Universitat Autònoma de Barcelona

EVALUATION OF HOLMIUM: YAG LASER SETTINGS FOR THE NON-CONTACT STONE FRAGMENTATION TECHNIQUE AND THE CURVED LASER FIBER

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DOCTORAL THESIS

EVALUATION OF HOLMIUM: YAG LASER SETTINGS FOR THE NON-CONTACT STONE FRAGMENTATION TECHNIQUE AND THE CURVED LASER FIBER

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UAB
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El Dr. Joan Palou Redorta, jefe del servicio de urología de la Fundació Puigvert y el Dr. Félix Millán Rodriguez, jefe clínico de la unidad de urolitiasis del servicio de urología de la Fundació Puigvert, certifican que el Dr. Esteban Emiliani Sanz, licenciado en medicina y especialista en urología, ha realizado bajo su dirección la tesis titulada: **“Evaluation of holmium: YAG laser settings for the non-contact stone fragmentation technique and the curved laser fiber”** para optar al grado de doctor en medicina con mención internacional y que esta tesis cumple todos los requisitos necesarios para ser defendida ante el tribunal de evaluación correspondiente.

En Barcelona, a 9 de mayo de 2019

Dr. Joan Palou Redorta

Dr. Félix Millán Rodriguez

A Bibiana por su apoyo incondicional

A mis padres y hermanos por su constancia

A Olivier Traxer pour me montrer le chemain

A Michele per la sua collaborazione nel lavoro e per la sua amicizia

Als meus companys de la Fundació Puigvert per la seva confiança i amistat

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ABBREVIATIONS

EAU: European Association of Urology

SWL: Shock wave lithotripsy

fURS: Flexible ureteroscopy

URS: Semirigid ureteroscopy

PCNL: Percutaneous nephrolithotomy

Ho: YAG: holmium: YAG laser

J: Joules

Hz: Hertz

INTRODUCTION

The prevalence of urolithiasis varies from 1% to 20%[1] depending on many factors, including genetics, ethnicity and consanguinity, geographic area, dietary, socioeconomic, and life-style factors, and even local climate.[2, 3, 4] In the United States the prevalence of kidney stones has been found to be 8.8%, the rate being higher among men than women (10.6% vs 7.1% respectively)[5]. In the same survey, white patients and non-Hispanics were found to be more likely to have a kidney stone than black and Hispanic populations [odds ratio (OR) 0.60 vs 0.37 respectively].

According to Sanchez-Martin et al[6, 7], based on a review of 16 articles, the prevalence of urolithiasis in Spain is 5.06%, with an incidence of 0.73%, corresponding to 325,079 new cases each year. The peak incidence occurs in patients aged 39 to 55 years. Most of the reviewed articles concluded that the prevalence in males and females is similar. Sanchez-Martin et al also reported a higher prevalence in southern Spain than in northern Spain (20% vs 17% respectively), probably because of the higher maximum temperatures in southern Spain.[4]

Urolithiasis carries a high morbidity. Asymptomatic stones were diagnosed incidentally in 8% of 5047 patients undergoing routine CT colonography screening[8]. Subsequently Glowacki et al [9] reported a 31.8% likelihood that such stones would become symptomatic in a series of 107 patients followed up for an average of 31.6 months. The annual likelihood that the patients would experience a stone event was estimated to be 10%, with a cumulative 5-year likelihood of 48.5%.

Regarding patients with asymptomatic stones, a recent study reported that the likelihood that they will develop renal colic is as high as 30%, with painless obstruction and hydronephrosis in 2%[10]. Goldsmith and Lipkin reported that stones of less than 10 mm may cause a related event in 13%–32% of patients; increase in stone size occurs in 30%–46% and there is a need for intervention in 7%–26%. On the other hand, stones larger than 15 mm, especially those in the renal pelvis, are at a high risk for progression. The authors suggested that patients with asymptomatic stones larger than 15 mm, with stones in the renal pelvis, in high-risk categories and occupations, with poor access to a health care facility or compliance, or with solitary kidneys or immunodeficiency may benefit from active stone removal rather than observation[11].

The symptoms of urolithiasis include acute and chronic pain, de novo urinary obstruction, renal function impairment, and urinary infection. The European Association of Urology (EAU) guidelines recommend active stone treatment if patients experience these events or if stone growth is demonstrated[12].

Active treatments for urolithiasis are nowadays predominantly non-invasive or minimally invasive. They include extracorporeal shock wave lithotripsy (SWL), flexible ureteroscopy (fURS), semirigid ureteroscopy (URS), percutaneous nephrolithotomy (PCNL), and laparoscopic nephro- and ureterolithotomy.

The EAU guidelines[12] recommend URS as the first-line treatment for ureteral stones regardless of whether they are larger or smaller than 10 mm and regardless of the location. URS may compete with SWL in stones of less than 10 mm. For kidney stones larger than 2 cm, PCNL is considered to be the first-line treatment as it provides better stone-free rates; fURS and SWL may be considered as second-line treatments. For stones of 1–2 cm, SWL and endourology methods are equally indicated, except in the case of lower pole stones, for which fURS is preferred in the presence of unfavorable anatomic factors for SWL such as acute infundibulopelvic angles or large and narrow infundibula. Finally, SWL and fURS are both considered first-line treatment options for stones smaller than 1 cm.

For the performance of all minimally invasive procedures for treatment of lithiasis (fURS, URS, and PCNL (mainly using sheaths of <24Fr), holmium:YAG (Ho:YAG) laser has become one of the gold standards. It has been advocated as the most effective stone lithotripter by the EAU guidelines[12] as it effectively disintegrates all kinds of stone[13] while carrying a low risk of peripheral injury. Accordingly, it is currently the most widely used and studied laser in urology[14].

The laser beam, as the acronym implies (L.A.S.E.R.), is a beam of light amplified by a stimulated emission of radiation. The laser generators are basically composed of an external energy source and an amplifying optical resonator that contains the crystal or laser medium (such as holmium) between highly and partially reflective mirrors. As the energy source excites the medium, photons are produced. The free photons bounce between the mirrors, exciting the material even more and increasing the production of photons. Once produced in high quantity, the bouncing photons exit the generator in a compact and directional way, being conducted through an optical fiber of variable diameter.[15] The laser light is reflected along the fiber in a zig-zag fashion. The angle at which the laser is reflected (called the numerical aperture) is generally <12°.[17]

The Ho:YAG laser is a pulsed laser, with a wavelength of 2100–2140 nm and a pulse duration of 200–1000 µs. Each pulse can be set in a different range of emitted energy measured in Joules (J) and repetition rates per second (Hz); additionally, new Ho:YAG machines allow the delivery of each pulse of energy in short or long time lapse[14, 16].

The Ho:YAG laser has also become the standard as it can be transmitted through small, flexible fibers ranging from 200 to 1000 µm in diameter. This versatile feature has made possible its use in fURS and flexible nephroscopy, allowing lithotripsy throughout the upper urinary tract.[17]

The optical fibers are composed of several layers comprising different materials for transmission and protection. Once the fiber has been plugged and coupled to the laser generator, the inner fused and compact OH-silica core is responsible for collecting the light from the generator and transducing it to the tip. This material allows the photons to be reflected linearly (called the "coherence" of the beam) and to be transmitted while minimizing the thermal energy of the beam. Two cladding layers made of fluorine-doped silica and fluoroacrylate surround the silica core to protect it and decrease transmission losses. Finally a protective outer layer or jacket made of ethylene tetrafluoroethylene (ETFE) is necessary to ensure adequate reflection of the beam.[17]

As mentioned above, the fibers may range from 200 to 1000 µm in diameter. Generally the laser fiber diameter cited by the manufacturer refers to the inner silica core, and the fiber diameter increases y up to 87.3%when the outer cladding is taken into consideration.[18]

The Ho:YAG laser has a variety of adjustable parameters that can be manipulated to ensure maximum efficiency. Basic research has provided us with knowledge that can improve our surgical performance, including the facts that lithotripsy ablation increases at increasing the pulsed energy but not the frequency, that short pulses are more ablative than long ones, and that small fiber diameters can be used without compromising ablation while providing better irrigation and ureteroscopic maneuverability[14]. However, controversy remains as to which is the most appropriate combination of adjustable parameters and only a few in vitro studies have evaluated the real power output and its repercussions.

The Ho:YAG parameters can be set to achieve different ablative effects, bearing in mind that the stone treatment must be tailored according to various characteristics such as the number of stones and their hardness, size, location, and composition. Several techniques have been described, including “dusting”, fragmentation, chipping, and the “popcorn” technique. Settings are routinely combined during surgery to reduce stone burden and to obtain the desired outcome, such as complete dusting or fragmentation for active stone extraction.

In addition to enabling us to improve laser settings, basic research has provided us with useful ways to manipulate the laser fiber in order to achieve better performance and improve safety during the procedure. One such manipulation is cleaving he transparent tip of the fiber, leaving only the fiber coated. It has been shown that once the laser fiber has been used, damage to the tip caused by the thermal action of the laser translates to increasing reflection of the laser beam, resulting in decreasing efficiency[19]. Kronenberg and Traxer[19] found coated fibers to be significantly more effective than uncoated fibers (increasing stone ablation by up to 50%). They compared the use of metallic scissors vs ceramic scissors (recommended by manufacturers for cleaving of the tip) and found no difference when the fiber retained the coating. Even if, when manufactured, the laser fiber is always stripped from the protecting cladding at the tip, leaving only the transparent silica core, the authors recommend cutting the fiber tip at the beginning of and regularly during the procedure[20].

On the other hand, proper and safe transmission of energy within the fiber is strictly related to the procedure itself. The calyceal anatomy varies widely, and the fact that some collecting systems have acute angles may force the surgeon to excessively bend the fiber in the fURS in order to reach a stone. Such excessive bending may increase laser reflections in the fiber, leading to energy leaks and fiber damage and failure.[17] If the fiber fails while in the working channel, fURS damage is inevitable. Working in excessive deflection with resultant loss of integrity of the working channel is one of the most common causes of fURS damage.[21]

Means of optimizing laser settings in order to achieve better fragmentation while ensuring a safe procedure for the instrument and the patient remains an open field in laser research.

HYPOTHESIS

1. Evaluation of the non-contact fragmentation (popcorn) technique

There are many variables (energy, frequency, pulse length, fragmentation time and laser fiber size) that influences the efficiency of the non-contact stone fragmentation (popcorn) technique when using Ho:YAG.

2. Evaluation of the laser fiber bending

There are many variables (energy, frequency, pulse length, deflection diameter and laser fiber size) during Ho:YAG laser fiber manipulation that are related to a lower risk of fiber fracture wile firing.

OBJECTIVES

3. Evaluation of the non-contact fragmentation (popcorn) technique

To evaluate the different variables relevant when using the Ho:YAG laser in order to identify which factors predict an optimally efficient non-contact fragmentation (“popcorn”) technique. Variables considered included:

- Energy
- Frequency
- Pulse length
- Fragmentation time
- Laser fiber size

4. Evaluation of the laser fiber bending

To evaluate laser fiber manipulation and the safety of laser fiber bending and to identify which Ho:YAG parameters may reduce the risk of failure. Variables considered included:

- Energy
- Frequency
- Pulse length
- Laser fiber size
- Deflection diameter

MATERIALS AND METHODS

1. Evaluation of the non-contact fragmentation (popcorn) technique

To evaluate the non-contact fragmentation (popcorn) technique, an in vitro experiment was designed.

In order to simulate small calyceal cavities a conventional vacutainer was used as a reservoir to perform the lithotripsy. A standard ureteral access sheath (10/12 Re-Trace®, Coloplast™, France) was placed in each vacutainer to allow introduction of the flexible ureteroscope. A Flex-XC® ureteroscope (Karl Storz™, Germany) was inserted through the access sheath, into the vacutainer, loaded with the laser fiber. The ureteroscope was kept stable, the laser fiber was placed 1 cm from the bottom of the vacutainer and 3 mm from the tip of the scope (Figure 1). A bag of saline solution was connected to the ureteroscope at 40 cm from the experiment site to obtain constant irrigation at a pressure of 40 cmH_20, which was allowed by use of the access sheath (Figure 2). The endoscopic vision of each procedure was recorded.

Artificial stone phantoms were produced to simulate urolithiasis, as described in the literature. A BegoStone mixture of 30 g per 6 ml saline was used, as recommended, to simulate hard kidney stones. The plaster was poured into plastic cylinders and left to dry overnight. The stones were then cut to obtain 4- to 5-mm specimens (up to 125 mm^3) (Figure 3). Computerized tomography, performed to evaluate stone hardness, revealed a 1900-HU structure (Figure 4).

To perform the tests the specimens were divided into four stone groups (subjected to a total of 144 evaluations). Each experiment was done with a group of four stones that had previously been weighed using a Mettler Toledo-AT200 electronic balance scale (weighting capacity of 205 g) and recorded.

Various settings were used, including an overall power count between 5 and 60 W with a PULSE 120® Ho:YAG laser (Lumenis™, Israel). Setting combinations of 0.5 and 1.5 J, 10, 20, and 40 Hz, and short and long pulses of 500 and 750 µs were used. Evaluations were performed with 273-µm and 365-µm fibers, which were cleaved for each experiment to avoid bias due to fiber degradation. Each setting and fiber combination was investigated for 2 and 4 min of laser lithotripsy, and each trial was repeated 3 times.

After lithotripsy, the ablated stones were passed through a strainer, retaining only fragments larger than 0.3 mm remove dust. These remaining fragments were kept in a tube and dried overnight to ensure that water absorption would not influence weight. Then they were weighed again using the electronic balance scale.

Stone weights and sizes before and after ablation were compared. A stone volume reduction of 50% was used as the cut-off level above which the popcorn technique was defined as highly efficient.

Logistic regression analysis was performed. Significant predictors of a highly efficient popcorn technique were analyzed, with $p<0.05$ being considered significant.

All the experiments were recorded from the outside and endoscopically for further evaluation.

2. Evaluation of the laser fiber bending.

For this in vitro study, single-use 272- µm and 365-µm fibers were tested as representative of small and large fibers (Rocamed®, Monaco). For the experiment a MH01-ROCA FTS-30W holmium laser (Rocamed®, Monaco) was used.

Five different fiber-bending diameters were tested: 9, 12, 15, 18, and 20 mm (Figure 5). The diameter was defined as the distance between the opposite sides of a fully deflected fiber measured at 180° (Figure 6).

For the setup, the laser fibers were fixed while bent in a support made of silicone tubes and secured by plastic screws.

The setting combination tested with each of the fibers bent at the different diameters were: short pulse, 1.5 J, and 5 Hz to simulate fragmentation settings and long pulse, 0.5 J, and 15 Hz to simulate dusting settings. Both achieved an overall power output of 7.5 W. To ensure the correct energy transmission, the power output and transmission were measured with a Molectron EPM1000 (Coherent, Inc.) wattmeter during the tests. A high-speed camera (Photron Ultima APX-RS 3000) at 10,000 frames per second was used to record fiber fractures. Image analysis was performed using the Photron FASTCAM Viewer 2.4 software.

The laser was activated for 5 min in every experiment until either the end of the 5-min period or fracture of the fiber. The experiments with each setting, bend diameter, and fiber size were repeated 10 times.

Statistical analysis was performed using the Fischer test on BioStaTGV (France), with $p<0.05$ being considered significant.

RESULTS

1. Evaluation of the non-contact fragmentation (popcorn) technique

A total of 144 evaluations were conducted using 576 stone phantoms. The mean phantom base size was 4.3 mm (4.1–5 mm) and the mean height, 4 mm (3.9–4.4 mm), with no statistical difference among stones. Overall the stone groups (comprising four stones per group) were comparable and had a consistent weight, with a mean of 0.23 g (0.16–0.35 g).

After lithotripsy and passage of the stone fragments through a strainer, thereby removing dust, the mean weight loss of the stones was 0.7 g (0.01–0.24 g).

When using a median stone volume reduction of 50% as the cut-off level above which the popcorn technique was defined as highly efficient, factors predictive of a highly efficient technique were:

- High energy (OR =19.2, 95% CI 6.40-57.74, $p<0.001$)
- Long pulse (OR = 2.6, 95% CI 1.02-6.52, $p = 0.045$)
- Frequency of 20 or 40Hz vs. 10Hz (OR = 13.9, 95% CI 4.37 – 44.18, $p <0.001$),
- Longer time (OR = 10.2, 95% CI 3.59-28.93, $p <0.001$)
- Small (273 µm) laser fibers (OR = 3.3, 95% CI 0.12 – 0.81, $p = 0.016$)

In the multivariate analysis, small laser fiber size, longer pulse, and longer fragmentation time were found to be the most important factors predicting an efficient popcorn technique (Table 1).

In the endoscopic video evaluation of the experiments, a low energy (0.5 J) yielded mostly clear views. When the energy was increased to 1.5 J, in combination with a frequency of 10 or 20 Hz, a clear view was retained whereas use of a frequency of 40 Hz was associated with blurred vision in all combinations.

2. Evaluation of laser fiber bending

A total of 200 experiments were conducted. Both laser fibers broke when bent at acute angles; small 272-µm fibers broke only at a fiber bend diameter of 9 mm while large (365-µm) fibers broke at bend diameters of 9, 12, and 20 mm. Although large fibers failed more frequently, the difference did not reach statistical significance.

When using dusting settings, both small and large fibers broke only at a bend diameter of 9 mm (p= 0.037 and 0.006, respectively), though only 20% of small fibres broke compared with 30% of large fibers.

When using fragmentation settings, fibers broke more frequently at bend diameters of <12 mm for small fibers and <15 mm for large fibers (p=0.007 and 0.033, respectively). None of the small fibers broke at bend diameters of more than 9 mm. As for the large fibers, 33% failed at bend diameters from 9 to 15 mm and 5% at bend diameters of 18 and 20 mm. Large fibers broke in 90% of the tests at a bend diameter of 9 mm, and 10% failed at bend diameters of 12–20 mm (table 2 and 3).

Short pulse and high energy were significant risk factors for fracture of the 365-µm fibers (p=0.02), but not for fracture of the 272-µm fibers (p=0.35). High frequency was not a risk factor for fiber failure.

When analyzing the high-speed camera footage of fiber failure (Figure 7), leaking light beam was seen in the fiber coating before fiber breakage. This burning point was seen only at the beginning of the bending curve (Figure 8).

DISCUSSION

1. Evaluation of the non-contact fragmentation (popcorn) technique

Ho:YAG laser treatment has become the standard of care for urolithiasis, and several laser techniques have been reported to achieve adequate stone disintegration, the choice depending on the effect that the surgeon wants to exert upon the stone.

Classic techniques include[22]:

- Dusting: This technique aims to dust the stone completely, the goal being spontaneous and painless evacuation without the need for active stone extraction. This technique is commonly used for soft stones such as uric acid and calcium oxalate dihydrate stones as they are easily dusted. Dusting is achieved with low ablation settings using a low energy, a long pulse, and a high frequency (as Ho:YAG machines may produce low amounts of energy very quickly). Further it is not a clear definition of what is "dust" in terms of stone volume being subjectively identified. Studies have shown that better outcomes of dusting are achieved in the case of fragments sized less than 4 mm: such fragments are less likely to grow and fewer complications occur (in terms of emergency department visits, pain, and need for surgery[23]).

- Fragmentation/chipping[22]: The aim of the fragmentation technique is to break the stone into small pieces for active extraction with a basket or forceps. This technique is achieved with high ablation settings (high energy, low frequency, and short pulse). It has been reported that fragmentation can be useful for hard stones such as calcium oxalate monohydrate stones. Generally fragmentation entails the use of a ureteral access sheath to protect the ureter and increase the speed of stone extraction while maintaining low intrarenal pressures during the procedure.

- Non-contact fragmentation (popcorn): This technique, as first described by Chawla et al[24], entails constant firing of the Ho:YAG laser in a fixed position between multiple stones in a calyx, reducing the stone burden as the stones move around the cavity (whirlpool-like phenomenon), hitting the laser randomly. This technique is reported as suitable when multiple fragments are present in a small cavity (a calyx) in which the whirlpool-like phenomenon can ultimately be achieved. Initially the authors recommended a setting of 1J-20Hz although use of only 365 µm fibers and the laser pulse that was not measured. The technique was also described to be more effective if the fiber is directly in contact with the stones[25]. Over the years the technique has been given different names, including lottery ball, washing machine, and hot tub. We decided to call it the popcorn technique in accordance with the initial description.

- High-frequency dusting (pop-dusting)[26]: Recently, “high-frequency dusting” has been reported as a variation on the popcorn technique that dusts stones in the same manner. The technique was described with the use of new high-power Ho:YAG lasers that can deliver an output power of up to 120 W. The setting described is low-energy (0.5 J) and high frequency (50–80 Hz), avoiding retropulsion.

In practice it is common to use several techniques during one procedure, regarding them as complementary rather than exclusive. Different settings are routinely combined during surgery to reduce the stone burden and to obtain the desired outcome.

After initial dusting or fragmentation of a stone, some fragments may remain that can be further fragmented, extracted, or pulverized by means of the popcorn technique. The stone-free rate may vary depending on the technique employed, although the evidence in this regard is limited. A randomized trial showed fragmentation and stone extraction to be associated with fewer visits to the emergency department and a non-significant tendency toward a lower number of residual stones and fewer ancillary procedures[27]. A recent prospective study showed a better stone-free rate for fragmentation and extraction vs dusting (74.3% vs 58.2% respectively) at univariate analysis but not multivariate analysis[28]. In this regard, the popcorn technique can be effective in achieving stone dusting or reduction of stone burden until extraction is possible. Nevertheless, the stone fragmentation technique should be decided upon on a case-by-case basis as one technique does not fit all patients[29].

Chawla et al[24] reported a setting of 1.5 J and 40 Hz to be most efficient for stone fragmentation, with achievement of a 63% reduction in stone weight after 2 min of continuous laser firing. However, they recommended 1 J and 20 Hz as the optimal setting owing to a reduction in efficacy when using the higher energy settings of 1.5 J and 40 Hz, i.e., 1 J and 20 Hz resulted in the greatest weight reduction (18%) in relation to kJ delivered[24].

Limitations of Chawla et al’s study included the use of only 365-µm fibers and lack of laser pulse measurement (as the technology was not available at the time). The purpose of our study was to evaluate all the variables currently of relevance when using the Ho:YAG laser in order to determine which combination achieves the most effective non-contact fragmentation. In terms of settings we found that high energy (1.5 vs 0.5 J), high frequency (20–40 Hz), and long pulse is the best combination for optimization of the popcorn technique. Also, a longer fragmentation time (4 min rather than 2 min) and use of a small fiber significantly increased the efficiency[30].

Regarding Ho:YAG laser parameters, it is known that stone ablation is determined by energy and pulse. At increased energy and with use of a short pulse, higher ablation is achieved. Nonetheless, frequency does not affect the stone ablation but only the speed of the fragmentation[14 31].

Regarding the laser fiber size, Kronemberg and Traxer reported that small and large fibers (200 vs 500 µm) achieved similar ablation rates at the same power setting, observing that small fibers produced deeper fissures and large fibers produced wider fissures[31]. Further, large fibers increased retropulsion, as did increased energy and the use of a short pulse[14 32].

In the initial description of the popcorn technique by Chawla et al[24], not all settings (especially pulsed energy) were correlated with better efficiency, which may lead one to think that other settings and variables may interfere in the efficacy process. The achievement of higher efficiency by the use of a long pulse and small fibers may be explained by a decrease in retropulsion, which allows more contacts between the moving stones and the laser fiber. Use of a long pulse and small fibers may compensate for the increase in retropulsion that may accompany increasing energy while having the most efficient ablation on each impact [33]. Further current recommendations on fURS promote the use of small fibers as they allow better irrigation (and visibility) and better deflection[34]; the results of the current study support this recommendation.

During lithotripsy the laser fiber is at constant risk of failure and tip damage due to the burnback effect[35]. The fiber may be manipulated to avoid such an effect by cleaving the tip or stripping the external coating of the fiber. In this regard, some recent studies have shown that coated fibers achieve better ablation rates than stripped fibers[35] whereas other authors have suggested that stripped fibers may achieve better ablation rates [36] [37] (although this last study was conducted with large fibers, in a non-systematic fashion, and using laboratory utensils rather than surgical cleaving methods). Finally, it has been concluded by several groups that after one minute of use, the efficiency and the power output in the fiber tip are the same regardless of the cleaving or stripping method[38].

It is to be borne in mind that the recommendation to cleave the fiber tip has been made not only to avoid failure but also for several other reasons, including (a) ability to see the laser fiber during the procedure on account of avoidance of the transparent tip, (b) the fact that the fibers remain attached in the event of rupture, and (c) the coating may offer protection to the working channel during fiber insertion[39] [40]. All this evidence has made cleaving the fiber tip with metallic scissors a standard procedure when performing fURS. For this reason, it was decided in this study to cleave the tip of the fiber with metallic scissors before each experiment[34].

In the current study, synthetic stones of 1900 HU were used. Clinically synthetic stones of this nature can be compared to brushite or calcium oxalate monohydrate stones. Although the experiment was designed to be systematic, the results may accordingly be viewed as most applicable to the treatment of hard stones, and it is possible that even better results might be achieved when treating softer stones.

Regarding the endoscopic view evaluation, all the experiments with a low energy (0.5 J) always had clear views. When the energy was increased to 1.5 J, the vision depended on the frequency. When using frequencies of 10 and 20 Hz, a clear view was retained, whereas a frequency of 40 Hz was associated with blurred vision after a few seconds.

Finally, a clinical recommendation can be made on the basis of the results of the current study: In order to perform an efficient popcorn technique, the Ho:YAG laser should be used with a long pulse, high energy (1.5 J), and high frequency (20 Hz) – this combination represents the best compromise in terms of ensuring efficient ablation while retaining adequate vision quality. Combining these settings with the use of small laser fibers and a lithotripsy duration of at least 4 min will significantly reduce stone burden.

2. Evaluation of laser fiber bending

Flexible ureteroscopy has become the gold standard for treatment of stones up to 2 cm (and larger with an eventual two-stage procedure). It achieves a high stone-free rate with low complication rates[12], including in the case of stones in the lower pole, where PCNL and fURS are superior to SWL[41]. Treatment of lower pole stones does, nevertheless, represent one of the main challenges when performing fURS as the stone-free rate remains lower than for other renal locations and there is an increased chance of instrument damage.

Unfavorable factors for stone clearance include multiple stones or multiple locations, stones larger than 1 cm, and unfavorable lower infundibulum anatomy, especially acute (<30°) infundibulopelvic angles[42 43 44]. On the other hand, flexible scopes may suffer deflection mechanism damage (as a mechanical defect), damage in the working channel if the laser fiber breaks, or secondary complications such as locked deflection, and all of these scenarios involve costly repairs[45 46].

Regarding scope damage, the most relevant mechanisms identified in a prospective study by Carey et al. included breakage due to laser misfiring (>35.9%) and excessive torque (>28.2%) resulting in decreased deflection (20.5%) or another mechanical defect without apparent damage (7.7%)[47]. Legemate et al found in a recent prospective study that shaft damage due to manual forcing is the most important limitation to the durability of reusable ureteroscopes. That these authors did not experience laser breakages or misfiring may be explained by the fact that the procedures were all done by highly experienced endourologists with optimal equipment[48].

Lower pole access with acute angles that require manual intraoperative forcing and small deflection diameters to achieve good stone fragmentation is a particularly high-risk maneuver that increases the likelihood of fURS damage and breakage, especially at the junction between the shaft and the bending tip, which is considered the most fragile portion of the flexible ureteroscope[47]. Moreover, as mentioned previously, working channel perforation may be an important cause of damage[49]. For these reasons, the clinical recommendation is that lower pole stones should be relocated to another calyx when possible, thereby increasing the stone-free rate and reducing the chance of instrument damage[50].

Several studies have demonstrated that the attributes of Ho:YAG laser fibers may vary according to the manufacturer. Variation among manufacturers in respect of flexibility, energy transmission, fiber diameter, and durability can result in different fiber performances, as can differences in specific attributes such as fiber size[51] [52] [53].

Regardless of the fiber brand, when firing increasing pulsed energy to acute bent laser fibers, similarly to our study Knudsen et al. showed that bent laser fibers are at high risk of fracture while having different levels of resistance and braking at different bend diameters ranging from 10 to 30 mm[51]. In this regard Lusch et al[54]., evaluating the performance characteristics of laser fibers in a bench model, showed that high energy, low frequency, and a long pulse were associated with reduced risk of fiber fracture.

This is in contrast to our study, where dusting (low energy, high frequency, and long pulse) settings showed a lower risk of fracture than high energy, low frequency settings. Our finding that a short pulse is associated with a higher risk than a long pulse may be attributable to the fact that the former achieves higher ablation rates and is frequently used as standard in fragmentation settings[14]. Again, the studies are consistent in finding that the larger the fiber and the more acute the bending angle, the higher the risk of fracture.

Laser fiber failure involves three physical phenomena relating to the fiber mechanism. The first is the numerical aperture (NA), that is the angle at which the laser beam is fired from (or exits) the laser generator to the fiber. This will allow the laser beam to be transmitted through the fiber in a zig-zag motion as the core and cladding reflect the beam in a linear way up to the end of the fiber[17]. The NA can be calculated by means of the following equation when one knows the refractive index of both OH-silica cores of the fiber ($n1$ and $n2$):

$$NA = sin\,\emptyset = \sqrt{}n1 - n2$$

The angle of this internal reflection (IR) is the second phenomenon. A proper IR will allow the laser beam to be transmitted successfully to the tip. The Ho:YAG divergence angle has been described to range from 8° to 12°.

Laser beams are not equally transmitted through bent and straight fibers[55]. Laser fiber bending may alter the IR, resulting in realignment of the beam; the divergence angle will become more acute, increasing the number of reflections and thereby exceeding the maximum propagation angle of the fiber. This will allow the laser beam to be transmitted (leaking) through the cladding, causing fissures, burns, and ultimately fiber failure[17] (Figure 9). This was shown in the video resulting from our experiments and was termed the burning point, a phenomenon seen microseconds before rupture, just beginning the curve where total IR is lost, where total IT is lost.[56]

The third physical property involved in fiber failure is evanescence, which is the wave loss or the small portion of the light beam that is not correctly reflected to the end and penetrates the cladding. Evanescence can occur due to the material of the fiber, the use of high energy, and bending of the fiber (increasing stress); the last mentioned can increase the penetration of the beam five times further into the cladding as the laser beam is not equally transmitted in straight and bent fibers[17, 32].

In addition to well-known practices such as stone relocation from the lower pole, the following clinical recommendations can be drawn from the findings of this study: If lower pole lithotripsy is necessary then small (<272 µm) fibers should be used and the Ho:YAG laser should be set to dusting settings with low energy and long pulse until the stone burden is small enough for relocation. If possible, one should avoid working while bending the ureteroscope acutely or, if necessary, use single-use ureteroscopes to avoid fiber failure and instrument damage.

CONCLUSIONS

1. Evaluation of the non-contact fragmentation (popcorn) technique

The most efficient popcorn setting combination with the Ho:YAG laser was long pulse, high energy (1.5 J), and high frequency (20 Hz). Combining these settings with the use of small laser fibers and a lithotripsy duration of at least 4 min significantly reduced stone burden.

2. Evaluation of laser fiber bending

Small (<272 µm) laser fibers and Ho:YAG laser dusting settings with low energy and long pulse significantly reduce the risk of fiber failure when bending the fiber. Fiber bend diameter of 9 mm showed the highest risk of failure compared to less acute angles. The frequency setting did not show to be a risk factor for fiber failure.

FIGURES

1. Figures: Evaluation of the non-contact fragmentation (popcorn) technique

Figure 1. External (*left*) and endoscopic vision (*right*) of the ureteroscope and the laser fiber placed in between the artificial stone phantoms.

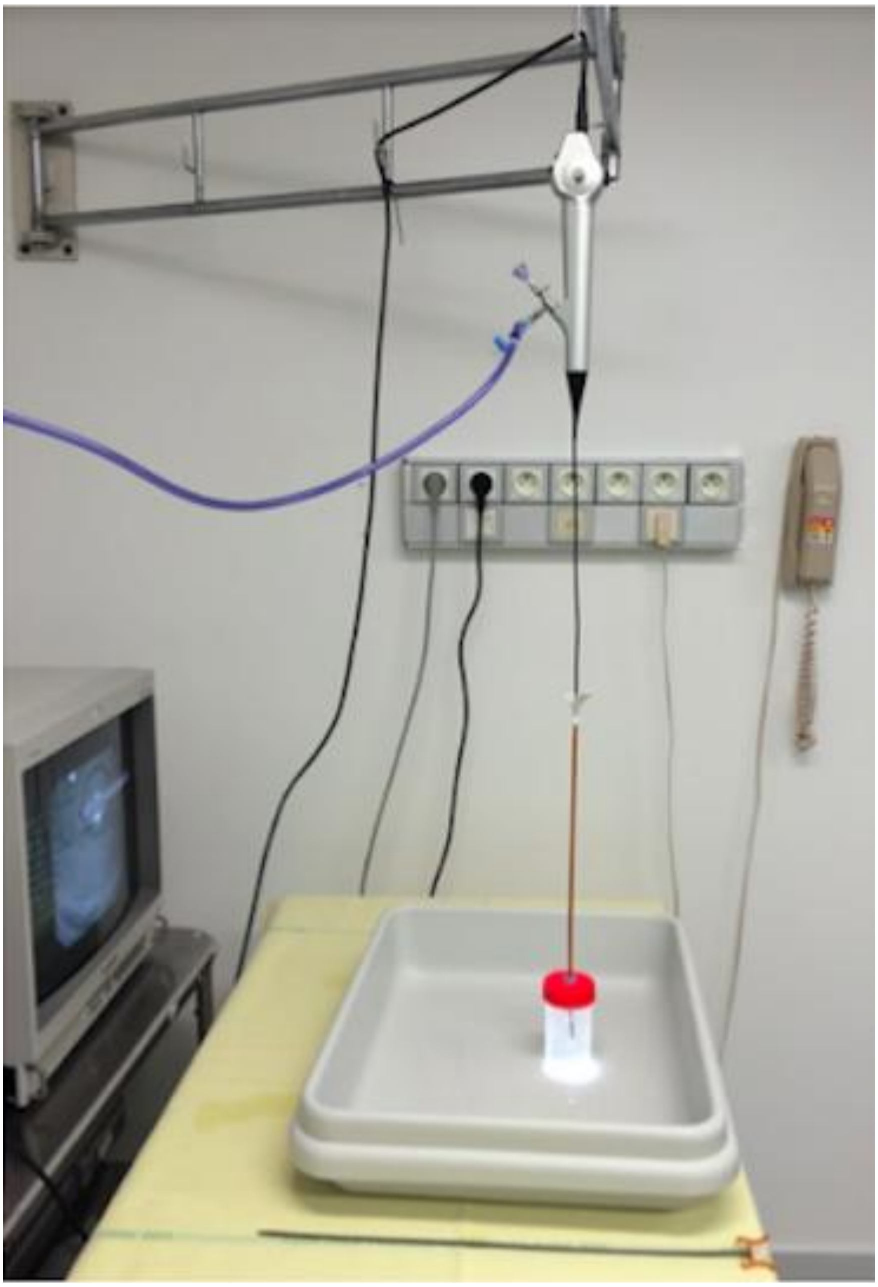

Figure 2. Evaluation of the non contact fragmentation (“pop-corn”) technique setup.

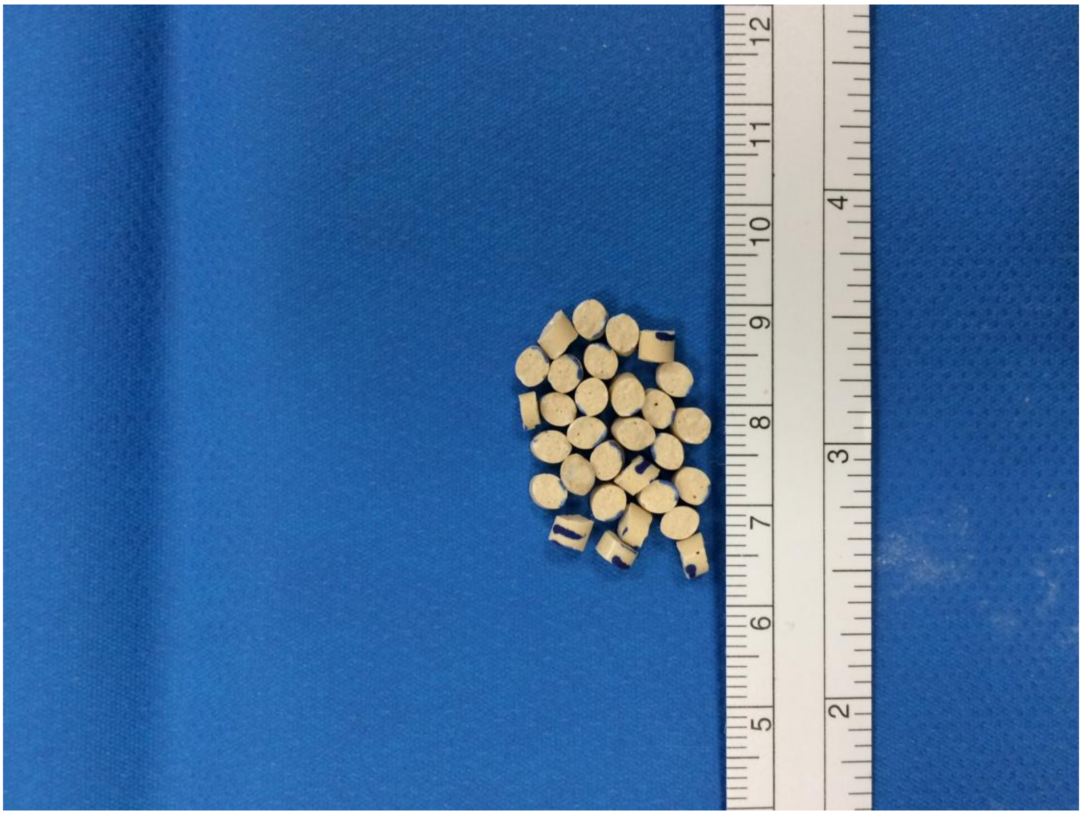

Figure 3. Artificial stone phantoms.

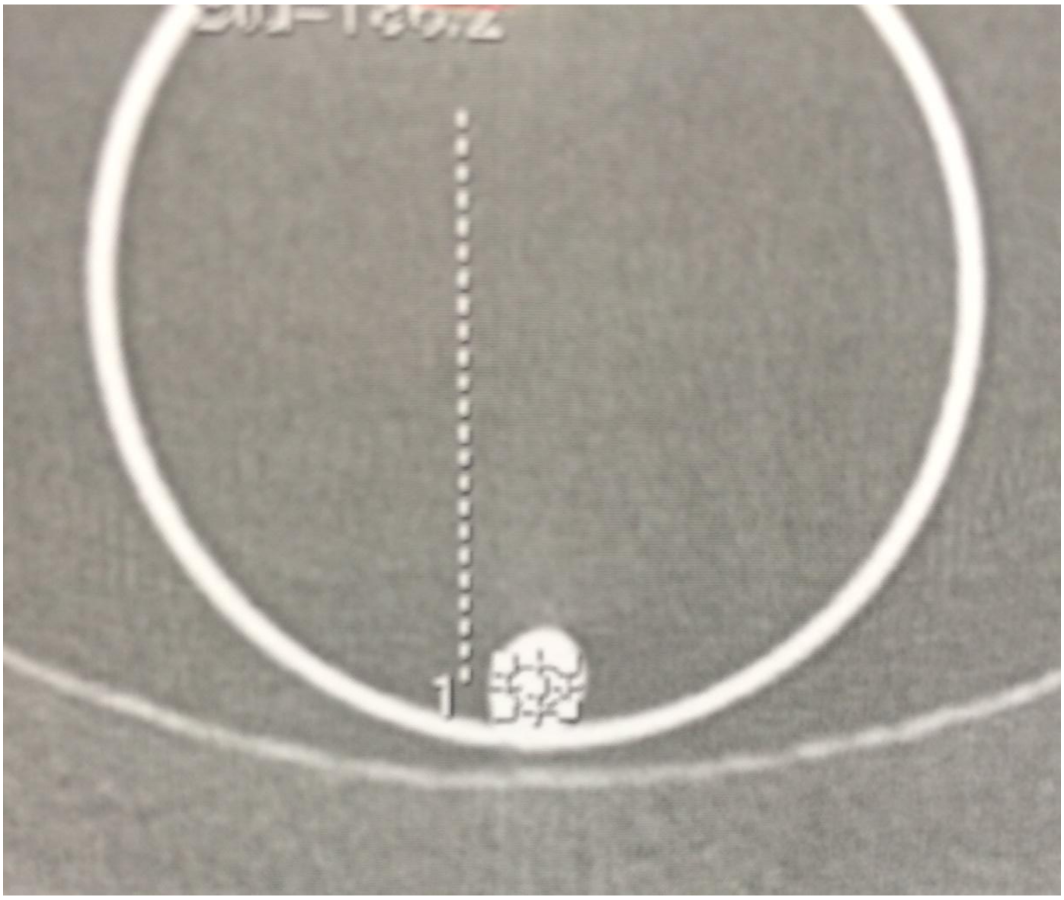

Figure 4. Artificial stone phantoms computerized tomography.

2. Figures: Evaluation of laser fiber bending

Figure 5. Laser fiber-bending diameters tested: 9, 12, 15, 18, and 20 mm.

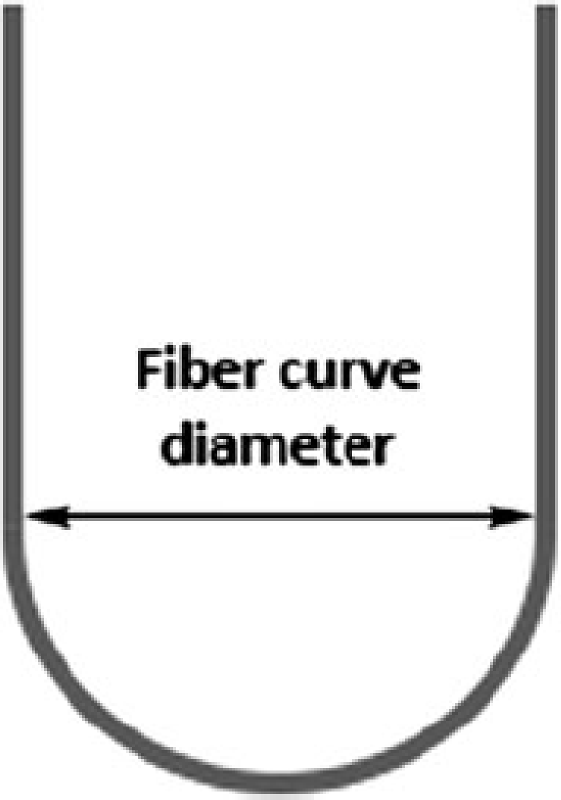

Figure 6. The diameter was defined as the distance between the opposite sides of a fully deflected fiber measured at 180°.

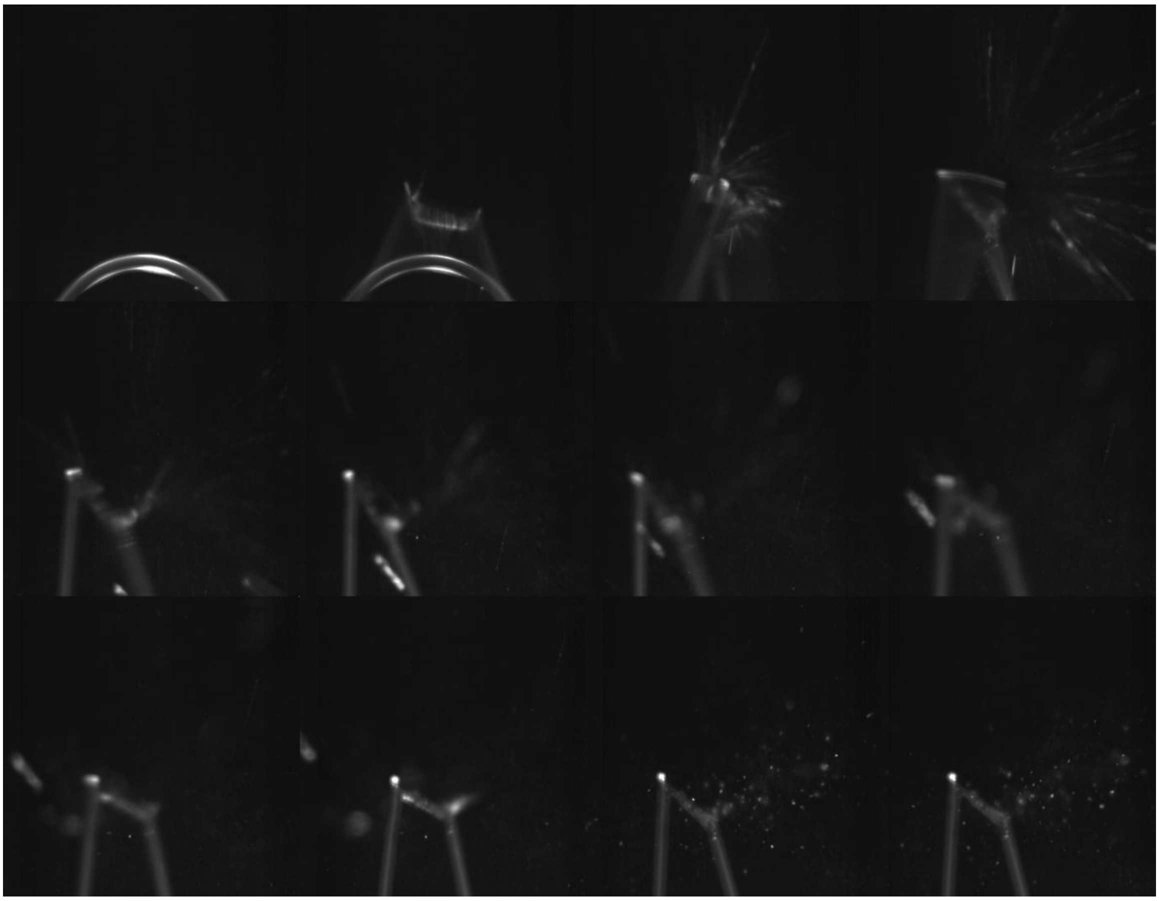

Figure 7. High-speed camera footage of fiber failure sequence.

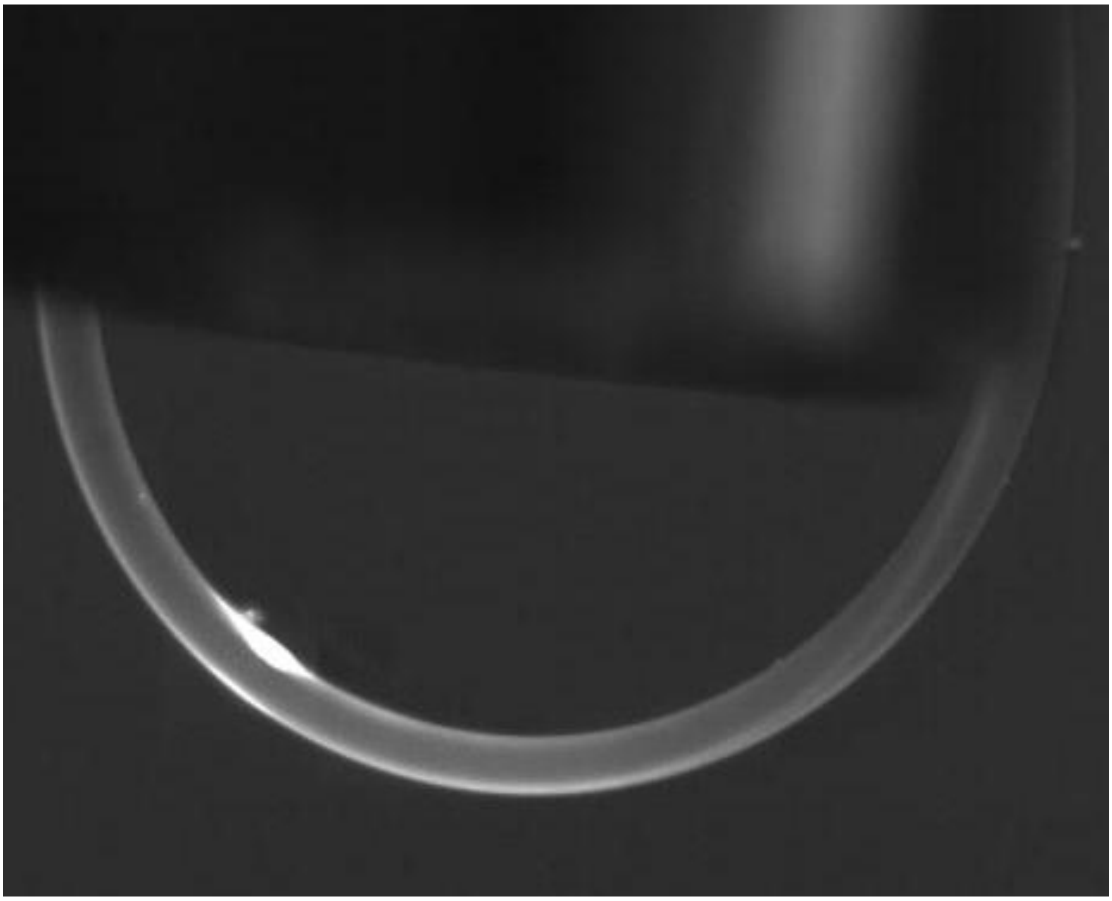

Figure 8. Leaking of the light beam "burning point", seen in the fiber coating before fiber failure at the beginning of the bending curve.

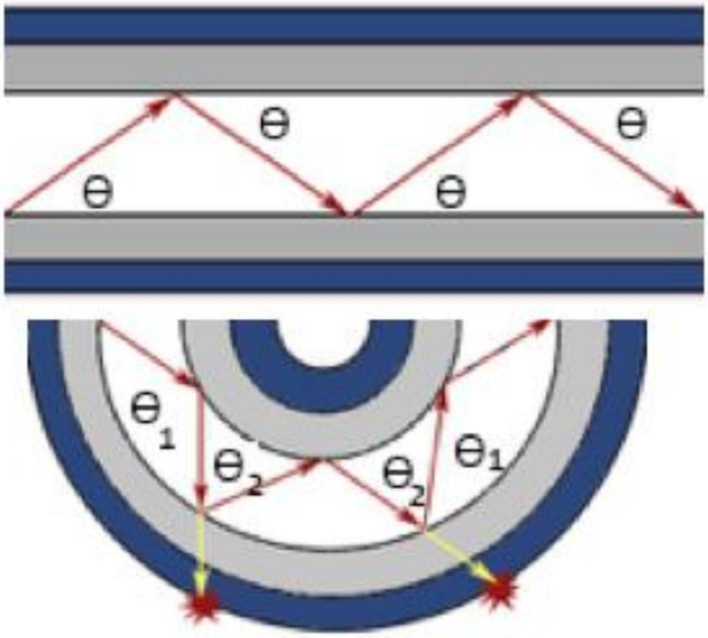

Figure 9. Comparison of laser beam transmission (internal reflection angles) between straight fibers (*top*) and bent fibers (*bottom*) altered by laser fiber bending. The acute divergence angles in bent fibers increases the number of reflections allowing the laser beam to be transmitted (leaking) through the cladding.

TABLES

1. Tables: Evaluation of the non-contact fragmentation (popcorn) technique

Setting variables	p-value	OR	95%CI
Energy (0.5J vs 1.5J)	<0.001	19.229	(6.404-57.737)
Frequency (10 vs >20 Hz)	<0.001	13.891	(4.367-44.178)
Pulse (Short vs Long)	0.045	2.579	(1.020-6.522)
Other variables			
Time (2 vs 4 min)	<0.001	10.187	(3.588-28.925
Fiber (273 vs 365)	<0.016	0.316	(0.120 – 0.810)

Table 1. Multivariate analysis of significant predictors of popcorn technique.

2.Tables: Evaluation of laser fiber bending

Settings	Failure	Curved diameters					
		9 mm	12 mm	15 mm	18 mm	20 mm	*P value*
Dusting	Failure	2	0	0	0	0	*p=0.037*
	No failure	8	10	10	10	10	
Fragmentation	Failure	5	0	0	0	0	*p=0.007*
	No failure	5	10	10	10	10	

Table 2. 272μm fiber number of failures (ruptures) out of 10 experiments at different settings and different curve diameters.

Settings	Failure	Curved diameters					
		9 mm	12 mm	15 mm	18 mm	20 mm	*P value*
Dusting	Failure	3	0	0	0	0	*p=0.006*
	No failure	7	10	10	10	10	
Fragmentation	Failure	9	1	0	0	1	*p=0.033*
	No failure	1	9	10	10	9	

Table 3. 365μm fiber number of failures (ruptures) out of 10 experiments at different settings and different curve diameters.

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PUBLISHED ORIGINAL ARTICLES

OPTIMAL SETTINGS FOR THE NON-CONTACT HOLMIUM: YAG STONE FRAGMENTATION, POP CORN TECHNIQUE

Optimal Settings for the Noncontact Holmium:YAG Stone Fragmentation Popcorn Technique

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Purpose: The purpose of this study was to evaluate the popcorn technique using a wide range of holmium laser settings and fiber sizes in a systematic in vitro assessment.

Materials and Methods: Evaluations were done with 4 artificial stones in a collection tube. A fixed ureteroscope was inserted through a ureteral access sheath to provide constant irrigation flow and the laser was placed 1 mm from the bottom. Combinations of 0.5 to 1.5 J, 10 to 20 and 40 Hz, and long and short pulses were tested for 2 and 4 minutes. We used 273 and 365 μm laser fibers. All tests were repeated 3 times. The stones were weighed before and after the experiments to evaluate the setting efficiency. Significant predictors of a highly efficient technique were assessed.

Results: A total of 144 tests were performed. Mean starting weight of the stones was 0.23 gm, which was consistent among the groups. After the experiment the median weight difference was 0.07 gm (range 0.01 to 0.24). When designating a 50% reduction in stone volume as the threshold indicating high efficiency, the significant predictors of an efficient popcorn technique were a long pulse (OR 2.7, 95% CI 1.05–7.15), a longer duration (OR 11.4, 95% CI 3.88–33.29), a small (273 μm) laser fiber (OR 0.23, 95% CI 0.08–0.70) and higher power (W) (OR 1.14, 95% CI 1.09–1.20).

Conclusions: Higher energy, a longer pulse, frequencies higher than 10 Hz, a longer duration and a smaller laser fiber predict a popcorn technique that is more efficient at reducing stone volume.

Key Words: kidney calculi; lasers, solid state; ureteroscopy; ablation techniques; in vitro techniques

FLEXIBLE ureteroscopy and HL are a standard of care for renal urolithiasis less than 2 cm.[1] HL is a safe and versatile laser that has been shown to efficiently fragment urinary stones of all compositions.[2,3] HL even offers the possibility of adjusting laser parameters to perform different modalities of stone ablation such as dusting and fragmentation.[4] Several techniques of laser lithotripsy have been described for efficient treatment of stones.[4]

In situations in which multiple fragments are present in 1 calyx the popcorn technique was reported to significantly reduce the stone burden.[5] To our knowledge only 1

Abbreviation and Acronym

HL = holmium:YAG laser

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study has been done to evaluate the efficacy of this technique.[5]

New parameters such as pulse duration have been added to the HL in recent years and studies of laser fiber handling have provided new recommendations to improve performance.[2] However, with these added possibilities no consensus has been reached regarding the best settings for performing stone fragmentation.

The objective of this study was to systematically evaluate in an in vitro setting the efficacy of the popcorn technique when done using the newest HL parameters.

MATERIALS AND METHODS

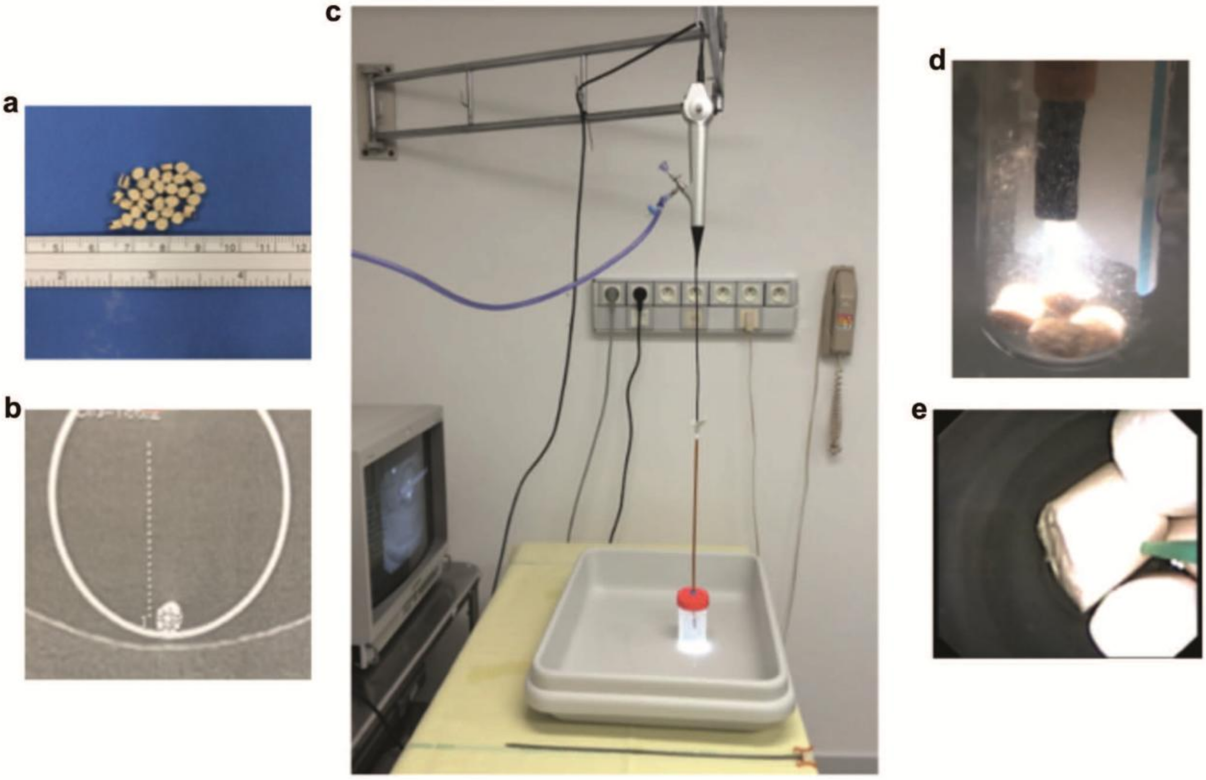
Artificial hard stones were made using a mix of 30 gm Bego Stone™ in 6 cc saline as recommended by the manufacturer. The plaster was poured into plastic cylinders and left to dry overnight. The stones were then cut to obtain 4 to 5 mm (125 mm^3) specimens (part *a* of figure). Computerized tomography performed to evaluate stone hardness revealed a 1,900 HU structure (part *b* of figure). To perform the tests the stones were divided into 144 groups with 4 stones per group.

Each evaluation consisted of placing 4 stones in a Vacutainer® collection tube. A ureteral access sheath was inserted in each tube to introduce a loaded ureteroscope, which enabled a constant flow at 40 cm H_2O as recommended for flexible ureteroscopy (part *c* of figure).[6] The laser was placed 1 mm from the bottom of the tube containing the stones (parts *d* and *e* of figure) and 3 mm from the scope tip.[7] The endoscopic vision of each procedure was recorded.

Various settings were used, including an overall power count between 5 and 60 W. We tested combinations of 0.5 and 1.5 J, 10, 20 and 40 Hz, and long and short pulses of 500 and 750 microseconds, respectively. Evaluations were performed with 273 and 365 µm fibers, which were cleaved for each experiment to avoid bias due to fiber degradation. Each setting and fiber combination was performed for 2 and 4 minutes of laser lithotripsy (table 1). Each trial was repeated 3 times. Each group of 4 stones was weighed in a Mettler Toledo® AT200™ electronic balance scale (205.000 gm) and recorded.

After the experiments the ablated stones were poured into a strainer to allow only fragments larger than 0.3 mm to be retained. These remaining fragments were conserved in the tube and dried overnight to ensure that water absorption would not influence weight. Stone weights and sizes before and after ablation were compared. A median stone volume reduction of 50% was arbitrarily determined as the cutoff level above which the popcorn technique was defined as highly efficient.

Logistic regression analysis was done. Significant predictors of a highly efficient popcorn technique were analyzed with significance considered at $p < 0.05$.



Experiment materials and methods

Table 1. *Experimental settings of each factor*

Energy (J)	0.5	1.5
Frequency (Hz)	10	20
Pulse	Short	Long
Time (mins)	2	4
Fiber (μm)	273	365

RESULTS

A total of 144 evaluations were performed using 576 stone specimens with a mean baseline size of 4.3 mm (range 4.1 to 5) and a mean height of 4 mm (range 3.9 to 4.4). There was no statistical difference among the stones. Overall the stone groups were comparable and had a consistent weight (mean 0.23 gm, range 0.16 to 0.35).

After the experiments the median weight loss of the stones was 0.07 gm (range 0.01 to 0.24). Using the median value of the stone volume reduction as the cutoff level above which the popcorn technique was defined as highly efficient, the significant predictors of a high efficiency popcorn technique were high energy (OR 19.2, 95% CI 6.40–57.74, $p < 0.001$), long pulse (OR 2.6, 95% CI 1.02–6.52, $p = 0045$), frequency 20 or 40 Hz (vs 10 Hz, OR 13.9, 95% CI 4.37–44.18, $p < 0.001$), longer time (OR 10.2, 95% CI 3.59–28.93) and small (273 μm) laser fibers (OR 0.3, 95% CI 0.12–0.81, $p = 0.016$, table 2). On multivariate analysis small laser fiber size, a longer pulse and longer time were the most important factors predicting an efficient popcorn technique.

When analyzing the endoscopic view, all views of fragmentation using 40 Hz were blurred.

DISCUSSION

HL is a safe and versatile laser that is the most widely used laser in urology, especially for stone treatment.[2] Today new laser parameters are available that can be used to perform different ablation effects on stones. Several techniques have been described (eg dusting, chipping or fragmentation)[2] since stone treatment must be tailored according to stone hardness, composition, size, number and/or location.[4]

The presence of multiple calyceal stones often presents a particular challenge as there may be too many to consider a time-consuming procedure of fragmentation and extraction. In addition, they may be too large to be considered insignificant residual fragments in the range of greater than 4 mm according to recent studies.[8] In this situation the popcorn technique was reported to significantly reduce the stone burden by taking advantage of the stone motion (a whirlpool-like phenomenon) created by the continuous firing of the laser from a fixed place between the stones, thereby creating constant stone-laser impacts.[5]

To our knowledge only Chawla et al have previously reported the efficacy of noncontact stone fragmentation.[5] They found that using a setting of 1.5 J and 40 Hz was most efficient for stone fragmentation after 2 minutes, achieving a 60% stone weight reduction. However, regarding the delivered kJ, the setting using 1 J and 20 Hz resulted in the greatest weight reduction of 18%. Chawla et al recommended 1 J and 20 Hz as the optimal setting due to decreased efficacy when using higher settings (1.5 J and 40 Hz). The study only included 365 μm fibers and the laser pulse was not measured. Hecht and Wolf described different settings (0.5 to 0.8 J and 16 to 20 Hz) based on the former study and their clinical experience.[4] Our evaluation produced similar results. Higher energy (1.5 vs 0.5 J) and higher frequencies (20 to 40 vs 10 Hz) resulted in a significant stone burden reduction.

Based on the original article by Chawla et al[5] the fact that not all settings were consistently efficient begs the question of the extent to which the technique depends only on energy. Stone motion can be affected by energy and frequency, by increasing retropulsion and by decreasing the number of stone-laser contacts.

It is known that 272 μm fibers generate higher energy density than larger fibers and the efficiency of all fibers decreases when energy greater than 1 J is applied with a smaller loss for large fibers. However, 272 μm fibers have the same irradiance fluency (J/cm^2) as 365 μm fibers according to the

Table 2. *Significant predictors of popcorn technique*

	Univariate		Multivariate	
	OR (95% CI)	p Value	OR (95% CI)	p Value
Energy (0.5 vs 1.5 J)	19.229 (6.404–57.737)	<0.001	19.229 (6.404–57.737)	<0.001
Pulse (short vs long)	2.579 (1.020–6.522)	0.045	2.579 (1.020–6.522)	0.045
Frequency (Hz):				
10 or Less vs 20 or greater	13.891 (4.367–44.178)	<0.001	13.891 (4.367–44.178)	<0.001
20 or Less vs 40	50.699 (11.671–220.237)	<0.001	50.699 (11.671–220.237)	<0.001
Time (2 vs 4 mins)	10.187 (3.588–28.925)	<0.001	10.187 (3.588–28.925)	<0.001
Fiber (273 vs 365 μm)	0.316 (0.123–0.808)	0.016	0.316 (0.123–0.808)	0.016

Significance was considered at $p < 0.05$.

separation distance.[9] The numerical aperture of the small fibers used was greater than that of large ones (0.22 vs 0.29). Therefore, despite the higher energy density at the fiber tip the effective energy density at the stone surface might be lower. Nonetheless Kronenberg and Traxer found no difference between small and large fibers at the same power or energy setting in regard to the fragmented volume of a stone.[2] Small fibers produced deeper fissures and large fibers produced wider fissures.

When assessing the new HL parameters, Kronenberg and Traxer also noted that short pulses produce a higher stone volume ablation rate than longer pulses.[2] Thus, they recommended short pulses for fragmentation rather than dusting. Furthermore, it is known that the combination of short pulses and larger laser fibers can increase retropulsion.[10–12] It has also been shown that less retropulsion may be more efficient for stone ablation.[11,13] In the current experiment this may explain why a longer pulse and a smaller fiber were more efficient because each causes less retropulsion and could lead to more frequent laser impacts.

Additionally, even at higher retropulsion rates better ablation can be achieved by increasing energy since higher energy increases the crater volume generated by the laser impact.[2,11,13] As stated, not only does energy need to be considered in this technique but also stone motion. More energy produces more ablation but less retropulsion in a closed environment such as calyces or a Vacutainer tube, which could signify more efficient impacts in a high energy setting.

New studies have resulted in recommendations regarding laser fiber size and handling, showing that coated fibers achieve higher ablation rates than stripped fibers.[14] It is for this reason that we cut the fiber tip before and during surgery as coated fibers are easier to see than transparent tips while working. Increased visibility means that they may remain attached if they accidentally break and prevent back burns to the scope during lasering. Following this line of thought we made a clean cut with metallic scissors for each experiment. Furthermore, smaller fibers are usually recommended because they allow for better irrigation and less deflection deterioration, and are as effective as large fibers.[15] Our current results support the recommendation of small fibers.

Regarding stone hardness, in the current study we systematically used 1,900 HU synthetic stones. Clinically these results may be more indicative for treating hard stones, although even better results may be achieved with soft stones.

Finally even if higher energy generates better ablation rates, the lack of a clear visual field during surgery may force the surgeon to repeatedly stop fragmentation, resulting in lost time. When we analyzed the endoscopic views of the experiment, energy and frequency were determinant factors of the quality of the field of vision. At 0.5 J the field of vision was always clear but when 1.5 J was used, clarity depended on the frequency. While 10 and 20 Hz resulted in a clear view, using 40 Hz resulted in the visual field being completely blurred by dust after a few seconds.

Our recommendation for an efficient popcorn technique is to use small laser fibers, a long pulse and an adequate duration (at least 4 minutes) to achieve a clinically insignificant stone burden. The best compromise would be to use 1.5 J and up to 20 Hz to allow for efficient ablation while retaining adequate vision quality.

This study has the limitation of the in vitro scenario. In real practice the calyces can differ from the environment of our experiments. Nevertheless, these results can provide useful indications for performing the popcorn technique.

CONCLUSIONS

Higher energy, a long pulse, a frequency of 20 to 40 Hz, a longer duration and small laser fibers are significant predictors of a highly efficient popcorn technique. A good compromise would be a long pulse, 1.5 J and 20 Hz with a 273 μm laser fiber and taking as much time as possible (more than 4 minutes) to produce clinically insignificant fragments.

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EDITORIAL COMMENT

The Ho:YAG laser works by a photothermal mechanism that involves direct absorption of photons on the stone surface.[1] Ho:YAG lithotripsy is most efficient when the stone is in a fixed position and the stone surface is targeted in contact mode with the laser fiber oriented to the stone surface at a normal incidence (references 2 and 13 in article).[1] Occasionally circumstances may render contact mode laser lithotripsy problematic. For example, in a calyx the fiber might not orient at all to the stone surface. The popcorn technique may be useful here.

Ho:YAG energy is well absorbed in water and it creates vapor bubbles that expand and collapse.[2] By agitating the water with vapor bubbles the stones will displace and periodically come into contact with the fiber tip, enabling contact lithotripsy to occur. This technique is useful when contact lithotripsy cannot be achieved by any other means. But if I am given the chance to target a stone directly with the laser vs this "lottery ball" (popcorn) technique, I would choose direct contact lithotripsy.

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REPLY BY AUTHORS

We absolutely agree that Ho:YAG lithotripsy is most efficient when stones are targeted directly with the laser fiber. Nevertheless the presence of multiple calyceal stones often presents a particular challenge, especially with hard stones such as calcium oxalate monohydrate. Direct fragmentation will produce fragments exponentially. Targeting each stone separately may not always be easy due to kidney movement or retropulsion at high energy and short pulse fragmentation settings (reference 10 in article). Also, fragmentation and extraction may be time-consuming. In these situations in which there are multiple clinically significant fragments in a calyx (reference 8 in article) the popcorn technique is useful when good settings are needed to be truly efficient.

Finally, we called the technique the popcorn effect according to the initial description by Chawla et al (reference 5 in article). Curiously we have found many names to describe it, such as lottery ball, pop-dusting or washing machine. A common name may be suggested to avoid confusion.

IMPACT OF THE CURVE DIAMETER AND LASER SETTINGS ON LASER FIBER FRACTURE

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Impact of the Curve Diameter and Laser Settings on Laser Fiber Fracture

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Abstract

Objective: To analyze the risk factors for laser fiber fractures when deflected to form a curve, including laser settings, size of the laser fiber, and the fiber bending diameter.

Materials and Methods: Single-use 272 and 365 μm fibers (Rocamed®, Monaco) were employed along with a holmium laser (Rocamed). Five different fiber curve diameters were tested: 9, 12, 15, 18, and 20 mm. Fragmentation and dusting settings were used at a theoretical power of 7.5 W. The laser was activated for 5 minutes and the principal judgment criterion was fiber fracture. Every test for each parameter, bending diameter, and fiber size combinations was repeated 10 times.

Results: With dusting settings, fibers broke more frequently at a curved diameter of 9 mm for both 272 and 365 μm fibers ($p = 0.037$ and 0.006, respectively). Using fragmentation settings, fibers broke more frequently at 12 mm for 272 μm and 15 mm for 365 μm ($p = 0.007$ and 0.033, respectively). Short pulse and high energy were significant risk factors for fiber fracture using the 365 μm fibers ($p = 0.02$), but not for the 272 μm fibers ($p = 0.35$). Frequency was not a risk factor for fiber rupture. Fiber diameters also seemed to be involved in the failure with a higher number of broken fibers for the 365 μm fibers, but this was not statistically significant when compared with the 272 μm fibers ($p > 0.05$).

Conclusion: Small-core fibers are more resistant than large-core fibers as lower bending diameters (<9 mm) are required to break smaller fibers. In acute angles, the use of small-core fibers, at a low energy and long-pulse (dusting) setting, will reduce the risk of fiber rupture.

Keywords: uretersocopy, urolithiasis, laser, fiber, deflection, lower pole lithotripsy

Introduction

Flexible ureteroscopy is an established procedure for urolithiasis, especially for renal stones <2 cm.[1] Nevertheless, treatment outcomes are associated with technical limitations of flexible ureteroscopes (fURSs) when working in acute angle calices, and breakages can be associated with costly repairs.[2] This is especially true for lower pole stones, and lower pole stone lithotripsy has been described as risky for fURSs.[3]

Mechanisms of scope damage include acute deflecting angles (or small bend diameters) that may cause mechanical damage and laser fiber rupture leading to thermal breakdown during firing, resulting in laser energy leaking directly in the ureteroscope.[4,5]

Physical properties of laser beams could explain why a fiber rupture can occur, but risk factors and laser settings that result in fiber fractures are not well determined using newer holmium laser parameters.

The purpose of this study is to analyze the risk factors for laser fiber fracture when deflected to form a curve including laser settings, size of laser fiber, and fiber bending diameter to determine safety measures for lower pole lithotripsy.

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Materials and Methods

Single use 272 and 365 μm fibers (Rocamed®, Monaco) were employed for these experiments along with an MH01-ROCA FTS-30W holmium laser (Rocamed). Although these fibers had similar composition, the numerical aperture of the 272 μm fiber was 0.27 and the numerical aperture of the 365 μm fiber was 0.22.

Five different fiber-bending diameters (mm) were tested: 9, 12, 15, 18, and 20 mm. A testing set was designed to keep the bending diameter static during the experiments. Soft silicone tubes, secured by plastic screws (to hold the fibers without causing damages), supported the fibers.

Fiber bending diameter was defined as the length between the opposite sides of a fully deflected fiber measured at 180° (descending and ascending sides of a curved fiber) (Fig. 1). We considered that 9 mm is the bend diameter that represents the most acute angle that a ureteroscope might deflect for lower pole lithotripsy in difficult anatomical situations. No previous publication supports this bend diameter, but it is the mean of diameters we measured over several cases. The other diameters were randomly chosen to test wider values mimicking calices easier to navigate through.

Two different laser settings were established: fragmentation settings (short pulse [265 ± 70 μs], 1.5 J, and 5 Hz) and dusting settings (long pulse [1100 ± 70 μs], 0.5 J, and 15 Hz). All the theoretical powers were set at 7.5 W. The energy power output and transmission were measured with a Molectron EPM1000 (Coherent, Inc.) wattmeter.

The laser was activated for 5 minutes in every experiment and the principal judgment criterion was fiber fracture. Every test for each parameter, bending diameter, and fiber size combinations was repeated 10 times.

A high-speed camera (Photron Ultima APX-RS 3000) at 10,000 frames per second was used to record fiber fractures. Images analysis was performed using the Photron FastCAM Viewer 2.4 software. Statistical analysis was performed using Fischer test on BioStaTGV® (France), with a significant level set at $p < 0.05$.

Results

Using the dusting settings, fibers broke more frequently at a bend diameter of 9 mm for both 272 and 365 μm fibers ($p = 0.037$ and 0.006, respectively). With these parameters, 20% of the 272 μm fibers broke at a bend diameter of 9 mm, whereas none of the fibers broke at diameters ≥12 mm. For the 365 μm fibers, 30% broke at a bend diameter of 9 mm, whereas none of the fibers broke at diameters ≥12 mm.

Using the fragmentation settings, fibers broke more frequently at diameters of ≤12 mm for 272 μm and ≤15 mm for 365 μm ($p = 0.007$ and 0.033, respectively). With these parameters, 25% of the 272 μm fibers broke at a bend diameter of 12 mm or below, whereas none of the fibers broke at diameters of 15 mm or above. For the 365 μm fibers, 33% broke at a bend diameter of 15 mm or below, whereas only 5% of the fibers broke at diameter of 18 mm or above.

Short pulse and high energy were significant risk factors of fiber fracture for the 365 μm fibers ($p = 0.02$), but not for the 272 μm fibers ($p = 0.35$). High frequency was not a risk factor for fiber rupture.

Fiber diameters also seemed to be involved in the failure, with higher number of broken fibers for the 365 μm fibers but no significant difference was found when compared with the 272 μm fibers ($p > 0.05$). All the fiber failures occurred within the first few seconds of use.

On the images analyzed with the high-speed camera (Fig. 2B, C), a light burning spot in the fiber protective sheath was seen before the rupture occurred. Also, the fibers did not fail at the maximal deflection point but failed slightly next to the beginning of the curve (Fig. 2C). Table 1 summarizes the laser fiber fractures for the 272 and 365 μm fibers.

Discussion

Findings from previous similar studies

The fURS fragility and breakages have always been a major concern for urologists because of their costly repairs[2] or secondary to complications such as locked deflection.[6]

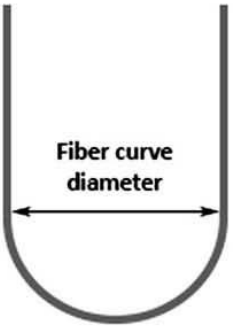

FIG. 1. Fiber bending diameter.

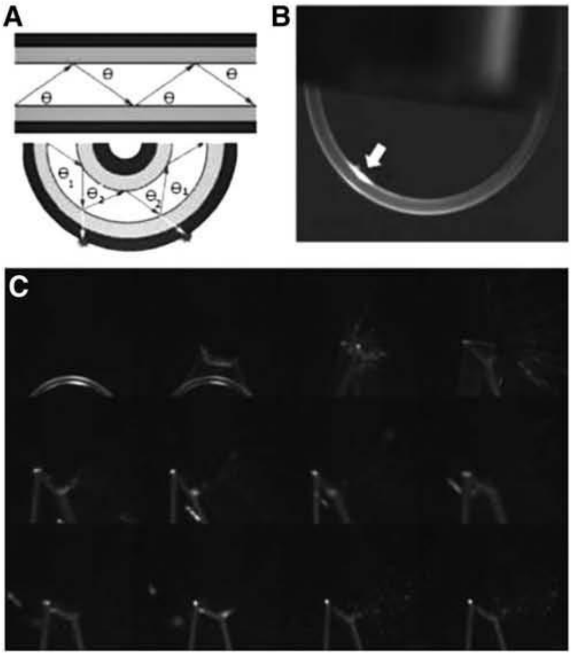

FIG. 2. **(A)** Laser refraction in a straight and bent fiber. **(B)** Bent fiber showing the burning point (*white arrow*) before breaking. **(C)** Fiber breakage sequence.

Table 1. Fiber Failure at Different Settings and Different Curve Diameters

	μm	9 mm, %	12 mm, %	15 mm, %	18 mm, %	20 mm, %
Dusting LP—0.5 J, 15 Hz	272	20	0	0	0	0
	365	30	0	0	0	0
Fragmentation SP—1.5 J, 5 Hz	272	50	0	0	0	0
	365	90	10	0	0	10

Several intraoperative mechanisms for fURS damage have been studied. It has been shown in a prospective study that >36% of cases of fURS breakages involved laser misfiring and >28% involved excessive torque.[7] Lower pole access and lithotripsy, which sometimes require forced positions with small deflection diameters, are particularly at risk for fURS breakages, and result in mechanical damages mainly in the junction between the shaft and the bending tip.[7] In addition, working channel perforations during laser firing have also been described as an important cause for fURS damage.[3]

Several studies have demonstrated that the properties of different laser fibers differ with their manufacturing brand, with regard to its flexibility, durability, failure, energy transmission, and true fiber diameter.[4,8,9] They all conclude that performance characteristics differ significantly between different laser fiber diameters and manufacturers.

Knudsen et al.[4] evaluated several brands of laser fibers with regard to the critical bend diameters while running increasing levels of pulsed energy. Their results showed that laser fibers, when bent, have different levels of resistance to fiber fracture and this differs from brand to brand. For similar sized fibers from different manufacturers, some fibers broke at a diameter of 10 mm, whereas others broke at 20 or 30 mm.

Findings from our study

As described in the literature, we chose to use the two parameters commonly used in real-life lithotripsy: dusting and fragmentation.[10] Our results confirmed that different fiber diameters do not have the same resistance to fiber fracture. The 272 μm fibers broke at a bend diameter of ≤9 mm for the dusting parameter and ≤12 mm for the fragmentation parameter, although the 365 μm fibers broke at 9 mm for the dusting parameter, but required a larger bend of 15 mm to break with the fragmentation parameter. Although not statistically significant, smaller fibers seemed to be less likely to break, probably because they are less rigid and bend more easily.

With regard to the settings, higher laser fiber fracture rates were seen with the fragmentation setting than with the dusting setting. As described, fragmentation settings require high energy and short pulse length, but it was not clear whether pulse length or the energy is more involved in the fiber failure. Lusch and colleagues[11] concluded that there is a trend for less fiber breakage with long pulse, high energy, and low frequency. Our results showed that there is a trend for less fiber fracture with long pulse, low energy, and high frequency.

Properties of laser fiber explaining our findings

Fiber fracture while bent involves two physical phenomenons: numerical apperture and total internal reflection.[12] Numerical aperture is a value of the laser fiber that determines the angle that the laser beam needs to enter the fiber from the machine. A correct angle allows the beam to be properly refracted until the fiber tip. This parameter can be calculated with the laser refractive indexes of the two silica layers that constitute the holmium laser fiber. It can be calculated by an equation where $n1$ and $n2$ are the refractive indexes of both silica layers: $N.A. = \sin\theta = \sqrt{n1 - n2}$.

Total internal reflection is defined by Snell–Descartes's law, which states that the incident and refracted light rays' angles are equal when the light beam reflects on an interface. It occurs when light rays in an optically dense medium try to propagate into a less optically dense medium. Light is reflected back into the original medium if the incident ray has an angle that equals or exceeds the critical angle of total internal reflection. This critical angle is a function of the numerical aperture. In laser fibers, these two media are the core and the cladding, and their interface acts as a reflector when the light rays' angle equals or exceeds the critical angle of total internal reflection.

When a laser fiber bends, the incident ray might be less than the critical angle, and energy leaks through the cladding, resulting in fiber failure at a burning point (Fig. 2A). This burning point was seen with the high-speed camera (Fig. 2B) before the fiber fracture (Fig. 2C) in microseconds.

Another physical property that is involved in fiber failure with curved/bent fiber is evanescence. When laser energy propagates through the fiber, not all the light is reflected through the core, some of it penetrates into the cladding: this phenomenon is called evanescence (Fig. 2A). Evanescence can be multiplied by high energy, or stressed fibers (for example, when they are curved/bent).

All of these properties explain why an over bent fiber is more likely to fail during laser firing.

Lee et al. [13] studied the optical beam profile with straight and bent fibers, with a pyroelectric camera. They demonstrated that straight fibers have a near-Gaussian beam profile, whereas bent fibers have a slightly flatter beam profile than the straight fibers. These results show that light, therefore energy, is not transmitted in the same manner if the fiber is straight or bent.

Fiber failure occurs at the first few seconds of laser firing and slightly next to the beginning of the curve, not at the maximal deflection point. We believe that this is caused by the difference between mechanical failure, which is caused by a tight bent diameter, and optical failure, which is caused by loss of total internal reflection and evanescence.[12]

Recommendations for clinical use based on our findings

The clinical applications for lower pole lithotripsy that we recommend from our results are to use small core fibers (<300 μm), with low energy and long pulse length, to reduce the stone size until it can be relocated in a safer location.

Small diameter curves may apply restrictions to the fiber leading to fiber breakage inside the fURS at the curving point. The small core fibers and dusting settings may lower the odds of fiber fracture during firing and avoid energy leaking directly to the ureteroscope, causing fURS damage and finally costly repairs.[7,14]

Nowadays, there is a trend for single-use fURS,[15,16] especially for difficult kidney anatomies. As fURS fragility is not a concern with this new disposable instrument, urologists must take those into consideration for selected cases wherein there is higher likelihood for fURS damage.

Limitations of our study

A limitation of this study is that we used only one brand of laser fiber (Rocamed) for purposes of experimental consistency. As already stated, several studies have demonstrated that every fiber brand does not have the same properties with regard to flexibility, durability, failure, energy transmission, and true fiber diameter. Also, we used a 365 μm fiber, which is not regularly used in lower pole lithotripsy. We chose to compare a flexible fiber (272 μm) and a more rigid fiber (365 μm) to assess whether small core fibers should be a standard in lower pole lithotripsy. Further studies are needed with more fiber brands, especially for the relationship between pulse length, energy, and fiber fracture.

Conclusion

The safety of using laser fibers in narrowed deflections could be improved by using small core fibers and low energy/long pulse setting as they have shown to be less likely to fracture.

Compliance with Ethical Standards

There were neither live human participants nor animals in this trial.

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Authors' Contributions

M.H. and O.T. contributed to protocol/project development; M.H., Y.R., F.C., and L.B. were involved in data collection or management; M.H. and S.B. carried out data analysis; and M.H., E.E., and S.D. wrote and edited the article.

Author Disclosure Statement

Prof. O. Traxer is a consultant for Olympus, Rocamed, Coloplast, and Boston Scientific. The rest of the authors declare that they have no conflicts of interest.

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Abbreviation Used
fURSs = flexible ureteroscopes