonstrated that, under high-power settings and insufficient irrigation, fluid temperature may reach values that are potentially dangerous for the urothelium [6; 7]. Thermal tissue injury is determined not only by peak temperature but also by the duration of exposure, which is why the concept of cumulative thermal dose is used.

The key factors in managing thermal load include ensuring adequate irrigation flow, reasonably limiting power, especially when working in narrow spaces or when using ureteral access sheaths that restrict outflow, and applying periodic pauses. Animal model studies have confirmed that the temperature in the renal collecting system during high-power lithotripsy substantially depends on the irrigation flow rate [7]. Thus, parameter optimization requires a balance between fragmentation efficiency and thermal safety; the selected settings should not be the maximum possible ones, but the safest effective ones.

Influence of Stone Characteristics on Parameter Selection

The efficacy of lithotripsy and the optimal set of parameters depend on the physical properties of the stone. Dense stones, such as calcium oxalate monohydrate, brushite, and cystine stones, are more resistant to fragmentation, whereas uric acid and struvite stones disintegrate more easily. Stone density determined by computed tomography and expressed in Hounsfield units serves as an indirect preoperative reference point: higher density is generally associated with greater hardness and may require different energy settings and a different fragmentation strategy.

Taking stone composition and density into account allows the surgical strategy to be planned in advance. For dense and large stones, fragmentation or a combined approach may be appropriate, whereas the dusting technique may be effective for less dense stones. In addition, laboratory studies of fragmentation efficiency using different combinations of frequency, energy, total power, and fiber diameter provide practical guidance for the rational selection of initial settings [8].

Clinical Optimization of Parameters

Parameter optimization does not mean searching for a single universal mode; rather, it means selecting settings that best correspond to a specific clinical situation and provide the optimal balance between efficacy and safety. The main clinical criteria of efficacy include the stone-free rate, duration of intervention, and complication rate [1; 3].

In practice, a rational selection algorithm may be presented as follows: assessment of stone characteristics, including size, location, and density, and evaluation of access; selection of the strategy, whether fragmentation, dusting, or pop-dusting; selection of initial energy and frequency according to the chosen strategy; selection of fiber diameter based on the type of endoscope; and intraoperative adjustment of parameters according to retropulsion, visibility, and thermal load. Such

a structured approach, based on an understanding of parameter interrelationships, contributes to improved treatment outcomes and fewer repeat interventions [4; 5].

The economic aspect also deserves separate attention. Proper selection of settings extends the service life of expensive laser fibers and reduces their consumption by decreasing tip degradation, which is particularly important in resource-limited settings.

Conclusion

Holmium fiber lithotripsy remains the principal method of contact stone fragmentation in modern endourology, and its outcomes are largely determined by the rational selection of laser exposure parameters. Pulse energy, frequency, power, pulse duration, and fiber diameter form an interconnected system; conscious control of this system makes it possible to implement different fragmentation strategies, from classical fragmentation to dusting and pop-dusting.

Parameter optimization involves finding a balance between the effectiveness of stone disintegration and the safety of the intervention, primarily with regard to retropulsion and thermal effects. The use of modern technologies, particularly pulse modulation, including Moses technology, fiber diameter selection, and consideration of stone composition and density, expands the possibilities for individualized treatment. In regions with a high prevalence of urolithiasis, including Central Asia, the implementation of rational principles for optimizing lithotripsy parameters can improve the effectiveness and accessibility of endourological care for the population.

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