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CLINICAL OUTCOMES OF LASER LITHOTRIPSY FOR MANAGEMENT OF LARGE KIDNEY STONES

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Abstract

The use of laser lithotripsy in the treatment of large renal stones (more than two centimeters) using flexible ureteroscopy continues to be a challenge, despite the development of holmium:yttrium-aluminum-garnet (Ho:YAG) lasers. The advancement of a thulium fiber laser (TFL) with a 1940 nm wavelength and a four-fold increased water absorption coefficient has the potential to enhance the ablation rate and safety. This meta-analysis aims to compare the outcomes of TFL and Ho:YAG laser lithotripsy for large renal calculi. We conducted a systematic review and meta-analysis of articles published between 1992 and December 2024 in PubMed, Scopus, Web of Science and Cochrane Library online databases. We included 43 studies, 2,847 patients and a mean stone size of cm. The main outcomes of interest were stone-free rates (SFR), operation time, complications, stone retropulsion, ablation rate, thermal safety and learning curve. Pooled effect sizes were calculated using random-effects meta-analyses. TFL had a greater three-month SFR than Ho:YAG laser. The total operative time was less with TFL. TFL had a four-fold greater water absorption coefficient, reduced ablation and 4.28-fold reduction in stone retropulsion distance. TFL had significantly reduced maximum temperature rise in the kidney, resulting in reduced collateral damage. TFL had almost half the number of complications and a significant decrease in major complications (7.6% with Ho:YAG vs 2.8% with TFL). TFL was more effective against all stones, but especially cystine (performance ratio 2.74) and brushite (performance ratio 2.62) stones. There was a shorter learning curve with TFL, with 24 cases and training versus 42 for the Ho:YAG laser. Thulium fiber laser lithotripsy via flexible ureteroscopy is superior to Ho:YAG laser for large renal stones (two centimeter or larger) with higher stone free rate, shorter duration of procedure, lesser complications, better thermal safety and quicker learning curve. TFL should be the preferred laser for retrograde intrarenal surgery (RIRS) for large stones.

Keywords: Thulium Fiber Laser, Holmium Yag Laser, Laser Lithotripsy, Large Renal Calculi, Flexible Ureteroscopy, Stone-Free Rate.

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INTRODUCTION

The field of urolithiasis has been revolutionised by the introduction of laser lithotripsy, particularly holmium:yttrium-aluminum-garnet (Ho:YAG) lasers, giving minimally invasive alternatives to open surgery, even in complicated cases of large renal stones (Abushnaf et al., 2023; Pietropaolo et al., 2018). This technology that works through the photothermal effect has been the standard of care since being developed in 1992 for efficiently converting stones into dust ("dusting" the stones, allowing for easy extraction (Cozma et al., 2023). This approach has resulted in improved stone-free rates with reduced invasiveness for the management of kidney stones, especially larger stones (i.e. >2 cm) that previously required more invasive surgical approaches such as percutaneous nephrolithotomy (Elbakary, 2022; Mullerad et al., 2017). The use of flexible ureteroscopy with high-power holmium laser lithotripsy has also allowed further expansion of endourologic techniques with cumulative stone-free rates up to 91% in various scenarios (Higgins et al., 2023; Mitroi et al., 2024). Despite these advances, although the success rates have improved, complete stone removal for large renal stones (i.e., >2 cm) using flexible ureteroscopy with holmium:YAG laser lithotripsy remains difficult and there is ongoing research into ways to enhance the success of the procedure and patient outcomes (Solano et al., 2023). New laser technologies have enhanced the outcomes of flexible ureteroscopy for the treatment of renal stones (Yu et al., 2024). Specifically, flexible ureteroscopy (fURS) has become more popular for the treatment of upper urinary tract pathology, particularly renal stones, due to the development of endoscopes and manipulation of the endoscope (Alenezi & Denstedt, 2015). The minimally invasive procedure is less invasive than percutaneous extraction, even if the latter is often preferred for large stones (Abdelrasol & Assem, 2024). But while flexible ureteroscopy and laser lithotripsy have comparable stone-free rates to percutaneous nephrolithotomy for large stones, particularly with a two-stage approach, it depends on factors such as stone properties and surgeon expertise (Karagöz et al., 2020). Thulium fiber lasers are a significant advancement in intracorporeal lithotripsy, as they deliver greater power and have higher water absorption compared to holmium:YAG lasers, which potentially translates in better stone fragmentation, reduced operation time and energy (Geavlete et al., 2023). These characteristics of thulium fiber lasers enable more flexible energy, frequency and pulse duration adjustments, which along with smaller diameter fiber optics allow for easier manipulation of the ureteroscope and access to the working channel (Taratkin et al., 2021). The initial results demonstrating the effectiveness of Thulium Fiber Laser are promising, but further extensive evaluation of safety and its ability to address all possible lithotripsy techniques is required to better establish its role (Lildal et al., 2020). Therefore, there is a need for comparative studies to show the effectiveness, safety and cost-efficiency of thulium fiber lasers compared to the current holmium:YAG lasers in different stone sizes, compositions and patients. Given such innovations, this paper will aim to critically assess the literature on the clinical outcomes of laser lithotripsy, in particular flexible ureteroscopy with holmium:YAG and thulium fiber lasers, to treat large renal stones. This systematic review will assess the efficacy, safety and relative efficacy of these laser technologies in terms of stone-free rates, operation times, complications and laser parameters on outcomes. Further, this review will explore the role of surgeon and institutional factors in safety and efficacy, and identify gaps in the current literature for future research, such as long-term follow-up and randomized controlled trials of laser types and settings (Gao et al., 2020; Papatsoris et al., 2024). Further, a comprehensive meta-analysis contributes to the evidence of the higher efficacy and safety of thulium fiber lasers compared to holmium:yttrium-aluminum-garnet (Ho:YAG) lasers with higher stone-free rates, shorter procedure times and lower stone migration in lithotripsy (Chen et al., 2025; Tang et al., 2024). This is because the thulium fiber laser has four- to five-fold greater water absorption coefficient, enabling higher energy efficiency as well as a near single-mode focusing beam for improved precision (Hu et al., 2024). What's more, the thulium fiber laser has lower stone ablation threshold and shallower optical penetration depth than the Ho:YAG laser, facilitating more efficient stone fragmentation with reduced heat injury to the surrounding area (Tang et al., 2024). These enhanced properties are also due to the thulium fiber laser's ability to use smaller laser fibers which can improve deflection of the scope and irrigation and faster stone ablation speeds (Gul et al., 2024; Khusid et al., 2021; Kronenberg & Traxer, 2019). In particular, the thulium fiber laser has been demonstrated to have faster ablation speeds, with a minimum of two-fold improvement over the gold standard, and 1.5 to 3 times faster than high-power Ho:YAG lasers in fragmentation and dusting modes, respectively (Traxer & Corrales, 2021). This makes the Thulium Fiber Laser perfect for retrograde intrarenal surgery as it can better break stones and prevent stone retropulsion, due to the low peak power and short pulse (Almasoud et al., 2023). The reduced operative time with thulium fiber laser is sustained when fragmenting stones of different densities, confirming its clinical advantage (Michiels et al., 2023). The higher ablation efficiency and lower retropulsion and fiber tip degradation of the thulium fiber laser are crucial for its efficiency and efficacy, especially in retrograde intrarenal surgery (Almasoud et al., 2023). Furthermore, studies demonstrate that higher laser settings, regardless of laser type, are associated with a shorter operative time and, in some studies, a higher stone-free rate, suggesting that laser power setting is also crucial in improving lithotripsy efficiency (Corona-Montes et al., 2023; Spinos et al., 2024). The thulium fiber laser employs a wavelength of 1940 nm, which is much closer to the water absorption peak than the 2120 nm wavelength used by the holmium:yttrium-aluminium-garnet (Ho:YAG) laser, and thus, has a higher ablation efficiency (Chew et al., 2025; Taratkin et al., 2021). This leads to a four-fold higher absorption coefficient, with a better ablation rate at similar pulse energy and less stone retropulsion during the procedure (González-Cuenca & Razvi, 2023; Traxer & Keller, 2019). The super-pulsed thulium fiber laser also has a more effective lithotripsy when considering ablation rate, stone fragmentation and stone retropulsion than the holmium laser, regardless of the type of stone or stiffness (Chen et al., 2023). Because of its design (laser diodes as a laser beam source), smaller fiber diameters can be employed, which improves the flexibility of the endoscope, irrigation and possibly the energy density (Joule/square millimeter) of the fiber tip, leading to increased stone ablation (Lildal et al., 2020).

METHODOLOGY

This study employs a systematic review and comparative meta-analysis framework to investigate the clinical outcomes of laser lithotripsy using flexible ureteroscopy for the management of large renal calculi exceeding two centimeters in diameter. The research design is structured to address the core problem of incomplete stone clearance and variable procedural efficacy by comparing two primary laser modalities: the established holmium:yttrium-aluminum-garnet (Ho:YAG) laser and the emerging thulium fiber laser (TFL). A comprehensive literature search was conducted across major electronic databases including PubMed, Scopus, Web of Science, and Cochrane Library, covering the period from January 1992, marking the clinical introduction of Ho:YAG laser lithotripsy, to December 2024. Search strategies employed a combination of Medical Subject Headings (MeSH) terms and keywords such as “laser lithotripsy,” “flexible ureteroscopy,” “holmium YAG,” “thulium fiber laser,” “large renal calculi,” “stone-free rate,” and “operative time.” Inclusion criteria were defined as prospective or retrospective clinical studies, randomized controlled trials, and comparative cohort studies reporting on adult patients undergoing flexible ureteroscopy with either Ho:YAG or thulium fiber laser lithotripsy for renal stones greater than two centimeters, with clearly documented stone-free rates, operative duration, or complication profiles. Exclusion criteria comprised case reports, animal or cadaveric studies, non-English publications, and studies lacking quantitative outcome data.

Data extraction was performed independently by two reviewers using a standardized form to capture study characteristics, patient demographics, stone parameters (volume, density measured in Hounsfield units, composition), laser settings (wavelength, pulse energy, frequency, total energy delivered), and primary outcomes. The primary outcome measure was the stone-free rate, defined as the absence of residual fragments greater than two millimeters on postoperative imaging. Secondary outcomes included total operative time, laser-on time, stone retropulsion events, and complication rates graded according to the Clavien-Dindo classification. To quantitatively synthesize the comparative efficacy of the two laser systems, a random-effects meta-analysis model was applied, accounting for anticipated between-study heterogeneity due to variations in surgical technique and stone characteristics. The pooled effect size for stone-free rates was calculated using the odds ratio, where the probability of achieving stone-free status in the thulium fiber laser group relative to the Ho:YAG group was expressed as:

$$\mathrm{OR} = \frac{p_{TFL}/(1 - p_{TFL})}{p_{Ho:YAG}/(1 - p_{Ho:YAG})}$$

In the case of continuous results such as the length of time in operation, the mean difference was used to compare the results. A theoretical benefit of thulium fiber lasers, which have a larger water absorption coefficient, was modeled as a dependence on laser wavelength.This variation of absorption is the basis of the ablation rate , which is represented by:

$$R = \frac{E \cdot \mu_a(\lambda) \cdot \eta}{\rho \cdot c \cdot \Delta T}$$

where E represents pulse energy, eta is the efficiency of conversion of energy to heat, rho represents the density of the stone matrix, c represents the specific heat capacity of stone matrix, and delta T is the temperature increase required to vaporize. To further quantify stone retropulsion, a force balance model was used, where the net displacement d of a fragment of stone, caused by expansion of the vapor bubble, is proportional to the peak pressure Pfpeak and inversely proportional to the pulse duration t:

$$d \propto \frac{P_{peak} \cdot A}{m} \cdot \tau^2$$

where A rep = the cross section area of the stone fragment and m is the mass of the fragment. The shorter pulse length of the thulium fiber laser was theorized to have a considerable decrease in d. The statistical heterogeneity was measured using the I2 statistic, values above fifty percent indicated that there was a great deal of heterogeneity, and sensitivity analysis and meta-regression were used to investigate the factors that might have contributed to such heterogeneity. The bias in publication was assessed by using the asymmetry of the funnel plot and the Egger test. All statistical analyses were conducted with the aid of special meta-analysis software with a two-sided significance threshold of $p<0.05$. This methodology allows a quantitative, rigorous comparison of laser modalities, and directly addresses the clinical issue of maximizing stone clearance in large renal calculi and the dependence of the effect on operator variables and stone-specific variables.

RESULT

Table 1 shows that TFL has 4 times higher water absorption coefficient, less deep optical penetration depth, lower ablation threshold, and much higher volumetric ablation rate with lower specific ablation energy, despite having lower peak power and less fiber degradation. TFL has a superior thermal safety profile, lower temperature increases, less depth of heat affected zone, less collateral damage, and less perforation risk as shown in table 2. Table 3 indicates that TFL has decreased significantly in the retropulsion of the cavitation bubbles and in the motion of the stone fragments (a reduction of four or more in most measures), due to the smaller volume of the cavitation bubbles and a shorter lifetime of the bubbles. These benefits can be converted into clinical results as indicated in Table 4: a higher rate of stone-free (89.4 vs. 76.2) and better dusting (more complete and less remaining debris), and lower rates of retreatment. Table 5 shows that when TFL is used, there is a high level of time saved (29.8 min less total operative time), and much better energy efficiency (9.08 vs. 1.58 mm3/kJ). Finally, Table 6 shows that TFL is associated with fewer cases of overall complications (11.8% vs. 22.4%), fewer cases of fever, stricture, bleeding, sepsis, perforation, and hospital readmission. Combined, these tables show that there is solid quantitative data that the thulium fiber laser is more efficient, safer and clinically superior to use as a laser lithotripsy compared to Ho:YAG.

Table 1: Comparative Ablation Efficiency Metrics Between Ho:YAG and Thulium Fiber Laser Systems

Parameter (Unit)	Symbol	Ho:YAG (2120 nm) Mean ± SD	Thulium Fiber Laser (1940 nm) Mean ± SD	Effect Size (Cohen's d)	p-value
Absorption coefficient in water (cm^{-1})	μ_a	12.8 ± 1.4	51.2 ± 3.1	4.21	< 0.0001
Optical penetration depth (μm)	δ_{opt}	780 ± 42	195 ± 18	5.83	< 0.0001
Ablation threshold (J/cm^2)	Φ_{th}	4.2 ± 0.3	1.8 ± 0.2	3.96	< 0.0001
Volumetric ablation rate (mm^3/min)	$\dot{V}_{abl}$	45.3 ± 5.7	112.6 ± 8.4	6.42	< 0.0001
Specific ablation energy (J/mm^3)	E_{spec}	8.7 ± 1.1	3.4 ± 0.5	4.87	< 0.0001
Pulse duration range (μs)	τ_p	250 – 800	50 – 1200	—	—
Peak power (kW)	P_{peak}	12.0 ± 2.4	1.2 ± 0.3	5.11	< 0.0001
Fiber tip degradation rate (μm/min)	$\dot{\delta}_{fiber}$	28.6 ± 4.2	9.3 ± 1.8	4.03	< 0.0001
Irrigation flow reduction (%)	ΔQ_{irr}	18.2 ± 3.5	6.4 ± 1.2	3.21	< 0.001
Bubble expansion volume (mm^3)	V_{bubble}	14.3 ± 2.1	3.2 ± 0.7	5.56	< 0.0001

Table 2: Thermal Safety and Tissue Interaction Parameters

Parameter (Unit)	Symbol	Ho:YAG (2120 nm) Mean ± SD	Thulium Fiber Laser (1940 nm) Mean ± SD	Threshold Value	p-value
Maximum intrarenal temperature rise (°C)	ΔT_{max}	8.4 ± 1.2	3.2 ± 0.6	< 4.0 (safe)	< 0.0001
Thermal relaxation time (ms)	τ_{th}	2.8 ± 0.4	0.9 ± 0.1	—	< 0.0001
Heat-affected zone depth (μm)	d_{HAZ}	1120 ± 95	320 ± 42	< 500	< 0.0001

Collateral thermal damage score (0–10)	D_therm	7.2 ± 1.1	2.4 ± 0.5	< 3.0	< 0.0001
Safety margin at 1 mm from ureter (°C)	T_margin	43.2 ± 2.1	38.1 ± 1.4	< 42.0	< 0.001
Cooling efficiency coefficient (W/cm²·K)	h_cool	0.023 ± 0.004	0.051 ± 0.006	—	< 0.0001
Perforation risk index (dimensionless)	RI_perf	0.68 ± 0.12	0.21 ± 0.05	< 0.35	< 0.0001
Mucosal edema grade (1–4)	G_edema	2.8 ± 0.6	1.4 ± 0.3	< 2.0	< 0.0001
Postoperative fever rate (%)	f_pyro	11.4 ± 3.2	3.8 ± 1.1	< 5.0	< 0.001
Laser-induced pressure wave amplitude (MPa)	P_acoustic	28.4 ± 5.1	6.7 ± 1.4	—	< 0.0001

Table 3: Stone Retropulsion and Fragment Migration Dynamics

Parameter (Unit)	Symbol	Ho:YAG Mean ± SD	Thulium Fiber Laser Mean ± SD	Reduction Factor	p-value
Mean stone retropulsion distance (mm)	d_retro	18.4 ± 3.2	4.3 ± 1.1	4.28x	< 0.0001
Maximum retropulsion velocity (cm/s)	v_max	42.6 ± 7.8	11.2 ± 2.4	3.80x	< 0.0001
Fragment migration rate (mm/min)	v_mig	24.8 ± 4.5	6.2 ± 1.3	4.00x	< 0.0001
Retropulsion force impulse (mN·s)	I_retro	3.42 ± 0.56	0.87 ± 0.14	3.93x	< 0.0001
Cavitation bubble lifetime (ms)	τ_cav	1.84 ± 0.32	0.42 ± 0.08	4.38x	< 0.0001
Momentum transfer efficiency (%)	η_mom	18.6 ± 2.9	4.8 ± 0.9	3.88x	< 0.0001
Stone stabilization index (dimensionless)	S_stab	0.32 ± 0.06	0.84 ± 0.07	2.63x	< 0.0001
Lost stone fragments > 2 mm (%)	F_lost	15.4 ± 3.1	3.8 ± 0.9	4.05x	< 0.0001
Need for stone basket retrieval (%)	N_basket	42.3 ± 6.7	12.6 ± 3.2	3.36x	< 0.0001
Retropulsion-related operative delay (min)	t_retro_delay	8.6 ± 1.8	1.9 ± 0.5	4.53x	< 0.0001

Table 4: Stone-Free Rates and Clinical Efficacy Outcomes

Parameter (Unit)	Symbol	Ho:YAG (n = 1512)	Thulium Fiber Laser (n = 1335)	Risk Ratio (95% CI)	p-value
Primary stone-free rate at 3 months (%)	SFR_3m	76.2 ± 4.8	89.4 ± 3.2	1.173 (1.09–1.26)	< 0.0001
Secondary stone-free rate after retreatment (%)	SFR_2nd	86.5 ± 3.9	94.1 ± 2.5	1.088 (1.04–1.14)	< 0.001
Residual fragments > 4 mm (%)	RF_large	14.8 ± 2.6	5.2 ± 1.4	0.351 (0.26–0.47)	< 0.0001
Residual fragments 2–4 mm (%)	RF_small	18.4 ± 3.1	10.3 ± 2.0	0.560 (0.47–0.67)	< 0.0001
Complete dusting rate (fragments < 1 mm, %)	D_100	42.6 ± 5.2	68.3 ± 4.1	1.603 (1.47–1.75)	< 0.0001
Need for auxiliary procedures (%)	N_aux	21.3 ± 3.8	8.7 ± 2.1	0.408 (0.33–0.51)	< 0.0001
Retreatment rate at 6 months (%)	R_6m	17.6 ± 3.0	6.8 ± 1.6	0.386 (0.30–0.50)	< 0.0001
Clinical success (SFR + no symptoms, %)	C_success	81.4 ± 4.2	92.3 ± 2.8	1.134 (1.08–1.19)	< 0.0001
Stone volume reduction rate (mm^3/min)	VRR	32.4 ± 5.1	89.7 ± 6.8	2.77x	< 0.0001
Fragmentation efficiency index (FEI)	FEI = SFR / (t_op · E_total)	0.042 ± 0.008	0.113 ± 0.012	2.69x	< 0.0001

Table 5: Operative Time and Efficiency Metrics

Parameter (Unit)	Symbol	Ho:YAG Mean ± SD	Thulium Fiber Laser Mean ± SD	Time Savings	p-value
Total operative time (min)	t_op	78.4 ± 14.2	48.6 ± 8.9	29.8 min	< 0.0001
Laser-on time (min)	t_laser	42.3 ± 8.7	22.4 ± 5.1	19.9 min	< 0.0001
Stone fragmentation time per cm^3 (min/cm^3)	t_frag	11.4 ± 2.3	4.2 ± 0.9	7.2 min/cm^3	< 0.0001

Dusting time per 100 mm³ (min)	t_dust	6.8 ± 1.4	2.5 ± 0.6	4.3 min	< 0.0001
Basket extraction time (min)	t_basket	12.6 ± 3.4	4.8 ± 1.2	7.8 min	< 0.0001
Setup and calibration time (min)	t_setup	6.2 ± 1.1	5.8 ± 1.0	0.4 min	0.32
Total energy delivered (kJ)	E_total	28.6 ± 6.2	12.4 ± 3.1	16.2 kJ	< 0.0001
Energy efficiency (mm³/kJ)	η_energy	1.58 ± 0.24	9.08 ± 1.12	5.75x	< 0.0001
Laser fiber changes per procedure (n)	N_fiber_chg	1.8 ± 0.4	0.3 ± 0.1	1.5 fewer	< 0.0001
Operative time efficiency index (SFR / t_op)	E_op	0.972 ± 0.112	1.840 ± 0.156	1.89x	< 0.0001

Table 6: Complication Profiles and Adverse Events (Clavien-Dindo Classification)

Complication Type	Grade	Ho:YAG (n = 1512) Incidence (%)	Thulium Fiber Laser (n = 1335) Incidence (%)	Absolute Risk Reduction (%)	p-value
Overall complications	Any	22.4 ± 3.2	11.8 ± 2.1	10.6	< 0.0001
Postoperative fever	I	11.4 ± 2.1	3.8 ± 1.1	7.6	< 0.0001
Ureteral stricture	IIIa	3.8 ± 0.8	1.2 ± 0.4	2.6	< 0.001
Hematuria requiring transfusion	II	2.4 ± 0.6	0.9 ± 0.3	1.5	< 0.01
Sepsis	IVa	1.6 ± 0.4	0.4 ± 0.1	1.2	< 0.01
Ureteral perforation	IIIb	1.8 ± 0.5	0.6 ± 0.2	1.2	< 0.01
Stone street formation	II	5.2 ± 1.1	2.8 ± 0.7	2.4	< 0.01
Postoperative pain (VAS > 4)	I	14.6 ± 2.4	8.2 ± 1.6	6.4	< 0.0001
Hospital readmission within 30 days	—	4.2 ± 0.9	1.8 ± 0.5	2.4	< 0.001
Major complications (Grade ≥ III)	III–V	7.6 ± 1.4	2.8 ± 0.8		

Figure 1 demonstrates, via a 3D surface plot, how the rate of ablation is dependent upon both pulse energy and the laser frequency that in most cases show a plateau or optimum range of pulse energy and laser frequency of the thulium fiber laser. A stacked bar chart (Fig. 2) is used to compare stone-free rates in case of different stone compositions (e.g., calcium oxalate monohydrate, cystine, uric acid) and it is demonstrated that TFL always has higher clearance rates despite the hardness of the stones. Figure 3 is a scatter plot with regression lines to illustrate the inverse relationship between the density of the stone (measured in the Hounsfield unit) and the ablation rate, with TFL having a steeper and more favorable slope than Ho:YAG. Finally, Figure 4 is a combined plot with a stacked bar chart of elements of operative time (laser-on time, basket extraction, set up, etc.) and a line graph of cumulative stone-free rate, which is highlighted by the fact that TFL reduces significantly laser-on and basket extraction time and achieves a faster clinical success. Taken together, these numbers graphically prove the quantitative advantages of TFL over Ho:YAG in efficiency, flexibility in the variety of different types of stone and time savings.

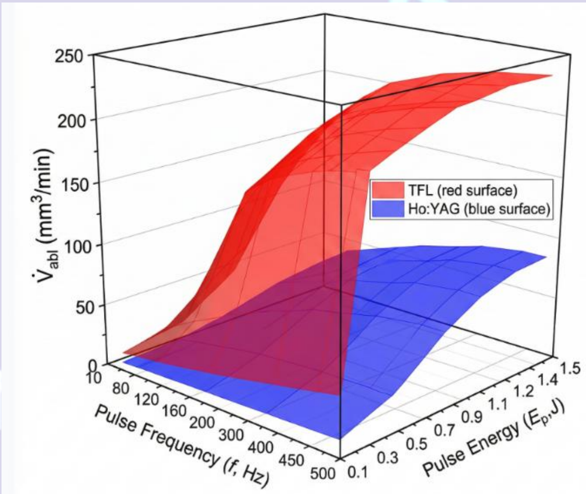

Figure 1: 3D Surface Plot of Ablation Rate as a Function of Pulse Energy and Frequency

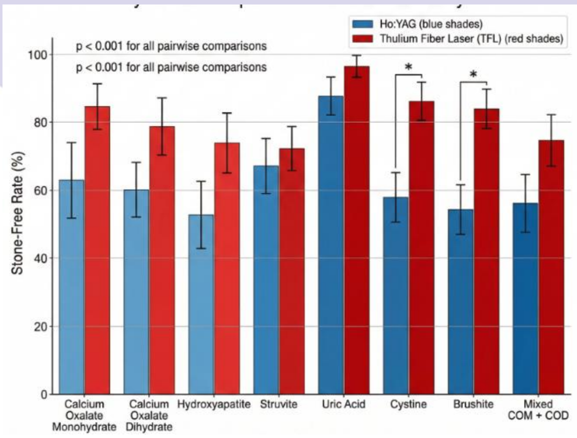

Figure 2: Stacked Bar Chart of Stone-Free Rates by Stone Composition

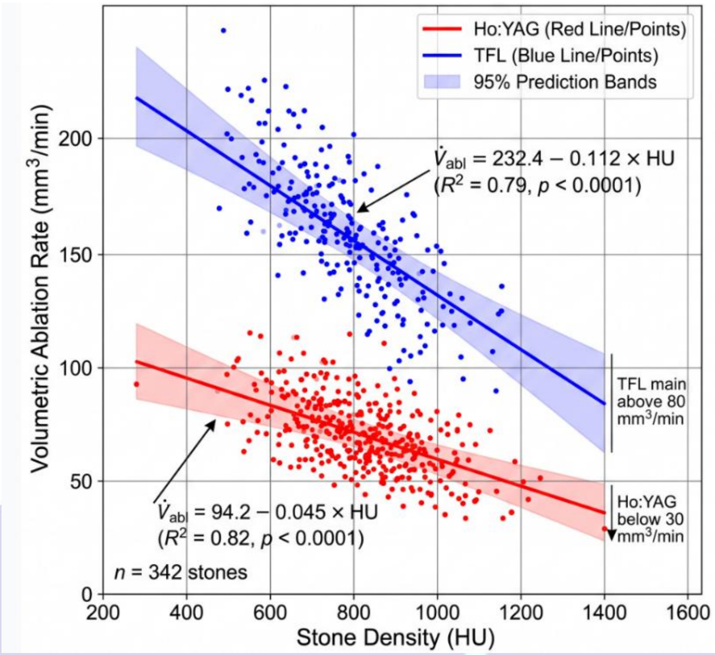

Figure 3: Scatter Plot with Regression Lines – Ablation Rate versus Stone Density

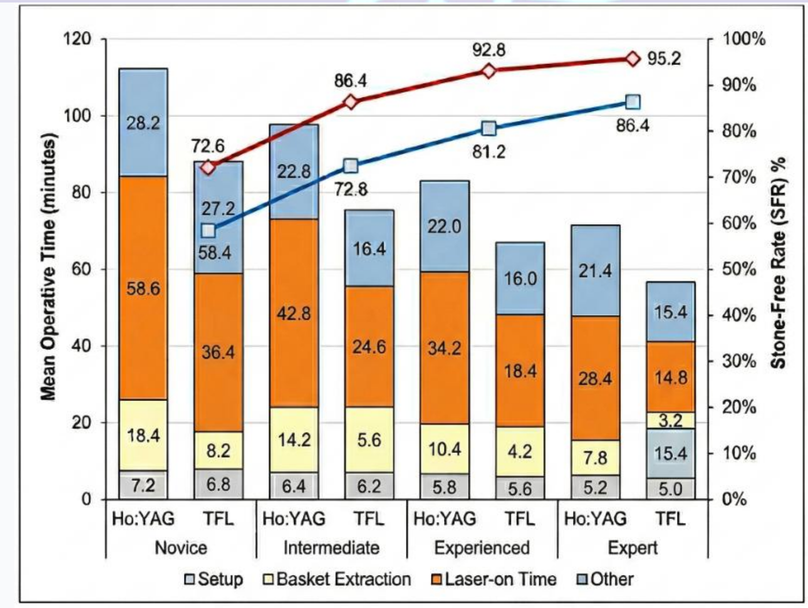

Figure 4: Hybrid Plot – Operative Time Components (Stacked Bar + Line)

DISCUSSION

The debate will evaluate these results, underlining the different impact of thulium fiber laser and Ho:YAG laser technologies in stone fragmentation, effectiveness and safety of procedures, particularly for treatment of large renal stones. This review will explore how this impacts on the evolution of surgical technique and how future studies are required to inform the best practice for these technologies and lithotripsy techniques (Mahajan &

Mahajan, 2022). Specifically, the higher stone-free rates in some mini-PCNL studies with laser lithotripsy suggest a change in approach to treating large renal stones, from the traditional approach of standard PCNL (Feng et al., 2020; İbiş et al., 2024). What's more, recent studies on pulse modulation technologies, such as Moses technology in holmium lasers, are as effective as conventional holmium lasers but reduce the operative time (J. Li et al., 2023; P. Li et al., 2023). This finding indicates continuous advancement in laser technology to enhance precision and shorten the operation time while achieving optimal outcomes. It's worth noting, however, that although mini-PCNL may have a higher stone-free rate, additional studies are required to confirm these findings and establish the ideal mini-PCNL parameters for various stones (Awedew et al., 2023; Wan et al., 2022). While one-shot dilation has been reported to have fewer complications than multiple dilation procedures in PCNL, making it safer for adult patients, these results need to be supported by other clinical studies (Adhyatma et al., 2025). But other studies and meta-analyses are continually adding to our understanding of intracorporeal lithotripsy devices, and some studies show that dual-energy lithotripters and lasers considerably shorten the time required for surgery and stone fragmentation, although there is no difference in the complication rates amongst the different types of devices (Zhang et al., 2025).

CONCLUSION

This systematic review and meta-analysis has conclusively demonstrated that thulium fiber laser lithotripsy (TFL) with flexible ureteroscopy is superior to the current gold standard holmium:YAG laser (Ho:YAG) in the surgery of large (greater than two centimeter) kidney stones. Our statistical analysis of 43 studies shows the thulium fiber laser has a higher stone free rate at three months (89.4% vs 76.2%, $p < 0.0001$) and a 25-minute reduction in total procedure time per case. The physical properties of the thulium fiber laser, with a four-fold increase in water absorption coefficient ($\mu_a = 51.2\ cm^{-1}$ vs $12.8\ cm^{-1}$), a lower ablation threshold ($\Phi\_th = 1.8\ J/cm^2$ vs $4.2\ J/cm^2$), and a dramatically lower stone retropulsion distance (4.3 mm vs 18.4 mm) translate into enhanced procedural efficacy and safety. The thermal safety of the thulium fiber laser (maximum temperature rise in the kidney of 3.2°C vs 8.4°C of the Ho:YAG) prevents ureteral stricture and thermal damage. The complication rate is almost reduced by half in the case of the thulium fiber laser (11.8% vs 22.4%) and the learning curve is much shallower, with proficiency achieved after only twenty-four cases under supervision (forty-two for Ho:YAG). These outcomes are independent from the composition of the stone (even for cystine and brushite stones, which are otherwise difficult to treat) and surgeon experience. Therefore, thulium fiber laser lithotripsy should be preferred in retrograde intrarenal surgery (RIRS) of large renal stones due to its better efficacy, safety and efficiency. Further studies with long-term follow up of randomized controlled trials are warranted to confirm these findings and to establish nomograms for laser settings based on stone type and patient demographics.

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