



Comparing dusting and fragmenting efficiency using the new SuperPulsed thulium fiber laser versus a 120 W Holmium:YAG laser

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Purpose: Holmium:YAG laser lithotripsy requires high amperage power and has an upper limit of frequency and a minimal fiber size. The technology utilizing thulium-doped fiber offers low pulse energy settings and high pulse frequencies up to 2,400 Hz. We compared the novel SuperPulsed thulium fiber laser (SOLTIVE™; Olympus) to a commercially available 120 W Ho:YAG laser.

Materials and Methods: Bench-top testing was conducted with 125 mm³ standardized BegoStones (Bego USA). Time to ablate the stone into particles <1 mm was recorded for efficiency calculations. Finite energy was delivered, and resulting particle sizes were measured to determine fragmentation (0.5 kJ) and dusting (2 kJ) efficiencies. Remaining mass or number of fragments were measured to compare efficacy.

Results: SOLTIVE™ was faster at ablating stones to particles <1 mm (2.23±0.22 mg/s, 0.6 J 30 Hz short pulse) compared to Ho:YAG laser (1.78±0.44 mg/s, 0.8 J 10 Hz short pulse) (p<0.001). Following 0.5 kJ of energy in fragmentation testing, fewer particles >2 mm remained using SOLTIVE™ than Ho:YAG laser (2.10 vs. 7.20 fragments). After delivering 2 kJ, dusting (1.05±0.08 mg/s) was faster using SOLTIVE™ (0.1 J 200 Hz short pulse) than 120 W 0.46±0.09 mg/s (0.3 J 70 Hz Moses) (p=0.005). SOLTIVE™ (0.1 J 200 Hz) produced more dust particles <0.5 mm (40%) compared to 24% produced by the P120 W laser at 0.3 J 70 Hz Moses and 14% at 0.3 J 70 Hz long pulse (p=0.015).

Conclusions: The efficacy of SOLTIVE™ is superior to the 120 W Ho:YAG laser by producing smaller dust particles and fewer fragments. Further studies are warranted.

Keywords: Holmium; Lithotripsy, laser; Thulium; Ureteroscopy; Urinary stones

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INTRODUCTION

Innovations in laser technology and flexible ureteroscopes have expanded the role of retrograde intrarenal sur-

gery (RIRS) for urolithiasis. The advantages of RIRS include minimally invasive, low complications, and short hospitalization [1]. The use of laser lithotripsy is an essential component for the high efficiency of RIRS.

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The holmium:YAG (Ho:YAG) laser was a major leap forward in ureteroscopic kidney stone treatment since its introduction in the 1990s. Improvements have been made, including widening the pulse width to decrease retropulsion and the addition of pulse modulation technology [2,3]. The Ho:YAG laser has been the standard of care for the ureteroscopic treatment of urolithiasis. However, there is room for improvement in dusting and fragmentation capabilities that may improve the efficacy of RIRS.

The thulium fiber laser (TFL), not to be confused with the Thulium:YAG (Tm:YAG) laser, employs an alternative laser technology to Ho:YAG. Utilizing energy input from diode lasers paired with a long silica fiber doped with thulium ions, TFL moves away from the flashlamp excited crystal in a laser cavity model seen with both Ho:YAG and Tm:YAG lasers [4]. TFL operates at a 1,940 nm wavelength which is closer to water absorption, thus producing different characteristics in how it fragments stones. The peak power is also much lower than Ho:YAG and can be delivered at higher frequencies.

In this study, we compared the fragmentation capabilities of the novel SuperPulsed thulium fiber laser (SOLTIVE™; Olympus) to a commercially available 120 W Ho:YAG laser (Lumenis Pulse™ 120H; Boston Scientific) in a controlled bench setting using various settings and techniques.

MATERIALS AND METHODS

1. Stone samples

Standardized, homogeneous BegoStones (Bego USA) (n=10 per parameter) were utilized in this experiment and constructed in uniform silicone cubic molds with a 2:1 ratio of BegoStone Plus (Bego USA) powder to water, and hydrated for up to one hour in room-temperature normal saline. A standard process for fabricating the BegoStones was used. This process included using a vacuum pump and vibration table to ensure that stones of consistent density were produced from the BegoStone Plus mixture. The stones were cubic in shape, measuring 5 mm in linear dimensions (5×5×5 mm, volume=125 mm³). Each stone was placed individually into a square cylindrical test cuvette, measuring 1×1 cm in axial dimensions. Irrigation was performed using a peristaltic pump for consistency in irrigation when conducting a side-by-side test at room temperature with normal saline. To ensure an adequate supply for the comparative arms of the study, more than 300 stones were produced in each lot of the silicone mold. Any defective or cracked BegoStones were discarded and deemed unsuitable for use in the study.

2. Laser parameters

1) Ho:YAG laser

The commercially available Ho:YAG laser (Lumenis Pulse™ 120H) was paired with a 272 µm core fiber or a 230 µm core diameter fiber when using Moses Dusting mode (at 0.3 J×70 Hz). The laser can operate at a maximum power of 120 W with a pulse frequency of up to 80 Hz. It is also equipped with a novel laser pulse modulation setting (MOSES®) to decrease retropulsion and increase stone ablation efficiency [3]. Optimal settings for pulse energy and frequency using the P120 laser have been widely studied and were utilized in these experiments [2,5-8].

2) SuperPulsed thulium fiber laser

The SOLTIVE™ laser produces an average power of (60 W) and a peak power of (500 W). Laser settings for the SOLTIVE™ laser can be adjusted up to 2,400 Hz frequency, and energy settings from 0.025–6.0 J. Pulse width has three settings: short, medium, or long. Pulse width is manually controlled and ranges from between 0.2 ms and 48 ms (200 µs and 48,000 µs), depending on the selected pulse energy.

3. Experimental setup

The three tests assessed three parameters: (1) ablation rate; (2) fragmentation; and (3) dusting ability of the two lasers. The parameters for each of the experiments are prescribed by the manufacturer for maximal efficiency with each of those techniques (Table 1). The first test determined the time and ablation rate to dust a stone into fragments <1 mm. BegoStones (125 mm³) were placed in 3 mm cuvettes with a sieve at the bottom with 1 mm holes (similar to geological sieves previously described) [9]. Once the stone was completely ablated into fragments that were <1 mm, the time to achieve complete reduction of the BegoStone was recorded, and an ablation rate was calculated (mg/s). The second test of fragmentation used 0.5 kJ of total energy delivered to the BegoStone in a cuvette with a sieve at the bottom with 2 mm holes, allowing fragments <2 mm to pass through. Pre-specified energy output of 0.5 kJ was used as the endpoint rather than time to ensure standardization. All remaining particles >2 mm pieces that remained inside the cuvette were categorized by size and counted using a progressive mesh system after desiccating the stone for 24 hours at 40°C. New fibers were used for each of the ten stones in each trial. The fibers were cleaved and stripped if the fiber started to burn back.

For the third test to assess dusting capability, 2.0 kJ of total energy was delivered to BegoStones in cuvettes with a sieve at the bottom with 1 mm holes. The resulting pieces

Table 1. Laser settings for the three different experiments

	Energy (J)	Frequency (Hz)	Pulse width	Laser fiber size (µm)	Outcome
Part 1. Ablation-fragmentation settings					
Ho:YAG	0.8	10	Short pulse	272	Time to ablate stone into fragments <1 mm to report an ablation score (mg/s)
SOLTIVE™	0.6	30	Short pulse	200	
Part 1. Ablation-dusting settings					
Ho:YAG	0.3	70	Moses mode	230	Time to ablate stone into fragments <1 mm to report an ablation score (mg/s)
SOLTIVE™	0.1	200	Short pulse	200	
Part 2. Fragmentation					
Ho:YAG	0.8	10	Short pulse	272	0.5 kJ total energy delivered with sieve allowing <2 mm to pass through to assess fragmentation. Particles >2 mm were weighed and counted
SOLTIVE™	0.6	30	Short pulse	200	
Part 3. Dusting					
Ho:YAG (Moses)	0.3	70	Moses mode	230	2.0 kJ energy delivered to cuvettes with 1 mm holes in the sieve. Remaining stones >1 mm in cuvette were weighed
Ho:YAG	0.3	70	Long pulse	272	
SOLTIVE™	0.1	200	Short pulse	200	

Ho:YAG, holmium:YAG; SOLTIVE™, SuperPulsed thulium fiber laser.

of BegoStones >1 mm that remained in the cuvette were categorized by size and counted using a progressive mesh system. The settings evaluated in this study were considered the optimal settings for each laser. The lasers were placed in a handheld laser holder, and they were maintained in contact with the BegoStone under direct visualization through the glass cuvette to maximize ablation efficiency; however, it was not always feasible to accomplish due to the challenges posed by stone retropulsion and stone breaking. Each test was repeated ten times for each laser at each testing parameter, and the mean and standard deviation were reported. To minimize the differences in technique from different operators, the testing in each arm of the comparative study was conducted by the same operator (Fig. 1).

4. Statistical analysis

The Student's t-test was used with a significance set at $p<0.05$. For the analyses of two or more groups, ANOVA was used with a significance set at $p<0.05$. Statistics were performed using SPSS software version 27.0 (SPSS Inc.).

RESULTS

1. Ablation rate

In the first test to determine the rate to ablate a stone into fragments <1 mm, the P120 laser had a significantly slower ablation rate than the SOLTIVE™ laser using both fragmenting ($p<0.001$) and dusting settings ($p<0.001$) (Fig. 2).

2. Fragmentation

Part 2 evaluated the fragmentation ability of the lasers. The number of particles produced by the P120 laser was significantly more than the SOLTIVE™ laser (720 vs. 210 fragments, respectively; $p<0.001$, Fig. 3). The majority of the stone treated with SOLTIVE™ turned into dust that was smaller than 0.5 mm, hence the fewer fragments. Clinically, this may result in fewer passes of the basket to remove stones when using SOLTIVE™.

3. Dusting

For the third test, dusting settings were used in both lasers and 2.0 kJ of total energy was delivered. There was no significant difference for the fragments in the 1.4–2 mm ($p=0.106$) or 0.5–1 mm ($p=0.261$) ranges (Fig. 4). However, there were significant differences between the 1–1.4

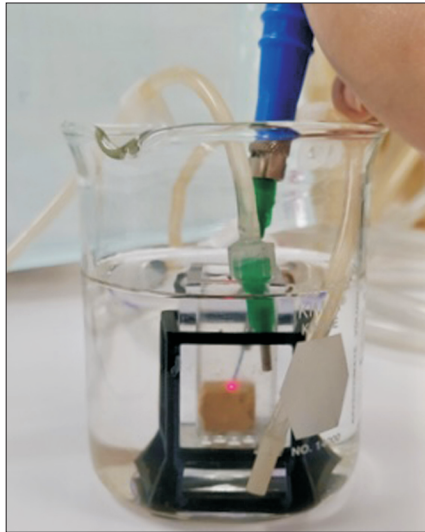


Fig. 1. Photograph of the experimental setup.

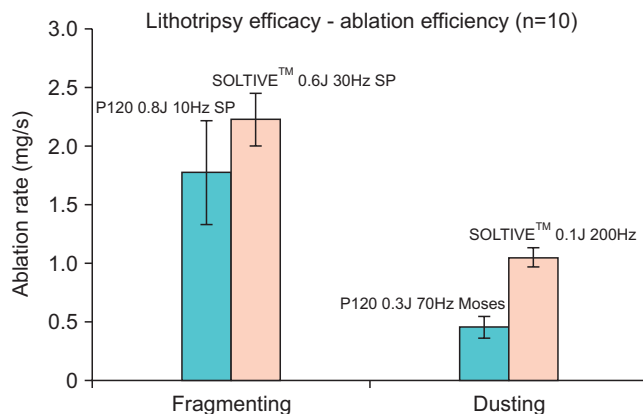


Fig. 2. Ablation rate to turn stone into fragments <1 mm (all $p < 0.001$). SOLTIVE™, SuperPulsed thulium fiber laser; SP, super pulse.

mm ($p=0.005$) and <0.05 mm ($p < 0.001$) groups. Specifically, there was less dust in the <0.5 mm size range in both the long pulse (LP) mode ($p < 0.001$) and the P120 in Moses mode ($p=0.003$) compared to the SOLTIVE™ laser. For the 1–1.4 mm fragment size, the P120 in long pulse width duration had significantly more fragments in this range than in the Moses mode ($p=0.015$) and the SOLTIVE™ ($p=0.009$). For the SOLTIVE™ laser, approximately 40% of the stone was made into dust smaller than 0.5 mm in size.

DISCUSSION

The Ho:YAG laser is the current gold standard. It requires high amperage current due to an electrical efficiency of approximately 1%. This results in generation of heat, requiring a large internal water cooling unit to prevent overheating [10]. Laser fibers larger than 200 microns in

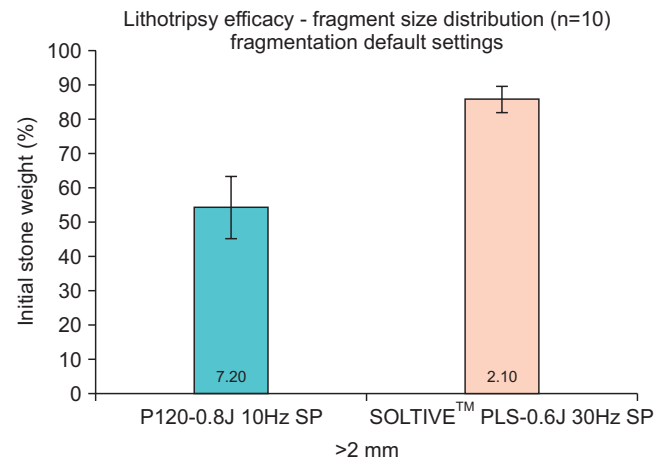


Fig. 3. The number of particles produced by fragmentation settings ($p < 0.001$). SOLTIVE™, SuperPulsed thulium fiber laser; SP, super pulse.

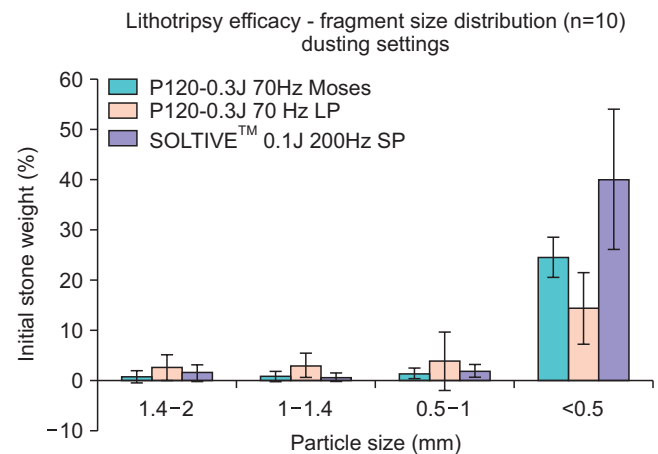


Fig. 4. Distribution of dusting particles after dusting experiments. There were differences between the 1–1.4 mm ($p=0.005$) and <0.05 mm ($p < 0.001$) groups. There was less dust in the <0.5 mm size range in both the LP mode ($p < 0.001$) and the P120 in Moses mode ($p=0.003$) compared to the SOLTIVE™ laser. For the 1–1.4 mm fragment size, the P120 in long pulse width duration had more fragments than the Moses mode ($p=0.015$) and the SOLTIVE™ ($p=0.009$). SOLTIVE™, SuperPulsed thulium fiber laser; LP, long pulse; SP, super pulse.

diameter are required due to the spatial beam profile of the Ho:YAG, potentially limiting irrigation flow through ureteroscopes [10]. The 150 μ m core fibers are available for Ho:YAG lasers that can deliver up to 6W of average power. In addition, high-power Ho:YAG lasers utilize multiple laser cavities, which require internal alignment mirrors that can be damaged or misaligned by shocks or vibration [4].

The newer TFL technology has increased electrical efficiency and can be plugged into a regular 20 A, 120 V or 240 V outlet, allowing for its use in any operating room without power modifications [10,11]. Utilizing an air cooling system instead of water, the dimensions, weight, and noise are reduced compared to high power HO:YAG machines [10]. It has

the capacity for lower pulse energies than Ho:YAG in addition to much higher pulse frequencies [11]. The spatial profile of the laser beam can be narrowed down to couple with fibers smaller than those used for Ho:YAG lasers [11,12]. The TFL, with a wavelength of 1,940 nm, more closely targets a water absorption peak than the Ho:YAG laser, providing a comfortable safety margin for endourological procedures [4,10,11].

The first use of a TFL for stone treatment was published in 2005 by Fried [12]. At that time, technological advances in TFLs allowed for increased maximum power output to 100 W. While successful at fragmenting stones in an ex-vivo model, concerns were raised as to the safety profile and efficiency due to the longer pulse width. These authors published that the heat generated by SOLTIVE™ is equivalent to the Ho:YAG for the same amount of energy delivered. Heat, and thus safety profile, is dependent on average power delivered to the fluid surrounding the stone and independent of wavelength or source of energy (i.e. Ho:YAG or TFL) [12].

Redevelopment and further modifications to the technology were introduced, enabling the current SOLTIVE™ laser to operate with a maximum power output of 500 W and variable pulse widths. Early studies comparing TFLs to Ho:YAG laser showed promising results. In 2010, Blackmon et al. [13] performed the first direct comparison of the TFL and the Ho:YAG laser. The experiment utilized a 100 W TFL coupled with a 100 µm core fiber at settings of 10 Hz and 0.070 kJ. Each laser was tested on human calcium oxalate monohydrate (COM) and uric acid (UA) stones. TFL ablation rates were five times faster for UA stones and 10 times faster for COM stones. In a follow-up study from the same group, the ablation threshold, defined as the lowest incident fluence at which stone material is removed, was four times lower for TFL compared to Ho:YAG laser [14]. Stone ablation rates were similar between the TFL and Ho:YAG lasers when the optimal settings to minimize retropulsion were used.

In a 2017 publication, Hardy et al. [15] investigated the proposed mechanisms behind the TFL's theoretical advantages over the Ho:YAG laser. Both lasers act via a photo-thermal mechanism but the authors anticipated that three primary characteristics of the TFL would differentiate it from the Ho:YAG laser. First, TFL operates at 1,940 nm, which more closely aligns with a water absorption peak. Second, the temporal beam profile of the TFL distributes energy in a more uniform fashion. Finally, the ability to focus the laser beam of the TFL would enable a more energy-dense delivery mechanism. What they discovered was that the cavitation bubble formed with the TFL was one quarter

the size of that produced by the Ho:YAG laser. In addition, the pressure transient at the tip of the laser fiber was ten-fold lower in the TFL compared to the Ho:YAG laser. Both of these characteristics would theoretically lead to reduced retropulsion and the ability to increase the efficiency of lithotripsy.

A preclinical study published in 2020 highlights the new SOLTIVE™ laser which possesses superior specifications compared to prior models. Andreeva et al. [16] investigated both dusting and fragmentation settings using a 100 W and 120 W Ho:YAG laser against the SOLTIVE™ laser. The fiber diameters used were 200 µm and 275 µm for the SOLTIVE™ and Ho:YAG, respectively. For COM stones, ablation rates for the SOLTIVE™ were threefold faster in dusting mode than the Ho:YAG laser though no difference was seen in fragmentation mode. SOLTIVE™ proved superior in treating UA stones with ablation rates 2.5 times and twofold higher in both dusting and fragmentation settings, respectively. Retropulsion was also decreased for SOLTIVE™ at equivalent settings to the Ho:YAG laser, and there was no difference in water temperature elevation between the two modalities. Hardy et al. [17] focused solely on the dusting technique looking at ablation rate and fragment size. The experimental model was similar to the study by Andreeva et al. [16], but they used only COM stones and added 1.0 mm and 0.5 mm sieves to collect and measure stone fragments after ablation. Ablation rates were lower with the Ho:YAG laser at all three experimental settings though not statistically significant at the highest power setting. The TFL produced a greater volume of dust <0.5 mm in each group which was statistically significant in two of the three groups. Overall, 9 out of 15 stones in the TFL group (60.0%) compared to 1 out of 15 stones in the Ho:YAG group (6.7%) were completely fragmented in five minutes or less. These findings correlate with the results found in our current study.

In our study with the lasers at optimal fragmentation settings, the SOLTIVE™ laser proved to be 25% more efficient at ablating stones. This is in contrast to the findings from Andreeva et al. [16] where there was no difference seen in the fragmentation of COM stones. In clinical practice, the improved efficiency would lead to a reduction in laser-ing time, leading to decreased operating room times or the ability to treat larger stones without extending operating room times. In addition, after delivering 0.5 kJ of energy the SOLTIVE™ left fewer fragments >2 mm behind than the Ho:YAG laser. A recently published randomized controlled trial showed that TFL lithotripsy resulted in a significantly higher stone free rate (SFR) and shorter operative time

compared to Ho:YAG [18]. In the pediatric population, a higher SFR was also observed in the TFL cohort compared to Ho:YAG [19]. Confirming the efficacy of TFL in clinical settings, Ryan et al. [20] showed a significant reduction of operative time (129 minutes per case) in favor of TFL which resulted in cost savings USD 440 per case with a total saving per year between USD 294,000 to USD 381,900 on the institutional level. For urologists who prefer the basketing technique, this would decrease the number of passes required with the basket. The reason for this difference between the two modalities is that significantly more dust is produced by the SOLTIVE™.

The results from the dusting settings were surprising. Due to the characteristics of the SOLTIVE™ laser, this is likely where it will provide the most clinical benefit over the Ho:YAG laser. We showed a greater than twofold increase in ablation rate with the SOLTIVE™ laser along with improved dusting capability into fragments less than 0.5 mm. What separates our study from those by Andreeva et al. [16] and Hardy et al. [17] is that we were able to compare to the latest Ho:YAG pulse modulation (MOSES™) technology. MOSES technology is a novel, pulse modulating system for the Ho:YAG laser that minimizes laser energy dissipation into irrigation, enabling more energy to be delivered directly to the stone. It has been shown to increase ablation rates over a standard Ho:YAG laser at equivalent settings [3,21]. Despite the use of MOSES technology in our study, the SOLTIVE™ laser exhibited superior ablation rates and smaller fragment sizes compared to the Ho:YAG laser.

With the ability to use smaller laser fibers than Ho:YAG, miniaturization of scopes will be possible and is under investigation by Wilson et al. [22]. This could allow easier access to tight ureters and improved drainage around the scope. The alternative is to use current ureteroscopes with smaller, SOLTIVE™ laser fibers allowing for increased irrigation and better visualization.

While our results for the SOLTIVE™ laser, along with those from other groups, are promising, the experiments were carried out in a highly controlled environment. Theoretically, based on a similar safety margin and more maneuverability with smaller fibers, we would expect the advantages seen with the SOLTIVE™ laser in bench testing to translate to clinical studies. We utilized only one type of simulated stone, which is similar to COM stones, so we were not able to verify prior findings in UA stones or other softer stone types. The advantage of testing only one stone type in a highly controlled environment is that we can attribute any differences in performance specifically to the laser platform and settings used. Lastly, our settings tested

were different for the two machines in some of the tests. For instance, in the ablation testing, the Ho:YAG was set to 8 W (0.8 J, 10 Hz) compared to 18 W (0.6 J, 30 Hz) for the SOLTIVE™ at fragmentation settings. These settings were chosen because they are the recommended settings by the manufacturer. For the dusting portion, the P120 was set to the recommended setting for Moses mode at 21 W (0.3 J, 70 Hz) and the SOLTIVE™ was similar at 20 W (0.1 J, 200 Hz), and the ablation rate was still more than twice as fast with SOLTIVE™. This could be addressed in future studies with tests of the exact same wattages, but we felt justified in our use as the total wattage used may not be reflective in the clinical performance, and we used settings recommended by the manufacturer. Because each laser has different characteristics, including differences in pulse shape and peak power, simply choosing the same wattages would still not equate to an equal comparison [23]. We believed that following the recommended settings optimized for each of these lasers produced a more balanced comparison.

CONCLUSIONS

The super-pulsed TFL is emerging as a promising alternative to the current gold standard Ho:YAG laser. Increased fragmentation rates for the SOLTIVE™ laser in our study corroborate findings from prior pre-clinical research and recent clinical studies. Clinical data is needed and further research is warranted to determine which clinical circumstances each laser is advantageous.

CONFLICTS OF INTEREST

BHC, BEK, and WRM are consultants to Olympus. They did not receive payment or any type of remuneration for their work in this manuscript.

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AUTHORS' CONTRIBUTIONS

Research conception and design: Ben H. Chew, Bodo E. Knudsen, and Wilson R. Molina. Data analysis and interpretation: Colin J. Lundeen, Bodo E. Knudsen, and Wilson R. Molina. Drafting of the manuscript: Ben H. Chew, and Colin J. Lundeen. Critical revision of the manuscript: Abdulghafour Halawani, Kyo Chul Koo, and Bodo E. Knudsen. Supervision: Ben H. Chew. Approval of the final manuscript: All

authors.

REFERENCES

1. Selmi V, Nalbant I, Ozturk U, Tuygun C, Goktug HNG, Imamoglu MA. Comparison of retrograde intrarenal surgery and percutaneous nephrolithotomy methods in treatment of upper calyceal stones of 10-20 mm. *J Laparoendosc Adv Surg Tech A* 2017;27:1293-8.
2. Kronenberg P, Traxer O. Update on lasers in urology 2014: current assessment on holmium:yttrium-aluminum-garnet (Ho:YAG) laser lithotripter settings and laser fibers. *World J Urol* 2015;33:463-9.
3. Elhilali MM, Badaan S, Ibrahim A, Andonian S. Use of the Moses technology to improve holmium laser lithotripsy outcomes: a preclinical study. *J Endourol* 2017;31:598-604.
4. Traxer O, Keller EX. Thulium fiber laser: the new player for kidney stone treatment? A comparison with Holmium:YAG laser. *World J Urol* 2020;38:1883-94.
5. Sea J, Jonat LM, Chew BH, Qiu J, Wang B, Hoopman J, et al. Optimal power settings for Holmium:YAG lithotripsy. *J Urol* 2012;187:914-9.
6. Chen S, Fu N, Cui W, Zhao Z, Luo X. Comparison of stone dusting efficiency when using different energy settings of Holmium: YAG laser for flexible ureteroscopic lithotripsy in the treatment of upper urinary tract calculi. *Urol J* 2019;17:224-7.
7. Spore SS, Teichman JM, Corbin NS, Champion PC, Williamson EA, Glickman RD. Holmium: YAG lithotripsy: optimal power settings. *J Endourol* 1999;13:559-66.
8. Emiliani E, Talso M, Cho SY, Baghdadi M, Mahmoud S, Pinheiro H, et al. Optimal settings for the noncontact holmium:YAG stone fragmentation popcorn technique. *J Urol* 2017;198:702-6.
9. Teichman JM, Vassar GJ, Bishoff JT, Bellman GC. Holmium:YAG lithotripsy yields smaller fragments than lithoclast, pulsed dye laser or electrohydraulic lithotripsy. *J Urol* 1998;159:17-23.
10. Fried NM, Irby PB. Advances in laser technology and fibre-optic delivery systems in lithotripsy. *Nat Rev Urol* 2018;15:563-73.
11. Kronenberg P, Traxer O. The laser of the future: reality and expectations about the new thulium fiber laser-a systematic review. *Transl Androl Urol* 2019;8(Suppl 4):S398-417.
12. Fried NM. Thulium fiber laser lithotripsy: an in vitro analysis of stone fragmentation using a modulated 110-watt Thulium fiber laser at 1.94 microm. *Lasers Surg Med* 2005;37:53-8.
13. Blackmon RL, Irby PB, Fried NM. Holmium:YAG (lambda = 2,120 nm) versus thulium fiber (lambda = 1,908 nm) laser lithotripsy. *Lasers Surg Med* 2010;42:232-6.
14. Blackmon RL, Irby PB, Fried NM. Comparison of holmium:YAG and thulium fiber laser lithotripsy: ablation thresholds, ablation rates, and retropulsion effects. *J Biomed Opt* 2011;16:071403.
15. Hardy LA, Kennedy JD, Wilson CR, Irby PB, Fried NM. Analysis of thulium fiber laser induced bubble dynamics for ablation of kidney stones. *J Biophotonics* 2017;10:1240-9.
16. Andreeva V, Vinarov A, Yaroslavsky I, Kovalenko A, Vybornov A, Rapoport L, et al. Preclinical comparison of superpulse thulium fiber laser and a holmium:YAG laser for lithotripsy. *World J Urol* 2020;38:497-503.
17. Hardy LA, Vinnichenko V, Fried NM. High power holmium:YAG versus thulium fiber laser treatment of kidney stones in dusting mode: ablation rate and fragment size studies. *Lasers Surg Med* 2019;51:522-30.
18. Ulvik Ø, Æsøy MS, Juliebø-Jones P, Gjengstø P, Beisland C. Thulium fibre laser versus holmium:YAG for ureteroscopic lithotripsy: outcomes from a prospective randomised clinical trial. *Eur Urol* 2022;82:73-9.
19. Jaeger CD, Nelson CP, Cilento BG, Logvinenko T, Kurtz MP. Comparing pediatric ureteroscopy outcomes with SuperPulsed thulium fiber laser and low-power holmium:YAG laser. *J Urol* 2022;208:426-33.
20. Ryan JR, Nguyen MH, Linscott JA, Nowicki SW, James E, Jumper BM, et al. Ureteroscopy with thulium fiber laser lithotripsy results in shorter operating times and large cost savings. *World J Urol* 2022;40:2077-82.
21. Stern KL, Monga M. The Moses holmium system - time is money. *Can J Urol* 2018;25:9313-6.
22. Wilson C, Kennedy JD, Irby P, Fried N. Miniature ureteroscope distal tip designs for potential use in thulium fiber laser lithotripsy. *J Biomed Opt* 2018;23:1-9.
23. Ventimiglia E, Doizi S, Kovalenko A, Andreeva V, Traxer O. Effect of temporal pulse shape on urinary stone phantom retropulsion rate and ablation efficiency using holmium:YAG and super-pulse thulium fibre lasers. *BJU Int* 2020;126:159-67.