A scoping review of the clinical efficacy and safety of the novel thulium fiber laser: The rising star of laser lithotripsy

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Abstract

Introduction: The holmium:yttrium-aluminum-garnet (Ho:YAG) laser is the gold standard for intracorporeal lithotripsy. Preclinical reports suggest the thulium laser fibre (TFL) may possess advantages over the Ho:YAG laser, including improved lithotripsy efficacy, enhanced safety, and lower costs. Although the TFL is well-characterized in vitro, there are no reviews examining TFL lithotripsy in a clinical setting.
Methods: A review of the literature was conducted using a systematic search of MEDLINE, PubMed, and Embase, yielding a total of 130 manuscripts published up to May 2020. Two independent reviewers selected studies for screening, eligibility, and inclusion into the scoping review. Following the title, abstract, and full-text review, 14 articles were analyzed.
Results: Within these articles, there were 13 prospective cohort studies and one case series. The average sample size was 100 participants. Study followup durations ranged from four weeks to three months. TFL had comparable stone-free rates to Ho:YAG lasers and improved operating time. TFL was subjectively favorable in terms of stone retropulsion, stone fragmentation, endoscopic maneuverability, and endoscopic visibility. TFL appeared clinically safe and did not result in any major complications. Many studies were underpowered and non-peer-reviewed, demonstrating the need for additional research in this field.
Conclusions: The TFL has the potential to catalyze a paradigm shift in laser lithotripsy. While the objective of this scoping review was to describe the contemporary landscape of the literature, it is important to consider that inferences posed by the studies described herein must be tempered by the low quality of available evidence.

Introduction

Renal colic is a common and costly disease which affects up to 10% of the population in the United States and results in an annual economic burden of over five billion dollars.[1] Furthermore, sedentary trends of the Western diet and lifestyle are leading to an increased incidence of stone disease requiring surgical intervention.[2] Endoscopy with intracorporeal lithotripsy is routinely utilized by urologists to manage stones. Advancements in the field of endoscopy have allowed the entire ureter and renal pelvis to be accessible for stone treatment while developments in intracorporeal laser lithotripsy technologies have enhanced stone fragmentation.

The selection of intracorporeal lithotripter is critical to limiting operation time, surgical risk, and costs. The holmium:yttrium-aluminum-garnet (Ho:YAG) laser has been the gold standard for intracorporeal lithotripsy for two decades.[3] Reported benefits compared to older electrohydraulic lithotripsy technology include decreased zone of thermal injury to adjacent tissue, reduced retrograde propulsion of calculi, increased scope maneuverability, and optimized stone fragmentation regardless of composition.[4]

The recent emergence of the thulium fiber laser (TFL) presents a potential paradigm shift in laser lithotripsy. Thulium (Tm^{69}) is a rare earth metal discovered in 1879 by Swedish chemist Per Theodor Cleve.[5] Thulium has previously demonstrated urologic applicability as the thulium:YAG laser in prostate ablation and en-bloc enucleation of bladder tumors; however, the physical parameters of the thulium:YAG laser does not permit effective lithotripsy.[6-8] The TFL is not equivalent to the thulium:YAG laser. Preclinical reports suggest that TFL technology is an attractive option for lithotripsy and may improve upon the strengths and limitations of the Ho:YAG laser.[9-12]

The technology

The TFL emits light at 1940nm, compared to the Ho:YAG laser which emits infrared light at approximately 2100nm. While both lasers are highly absorbed by water, the TFL has a higher water absorption coefficient with an optical penetration depth of 0.077mm - four times lower than Ho:YAG (0.3 mm).[3,10,12-15] This translates into lower water depth penetration as well as lower stone and tissue ablation thresholds for the TFL.[3,9,10,12,14]

The Ho:YAG laser employs a flash lamp assembly to generate and transmit laser energy. This energy-intensive design necessitates a large footprint and a complex water-cooling system. The TFL uses a smaller and simpler diode laser source that requires less power and a less cumbersome air-cooling apparatus. The more efficient electronically-modulated laser diode system works through a thin thulium-doped fiber, which also permits the use of much thinner laser fibers.[3,4,10,12,13]

The ingenuity of the TFL permits very high frequencies (upwards of 2200 Hz), low pulse energies (as low as 0.025 J) while also capacitating short and long pulse durations like state-of-the-art Ho:YAG lasers.[16,17] Current TFL systems have a much lower maximum power of 50 - 55W compared to newer generation Ho;YAG lasers which can reach >120W. Nonetheless, power levels in lithotripsy seldomly exceed 30 - 40W due to the risk of thermal tissue damage.[4,16,17]

These experimental findings demonstrate that the TFL could possess advantages over the Ho:YAG laser and present a truly innovative addition to the endourological armamentarium.[3,10,18-21] Table 1 identifies the primary technological specifications of both the Ho:YAG laser and the TFL.

Although the TFL is well characterized in in-vitro studies, there are no reviews examining TFL lithotripsy in a clinical setting. The quality and quantity of currently available clinical evidence surrounding safety and efficacy has not been systematically catalogued. Thus, the aim of this scoping review is two-fold. To familiarize urologists with the TFL and to investigate how clinical studies for thulium lithotripsy have been designed, in order to inform how future investigations should be designed to deliver more clinically relevant, safe, repeatable, and objective outcomes. Given the potentially limited amount of clinical evidence available, it is important to consider this review as a description of the contemporary TFL landscape rather than an inferential study or meta-analysis.

Methods

Search strategy and data sources

A scoping review of the literature published on the clinical efficacy and safety of the TFL lithotripsy was conducted in order to explore the breadth of evidence as well as summarize the current clinical data. This investigation will in turn identify knowledge gaps and help inform future research. The scoping review framework proposed by Arksey and O'Malley was employed.[22]

Once Medical Subject Headings (MeSH) were identified, a systematic search of Ovid MEDLINE, PubMed, Cochrane Reviews and EMBASE was performed. Articles published up to May 2020 were considered. There was no early limit. A boolean search was then conducted using the following search terms: (thulium*) and (laser or lithotripsy or fragmentation or treatment) and (stone or calculi or calculus) not "in vitro".

Study records were managed in a centralized database with electronic copies and backups available on a Cloud. Two independent reviewers were used for selecting studies for screening, eligibility and inclusion into the analysis. Following the removal of identifiable duplicate articles, two reviewers independently screened by title, then by abstract. Consensus regarding the inclusion or exclusion of studies was reached by the two authors, with discrepancies resolved through discussion between the two reviewers and adjudication by a third reviewer as necessary.

Study eligibility

Case reports, case series, conference abstracts and retrospective reviews pertaining to TFL lithotripsy efficacy and safety in a clinical setting with adult patients were included in the review. As previously mentioned, no time frame was enforced when considering the year of publication. In-vitro and pediatric investigations, editorials, as well as abstracts published in non-English languages were considered ineligible.

Data extraction

Data extraction was completed for all included studies. Briefly, we extracted data manually by first conducting a general screen of the titles and then abstract content. This was followed by a full text review, if applicable. Outcomes of the review included: procedure type, stone position, stone size (mm), stone density (HU), operative time (minutes), laser on time (minutes), stone retropulsion, endoscopic visibility, scope maneuverability, patient age, complications (Clavien-Dindo), and follow-up interval.

Data analysis

Descriptive statistics were used to summarize all data. For continuous data, the mean and standard deviation or median were reported based on the distribution of the data. Counts and proportions were used to describe all other data. No inferential statistical testing was performed.

Data items

There are no funding sources for this study.

Risk of bias in individual studies

Bias was assessed by level of evidence at the study level.

Results

Screening

A search of Ovid MEDLINE, PubMed, Cochrane Reviews and EMBASE returned a total of 130 articles. Deduplication reduced the number of unique articles to 93. Following independent review of titles and abstracts by two reviewers, a total of 14 publications were deemed eligible and retained for our analysis. Exclusions included publications utilizing thulium in a non-lithotripsy context, employment of Ho:YAG laser exclusively, thulium:YAG laser usage, in-vitro thulium experiments, and duplicate reports. Given the novelty of thulium in clinical practice, publications such as conference abstracts and non-English language articles were included in the analysis. The study selection process is summarized using a flow of information diagram as depicted in Figure 1.

Study characteristics

A total of 3 manuscripts and 11 conference abstracts were included in the review.[18,23-35] Study designs included 13 prospective cohort studies and 1 case series. A majority of published studies emanated from the Russian Federation. The average sample size of the studies was 100 participants. Study follow-up durations ranged from 4 weeks to 3 months. The most common primary outcomes related to operative time, laser on time, and stone free rate. Other targeted outcomes included subjective reporting of stone retropulsion, stone fragmentation, endoscopic maneuverability, endoscopic visibility and complications. Percutaneous nephrolithotomy (PCNL) was performed in 5 studies, ureteroscopy (URS) was performed in 10 studies and cystolithopaxy was performed in 4 studies. A summary of studies reviewed is shown in table 2.

Stone factors

Stone localization was reported in 12 studies.[18,23-35] Renal stones were present in all publications, while urethral and bladder stones were present in 5 and 4 studies, respectively. A wide variety of stone sizes were treated, the largest renal, bladder and ureteral stone was 25mm, 36mm and 13mm, respectively. Stone density was a metric included in nine reports.[9,23-27,29,30,32] Stone density inclusive of all locations ranged from 330 to 2053 Hounsfield units (HU). While TFL is known to ablate all stone types in the preclinical setting, none of the included studies reported on stone composition.

Stone fragmentation was measured by laser on time and operative time. Laser on time ranged from 0.4 to 35 minutes in all cases. The average laser on time for PCNL and URS cases was 13.4 minutes and 9.7 minutes, respectively. One study compared laser on time between TFL and Ho:YAG in upper tract stones.[25] The average time for TFL was 7.5 +/- 2.5 minutes and the average time for Ho:YAG was 15.5 +/- 5.5 minutes. Another study indicated that laser on time was related to stone diameter and not density with the TFL, which the authors attributed to the potentially improved stone ablation of TFL.[23] A study of solitary lower pole renal stones indicated laser on time of 0.4 - 2.5 minutes.[24] In regards to operative time, micro-PCNL and PCNL cases ranged from 23 - 105 minutes and URS cases ranged from 3 - 38 minutes. The average operative time for PCNL and URS was 29.3 and 17.7 minutes, respectively.

Stone retropulsion was subjectively graded by the surgeon in 6 studies, comprising a total of 548 patients.[23,25,27,30,31,35] Surgeons rated retropulsion as insignificant in almost all cases. Two studies described stone retropulsion in TFL lithotripsy as less notable than in Ho:YAG laser lithotripsy.[25,35]

Technical factors

Laser settings employed for lithotripsy were highly variable among all stone types. When renal stones were considered, pulse energy ranged from 0.025J - 4J, pulse frequency ranged from 7 - 2000Hz, and pulse power ranged from 6 - 40W. This diversity in laser settings is likely due to studies presenting this metric as a singular range rather than characterizing fragmentation and dusting settings separately. One study comparing the use of TFL and Ho:YAG in renal stone ablation reported that the TFL required a lower pulse energy and performed at a higher frequency than the Ho:YAG laser (5 - 35mJ at a rate of 10 - 500Hz and approximately 150mJ at a rate of 10 - 150Hz, respectively).[25] While 8 articles reported exclusively on the application of TFL in renal stone ablation, two reports elaborated on the laser settings used to erode ureter and bladder calculi.[18,23-30,32] Both studies described that ureteral stones required the least amount of power (range: 7 - 15W) and bladder stones necessitated a higher amount of power (range: 10 - 50W) for both fragmentation and dusting.[18,27]

Endoscopic visibility of the TFL was assessed in 4 studies.[18,23,27,30] Visibility quality was assessed by the operating surgeon using a Likert scale in 2 studies.[23,30] In one study, surgeons noted clear vision of the stone, urinary tract wall, guide-wire, and working instruments in all 14 micro-PCNL cases.[30] A larger PCNL study found that only 2.5% of cases had significant visibility issues, while another 3.3% reported minor visibility issues.[23] Two studies described an estimation of optimal intra-operative visibility, but provided little explanation on how this evaluation was obtained.[18,27]

Only one URS study commented on TFL intra-operative maneuverability.[24] This report suggested that the small diameter of the TFL fiber made for better deflection than the Ho:YAG laser. Six studies described the TFL laser model as the "SuperPulse" TFL. Cost, surgeon expertise, or number of surgeons was not documented in these studies.

Clinical and anatomical factors

Elaboration of clinical factors including symptom severity, associated infection, obesity, coagulopathy and hypertension was limited in the eligible studies. Anatomical factor description including horseshoe kidney, ureteropelvic junction obstruction, renal ectopia and system duplication was also lacking.

Safety and outcomes

Eight studies reported stone free rate after 3 months of follow-up.[23,24,26,28,30-34] The average renal stone free rate was 92.46% among all studies (range: 86.6% - 98.21%). One study reported stone free rates of 96% and 100% for ureteric and bladder stones, respectively, on non-contrast CT 30 days following treatment with URS utilizing TFL.[28]

Eleven studies commented on complications following TFL use in URS or PCNL procedures.[18,23,24,28-35] Six studies (54.5%) composed of 34 ultra miniature PCNL, 353 URS, and 40 URS and PCNL patients reported no complications following TFL use.[18,28,29,31,32,35] Post-operative antibiotic administration secondary to urinary tract infections (UTI) and pyelonephritis affered 18 patients across 4 students composed of 264, and was the most common complication necessitating a Clavien-Dindo grade of II.[23,30,33,34] Of the remaining 4 studies, double J stent insertion and undergoing postoperative extracorporeal shock wave lithotripsy (ESWL) secondary to steinstrasse composed the complications characterizing Clavien-Dindo grade 3.[23,30,33,34]

Discussion

The TFL is a novel innovation that has the potential to assume the role as the new benchmark in stone therapeutics. Based on preclinical in-vitro investigations and preliminary clinical research, table 3 outlines the potential benefits of the TFL compared to the gold-standard Ho:YAG laser for lithotripsy.[3,6,9-13,16-21,23-35]

There are currently no reviews examining TFL lithotripsy in a clinical context, making this review the first of its kind. At the time of this review, it is evident that there are clearly large gaps in the published literature. Only 3 full-length articles and 11 conference abstracts were available for review. The current clinical landscape as it pertains to TFL lithotripsy consists predominantly of a small number of underpowered, non-peer reviewed studies and is particularly limited in the domains described below as well as long term clinical and safety outcomes.

Stone factors

The TFL has been shown to be able to target a wide variety of stone densities and sizes. Stones of densities exceeding 2000 HU and renal stones as large as 25mm were reported to be successfully fragmented.[18,26] The TFL could also be maneuvered into any location along the genitourinary tract and proved to be an effective treatment of stones in the renal lower pole.[24] As measured by operative time and laser on time, stones were reported to be fragmented in a reasonable timeframe. The average operative time for PCNL and URS was 29.3 and 17.7 minutes, respectively and the average laser on time for PCNL and URS was 13.4 minutes and 9.7 minutes, respectively. However, metrics like laser on time and operative times require cautious interpretation as they are surrogate measurements of fragmentation and require stratification with stone size and density in future studies.

Both pre-clinical and clinical reports have reported TFL lithotripsy to result in less stone retropulsion compared to Ho:YAG.[3,10,12,19,21,25,35] Nonetheless, stone retropulsion was a subjective measure in most cases. In order to objectively quantify this phenomena and mitigate bias, future studies should consider distributing validated retropulsion scales to sizable cohorts of surgeons. Other factors such as placement of laser fibre and patient positioning should also be documented when evaluating stone retropulsion.

Technical factors

The TFL required less pulse energy and performed at a higher frequency than the Ho:YAG laser for effective fragmentation in one study.[25] Pulse energies as low as 0.025J and frequencies as high as 2000Hz were utilized. Although in-vitro and early clinical studies presented herein have provided preliminary recommendations for TFL lithotripsy settings, it is evident that large clinical-based trials will be necessary to elucidate ideal settings for approaching stone fragmentation and dusting.

The innovative design of the TFL permits the use of silica fibers with diameters as small as 50μm, which has been suggested to improve endoscopic maneuverability as well as endoscopic irrigation and visibility compared to the former Ho:YAG laser.[3,10,12,13,18,27,30] When these measures were assessed, surgeons described visibility as optimal and maneuverability as improved. One study assessing 130 patients with lower pole renal stones highlighted this finding.[24] While studies considering these measures reported improvements over the Ho:YAG, these findings were assessed subjectively in a similar fashion to stone retropulsion. Future studies with a standardized and validated scale of visibility and maneuverability are required. It will also be important to have large cohorts of surgeons involved in this survey to minimize bias.

Due to the novelty of the TFL, the SOLTIVE SuperPulsed Laser System by Olympus was the only system used in eligible articles. Other thulium laser systems, if any, are still pre-clinical and have yet to be tested in human trials.

Clinical and anatomic factors

Clinical and anatomic attributes of patients were not well documented in the current literature. Studies assessing these details are in progress and are essential in order to identify valid clinical applications, potential contraindications, and ideal candidates for TFL lithotripsy.

Safety and outcomes

Although surgeon expertise and patient factors may vary, stone free rates with the TFL appear to be similar to the Ho:YAG laser with an average renal stone free rate of 92.46% across studies assessing this metric.[36,37] The number and expertise of surgeons who participated in many of these studies was not disclosed and stone free rates may be due to technical expertise rather than the TFL. Due to limited access of TFL, the current literature is limited to studies originating exclusively from the Russian Federation or those that are largely dependent on Russian institutions. Further evaluation of the TFL as a lithotripter will be enhanced by incorporating studies from multinational institutions.

The current benchside and clinical data suggests that TFL is likely safe in the peri-operative and short term postoperative period. A majority of studies reported a limited number of complications. The majority of complications reported were minor and expected with endoscopic manipulation, such as UTI. Grade III complications were reported in 28.6% of studies requiring placement of a stent or ESWL for large and persistent fragments.[18,30,33] No patient mortalities were reported. The mean follow-up for eligible studies was 3 months, which stipulates the need for the assessment of complications and outcomes at long term follow-up. Indeed, ongoing data collection is required to evaluate the long term safety and benefits of the TFL.

Recommendations for future investigations

Randomized controlled trials comparing the Ho:YAG laser and TFL in a clinical setting are required. Ideally, these reports would consist of a diverse group of patients and stone factors, as well as multiple surgeons from a diversity of institutions in order to avoid bias based on level of expertise. The following variables should be assessed: procedure, stone position, stone size, stone composition, stone density, clinical factors, anatomical factors, operative and laser on times, laser settings employed, short-term and long-term complications (as reported through Clavien-Dindo scores), and stone free rates. Additionally, long term outcomes and complications require research. Objective assessment of maneuverability, stone retropulsion, and endoscopic visibility is also required as this is largely lacking from the current literature and should be incorporated into future proof-of-concept studies. Furthermore, future studies may assess noise levels, surgeon fatigue, and financial and environmental impacts.

Study limitations

As it currently stands, the current clinical literature pertaining to TFL is composed of only a small number of underpowered and non-peer reviewed studies. While an objective of this scoping review is to describe the contemporary landscape of the literature, it is important to consider that conclusions and assertions posed by the studies described herein must be tempered by the low quality of available evidence. There were three full-text articles, and only one of which is written in English. This may have prevented extraction of data such as clinical and anatomical factors of patients. In addition, detailed review of datasets and results were not possible in some cases. The results of the literature were also heterogeneous with multiple stones in multiple locations, sizes and numbers with different procedures. These studies were chosen to be included due to the limited amount of clinical evidence available; however, the data may be difficult to standardize. As such, it is important to interpret the results of this scoping review from a practical lens in order to familiarize surgeons with the TFL and to describe the current clinical landscape of TFL rather than to make inferences about the TFL.

Conclusions

Preliminary clinical data suggests that TFL lithotripsy appears to have efficient stone fragmentation, decreased stone retropulsion, improved maneuverability and is safe. While the available clinical reports seem to lend credence to the findings of pre-clinical studies that suggest the TFL has the promise to shift the standards of lithotripsy, these results require critical considerations. The paucity of completed and high-quality clinical studies speaks to the growth required in this field. Current clinical data is minimal and further mutli-center trials with sufficient power are needed to validate contemporary findings.

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Figures and Tables

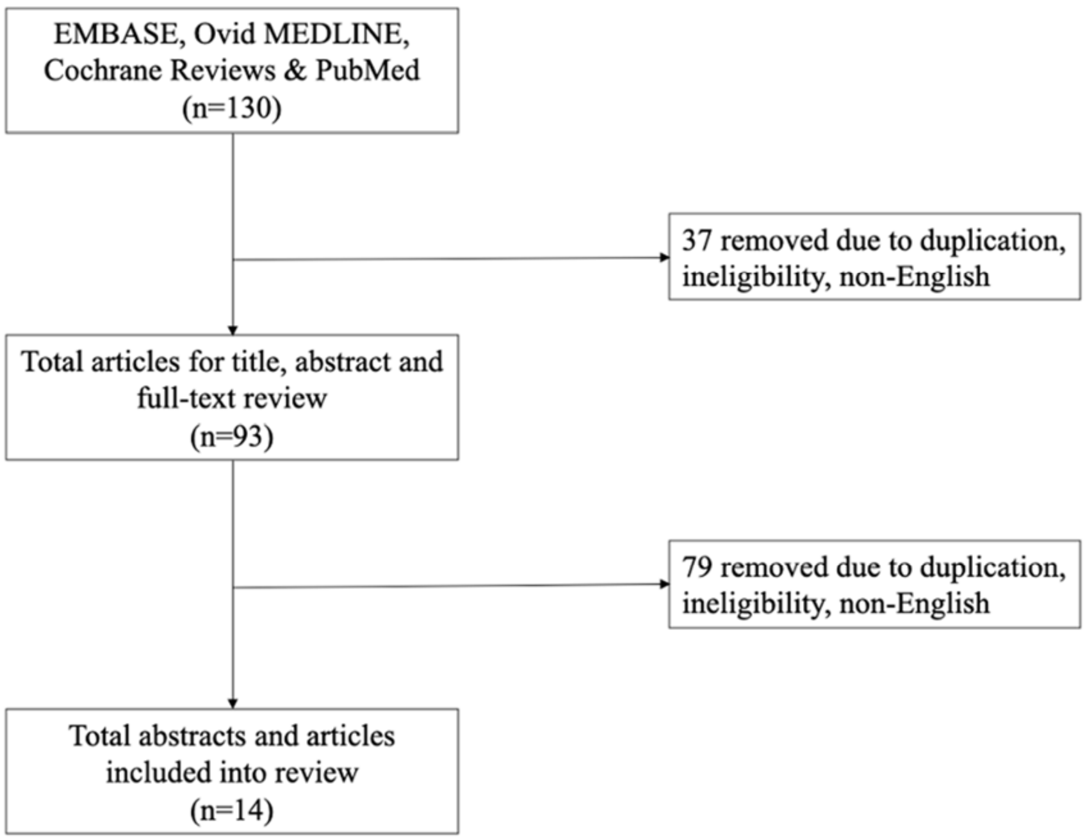

Fig. 1. Flow chart of study selection process.

Table 1. **In-vitro laser specifications of the Ho:YAG laser and TFL**

Laser specifications	Ho:YAG Laser	TFL (eg SOLTIVE^{TM} Premium)
Peak power	N/A	500W
Average power	120–140W	50–60W
Pulse energy	0.2–6.0J	0.025–6.0J
Pulse frequency	5–80Hz	1–2400Hz
Pulse duration	50–1300μs	200μs–50ms
Pulse profile	Irregular spikes with rapid descent	Approximately square wave
Wavelength	2100 μm	1920–1960 μm
Minimum laser fiber diameter	200 μm	50 μm
Energy efficiency	1%	12%
Power supply required	High amperage power outlet	Standard power outlet
Energy source	Flash lamp	Laser diodes
Gain medium	Crystal rods containing holmium ions	Laser fiber core containing thulium ions
Cooling apparatus	Water	Air
Weight	245–300kg	36 kg
Peak noise level	70 dB	N/A (reported to be quieter due to lack of flash lamp)

Ho:YAG: holmium/yttrium-aluminium-garnet; N/A: not available; TFL: thulium-fiber laser.

Table 2. Summary of all studies reviewed, and the clinical factors/outcomes gathered

Author	Pt age (yrs)	No. pts	Procedure	F/U interval	Stone position	Stone size (mm)	Stone density (HU)	Oper-ative time (min)	Laser on time (min)	SFR (%)	Compli-cations	Stone retropulsion	Endo-scopic visibility	Maneuver-ability of scope	Laser settings
Enikee et al	52± 1.8	120	PCNL	3 months	Renal	12.5± 8.8	1019 ±375	23.4± 17.9	5±5.7 *Correlated to stone diameter, not density	N/A	Clavien-Dindo Grade I: fever (3.3%), transient AKI (3.3%), clot retention (6%); Clavien-Dindo Grade II: transient urine leak (1.7%), UTI (1.7%), wound infection (1.7%); Clavien-Dindo Grade III: double J (5%)	Significant retropulsion in 1.7% cases	Significantly poor (2.5%), minorly poor (3.3%)	N/A	0.8 J/ 25–30 W/ 31–38 Hz
Korole et al	N/A	130	URS	3 months	Renal: lower pole	4–17	350–1459	12 min (3–30 min)	1.3 (0.4–2.5)	86.60%	All complications less than Clavien-	N/A	N/A	Better deflection with smaller fibre	0.1–4 J/ 7–300 Hz/ 6–40 W

											Dindo Grade II				
Pattnaik et al	N/A	50	URS	N/A	Renal, ureter	Up to 20	1000–1400	N/A	Holmium: 15.5±5.5, thulium: 7.5± 2.5	N/A	N/A	TFL had less fragment retropulsion than Ho:YAG	N/A	N/A	Holmium (10–150 Hz, energy <150 mJ), thulium (5–35 mJ, rate 10–500 Hz, duration 500 microsec)
Dymov et al	N/A	32	URS	Postop day 3 and 90	Renal	7–25	330–1960	N/A	N/A	91% (postop day 90)	N/A	N/A	N/A		(0.1–4J, 7–300 Hz, 6–40 W)
Dymov et al	N/A	268	URS	N/A	Renal, ureter, bladder	Renal: 7–25, ureter: 3–18, bladder: 9–36	Renal: 330–1960, ureter: 460–1700, bladder 860–1050	Renal: 27.2, ureter: 17.1, bladder: 19	Renal: 24.3, ureter: 12.7, bladder: 14.5	N/A	N/A	Insignificant in all cases with energy <0.5 J	Estimated as optimal in most cases	N/A	0.1–0.2 J/ 15–30 W; 0.2–0.5 J/ 10–15 W and 2–5 J/ 30–50 W were identified as optimal for kidney (dusting), ureter (dusting and fragmentation), and bladder (fragmentation) stones
Traxer et al	N/A	214	URS	Postop day 30	Renal, ureter, bladder	N/A	N/A	4–38	0.2–14.4	Renal: 94%, ureter: 96%, bladder: 100%	None	N/A			

Keller et al	55–65	3	URS	N/A	Renal: upper pole (3 stones), middle pole (1 stone), lower pole (1 stone), L pelvis (2 stones)	Renal: upper pole (10, 6, 6), middle pole (12), lower pole (10), pelvis (15, 30)	1100–1400	i) 40 ii) 24 iii) 37	i) 30 ii) 11 iii) 23	N/A	i) No complications ii) No complications, iii) No complications	N/A	N/A	N/A	Optimal parameters in this study were found to be 0.1e0.2 J and rep rate 100e300 Hz for fine dusting and pop corning, 0.2e0.5 J and 50e150 Hz for dusting and 1e5 J and 10–40 Hz for fragmentation
Martov et al	30–71	14	Micro-PCNL	Postop day 30	Renal: pelvis (6 stones), lower calyx (6 stones), middle calyx (2 stones)	7–19	560–1380	55–105	8±6	92.80%	Clavien-Dindo Grade II: UTI (7.14%), hematuria (7.14%); Clavien-Dindo Grade III: steinstrasse requiring a double J stent and ESWL (7.14%)	None or insignificant stone migration in all cases	N/A	N/A	From text: 0.1 J/ 250 Hz/25 W; from video: i) 0.2 J/ 50 Hz/ 10 W, ii) 0.1 J/ 300 Hz/ 30W , iii) N/A

Ali et al	N/A	40	URS and PCNL	N/A	Renal: 29 stones, ureter: 9 stones, bladder: 2 stones	Renal: 5.5–27, ureter: 5–13, bladder: 15–42	Renal: 524–2053, ureter: 700–1782, bladder: 779–900	Bladder: 30.2 (10–50), ureteral 19.2 (10–28), bladder: 23 (21–25)	Renal: 21.1 (7–35), ureter: 13.4 (7–20), bladder: 16 (14–18)	N/A	Not recorded, but study concluded TFL was safe	None or insignificant stone migration in all renal and ureter cases, retropulsion, which did not affect stone ablation in bladder stones	Clear vision of the stone, urinary tract wall, guide-wire, working instruments	N/A	0.1–0.8 J/ 8–20 W/ 13–100 Hz
Martov et al	19–82	136	URS	Postop day 30	N/A	N/A	N/A	4–19	0.2–8	94%	No complications	N/A	Optimal visibility reported	N/A	Renal: 10–20 W (0.025–2 J x 7– 400 Hz), ureter: 7–15 W (0.025–1 J/ 7–200 Hz), bladder: 10–50 W (0.1–6 J/ 3–500 Hz)
Martov et al	32–77	34	Ultra mini PCNL	Postop day 30	Renal: pelvis (13 pts), lower calyx (10 pts), middle calyx (4 pts), upper calyx (2 pts), pelvis	<20	670–1430	29±9	8±6	94%	No complications	N/A	N/A	N/A	N/A

					and lower calyx (3 pts), pelvis and middle calyx 2 pts)										
Martov et al	N/A	56	URS	4–6 weeks	Renal and ureter: 44 stones, bladder: 12 stones	Upper tract: 6–18, bladder: 11–35	N/A	N/A	19	98.21%	Clavien-Dindo Grade II: Pyelonephritis (15.9%); Clavien-Dindo Grade III: ESWL (1.79%)	None or insignificant stone migration in all renal and ureter cases	N/A	N/A	1–1.5 J/ 15–30 Hz (fragmentation), 0.1–0.3 J/ 50–100Hz (dusting)
Ergakov et al	19–82	56	N/A	N/A	N/A	N/A	N/A	17–25	Shorter for Tm system by a factor of 1.5 in fragmentation mode and by a factor of 3 in dusting mode	N/A	No complications	TFL had significantly reduced retropulsion compared to Ho:YAG laser	N/A	N/A	N/A

Martov et al	49.8± 16.3	74	Micro-PCNL	1 month	Renal: solitary (86.4%), pelvis (51.5%), lower pole (35.9%)	Renal: <15 (62.1%), >15 (37.9%)	N/A	N/A	30.6 +/- 11.6	89.1% (93.4% for stones <1.5 cm, 82.4% for stones >1.5 cm)	Clavien-Dindo Grade II: pyelonephrtis (8.1%); Clavien-Dindo Grade III: ESWL (9.4%)	N/A	N/A	N/A	N/A

AKI: acute kidney injury; ESWL: extracorporeal shock wave lithotripsy; F/U: followup; Ho:YAG: holmium/yttrium-aluminium-garnet; N/A: not available; PCNL: percutaneous nephrolithotomy; Pt: ; patient; SFR stone-free rate; TFL: thulium-fiber laser; URS: ureteroscopy; UTI: urinary tract infectio

Table 3. Potential advantages of new TFL technology over Ho:YAG laser for lithotripsy suggested by current clinical data

Potential advantage	**Specification of interest**	**Result**
Better lithotripsy efficacy	Lower stone ablation thresholds	Faster lithotripsy
	Increased water absorption results in mechanical stress waves at stone surface and micro-explosions within the stone pores	Faster lithotripsy
	Efficacious at lower energy settings	Less retropulsion, minimal "snow storm" effect and improved visibility
	Thinner fibers	Improved irrigation flow, endoscope flexibility and visibility, and facilitates use of tools through the same working channel (e.g., basket)
Safer lithotripsy	4x lower depth of penetration	Lower likelihood of perforating adjacent tissue
	Smaller fibers and better irrigation flow	Improved visibility, lower risk of temperature-related tissue damage
	Lower voltage requirements	Standard power outlets sufficient and improved electrical safety
Lower costs	Simple laser diode assembly	Lower maintenance costs
	Less energy requirements and less "snow storm" effect	Decreased fiber burn-back, damage from stone collisions
	Ability to use with standard electrical outlets	No need to retrofit OR with 20–50 Amp outlets
	Smaller footprint	Less storage space required in the operating room (1/8th size of Ho:YAG)
Less environmental impact	Lower stone ablation thresholds resulting in lower energy requirements	Reduced energy consumption
	Higher electrical energy efficiency	Reduced voltage required
	Air cooling is quieter	Lower noise pollution

Ho:YAG: holmium/yttrium-aluminium-garnet; TFL: thulium-fiber laser.