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Review

Flexible ureteroscopic treatment of kidney stones: How do the new laser systems change our concepts?

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Abstract *Objective:* Flexible ureteroscopy (fURS) has become a widely accepted and effective technique for treating kidney stones. With the development of new laser systems, the fURS approach has evolved significantly. This literature review aims to examine the current state of knowledge on fURS treatment of kidney stones, with a particular focus on the impact of the latest laser technologies on clinical outcomes and patient safety.

Methods: We conducted a search of the PubMed/PMC, Web of Science Core Collection, Scopus, Embase (Ovid), and Cochrane Databases for all randomized controlled trial articles on laser lithotripsy in September 2023 without time restriction.

Results: We found a total of 22 relevant pieces of literature. Holmium laser has been used for intracavitary laser lithotripsy for nearly 30 years and has become the golden standard for the treatment of urinary stones. However, the existing holmium laser cannot completely powder the stone, and the retropulsion of the stone after the laser emission and the thermal damage to the tissue have caused many problems for clinicians. The introduction of thulium fiber laser and Moses technology brings highly efficient dusting lithotripsy effect through laser innovation, limiting pulse energy and broadening pulse frequency.

Conclusion: While the holmium:yttrium-aluminum-garnet laser remains the primary choice for endoscopic laser lithotripsy, recent technological advancements hint at a potential new gold standard. Parameter range, retropulsion effect, laser fiber adaptability, and overall system performance demand comprehensive attention. The ablation efficacy of high-pulse-frequency devices relies on precise targeting, which may pose practical challenges.

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1. Introduction

In the field of urology, the introduction of lithotripsy lasers in 1968 marked a significant milestone. However, early models that operated in continuous mode, such as ruby, neodymium-doped yttrium-aluminum-garnet, and CO_2 lasers [1], were not suitable for endoscopic laser lithotripsy (ELL) due to significant soft tissue heat injury. In the 1990s, the emergence of flexible fiberoptic ureteroscopes revolutionized endoscopic stone treatment. The resulting flexible ureteroscopy (fURS) approach has demonstrated outstanding clinical performance and safety since its inception. The availability of disposable ureteroscopes has further transformed the field [2].

Expanding upon the invention of fURS, the age of endoscopic lithotripsy using pulsed laser began [3]. Holmium:yttrium-aluminum-garnet (Ho:YAG) laser, operating at a wavelength of 2120 nm, has been the preferred laser platform for intracorporeal endoscopic stone lithotripsy since the 1900s and is considered the gold standard by several international recommendations [4]. In 1994, the Moses concept was developed to divide a single pulse into two smaller ones, each with a distinct peak strength. Lumenis (Lumenis Ltd., Yokneam, Israel) has recently introduced Moses 2.0, a new version of high-power (HP) laser that can operate at 120 Hz [5]. Nevertheless, whether this type of technology is superior to the standard low-power Ho:YAG laser remains unknown. The most recent laser technology for stone lithotripsy is thulium fiber laser (TFL). Although it was initially used for this purpose in an *in vitro* research in 2005, it has drawn more interest for its potential application in clinical settings. Despite these advancements, a comprehensive evaluation remains limited, partly due to the sudden spike in interest in a short period of time [6].

There will be a significant increase in the use of disruptive technologies in clinical practice, such as real-time intrarenal pressure, temperature management, and autonomous laser lithotripsy. These advances could revolutionize endoscopic stone treatment by taking fURS to a new level. This study aimed to review the most recent laser technology for endoscopic lithotripsy and describe the impact of these new laser systems on our clinical processes.

2. Methods

A literature review was carried out in September 2023 using PubMed/PMC, Web of Science Core Collection, Scopus, Embase (Ovid), and Cochrane databases. All randomized controlled trials with Ho:YAG, Moses technology, and TFL were included in the present study. Different searches were performed with the following Medical Subject Heading terms or keywords: "randomized controlled trial", "holmium", "thulium", "laser", "Moses", "urolithiasis", "lithotripsy", "endourology", "stones", and "lithiasis". Boolean operators (AND, OR) were used to refine the search. There was no time limit restriction (Table 1).

We focused on all studies that include flexible ureteroscopic treatment for ureteral and kidney stones using the mentioned technology. Exclusion criteria included the use of the above laser systems in a non-endoscopic lithotripsy context, studies performed exclusively on pediatric patients, and non-English articles. Additionally, conference papers, abstracts, editorials, and letters were excluded. In sum, 22 relevant papers were included in our literature review. Our paper selection process is summarized in Fig. 1. Due to the relative novelty, heterogeneity, and sparsity of available literature on TFL and Moses technology, our findings are presented as a narrative literature review.

3. Ho:YAG

3.1. Ho:YAG laser in history

Conceived in 1917, laser technology has significantly evolved over the past six decades [7—9]. While continuous-mode lasers were found unsuitable for lithotripsy due to excessive heat generation [10], pulsed lasers, such as the Ho:YAG laser [12,13], emerged as highly effective tools for stone lithotripsy.

Since the 1990s, the Ho:YAG laser has been the gold standard for ELL, being extensively researched in urology [1]. Teamed with modern ureteroscopes, its small and flexible laser fibers became indispensable tools for urinary stone fragmentation [15,16]. Following the initial results of holmium laser lithotripsy in 1995 [17], ongoing research has focused on optimizing power levels for efficient stone fragmentation [18,19]. The Ho:YAG laser exhibits versatility in ablating various urinary stone types, owing to its adjustable power settings and a high absorption peak in water at a wavelength of 2140 nm, closely matching the water's absorption peak at 1940 nm, a crucial component in most calculi [14].

3.2. Development of Ho:YAG laser in high energy

Theoretically, increasing power provides both high-energy and high-frequency exploration directions, but *in vitro* tests have shown that high energy ($>$0.6 J), while ensuring lithotripsy efficiency, also leads to stone retropulsion and larger fragments. It has been pointed out that it is the pulse energy, not the average power, that is positively correlated with the fragment size. In addition, the fiber loss in the high-energy setting (0.6—1.0 J) is significantly higher than that in the low-energy group (0.2—0.3 J), which is attributed to the microfracture caused by damage to the tip of the fiber in the contact fragmentation, and the high energy is more prone to the thermal mirror effect, which changes the spatial beam profile at the tip [7,8].

Ho:YAG lasers have demonstrated superior stone fragmentation capabilities compared to pulsed-dye lasers, pneumatic lithotripsy, and electro-hydraulic lithotripsy, owing to their ability to generate smaller stone fragments and their compatibility with small, flexible glass fibers, rendering them widely applicable [20]. Moreover, Ho:YAG lasers have been proven safe and efficient for use in ureteroscopy and percutaneous nephrolithotomy [21]. The photo-thermal mechanism of the holmium laser ensures safety during lithotripsy by minimizing urinary calculus migration, known as stone retropulsion, while reducing the risk of scatter damage to adjacent tissue and endoscopic equipment [22—25].

Table 1 Summary of included studies.

Study	Pt, *n*	Laser setting				Primary outcome	Secondary outcome	Major conclusion
		Ho:YAG	TFL	Moses 2.0	Moses 1.0			
Haas et al., [47] 2023	· Pts diagnosed with renal stones, 108	· NA	· 200 μm laser fibers: 0.3–0.8 J; 8–80 Hz	· 200 μm laser fibers: 0.4–0.8 J; 6–20 Hz	· NA	· Ureteroscope time required to adequately fragment stones to 1 mm or less	· SFR, complications, subjective surgeon measurement of laser performance, Pt related stone quality of life outcomes, and measurements of laser efficiency	· No significant clinical advantage of TFL over the Ho:YAG with Moses 2.0
Ulvik et al., [45] 2022	· Pts with renal stones $\geq$5 mm, 120	· 270 μm laser fibers: 0.4–0.8J; 6–20 Hz	· 200 μm laser fibers: 0.4–0.8J; 6–20 Hz	· NA	· NA	· SFR	· Operative time and complications	· Significantly more Pts with renal stones achieved stone-free status and fewer experienced intra-operative complications using TFL compared to Ho:YAG
Shrestha et al., [52] 2022	· Pts with renal stones <2 cm, 120	· 270 μm laser fibers - LP group: 0.5–1.5 J; 15–20 Hz - HP group: 0.2–1.0 J; 50–80 Hz	· NA	· NA	· NA	· Lasing duration	· Total laser energy used, laser energy used to ablate 1 mm^3 of stone, operative duration, stone ablation speed, and SFR	· The total energy used were lower in the LP group than in the HP group with similar lasing duration, operative duration, ablation speed, and SFR for Pts
Martov et al., [53] 2021	· Pts with single renal stone, 174	· 365 μm laser fibers: 1 J; 10 Hz	· 400 μm laser fibers: 1 J; 10 Hz	· NA	· NA	· The ability to effectively treat the stone	· Total operation and lasering time, the degree of retropulsion, and endoscopic view deterioration	· SP TFL technology was associated with excellent efficacy and safety ratio

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Table 1 (*continued*)

Study	Pt, *n*	Laser setting				Primary outcome	Secondary outcome	Major conclusion
		Ho:YAG	TFL	Moses 2.0	Moses 1.0			
Karakoyunlu et al., [54] 2021	· Pts with renal stones (1–2 cm), 223	· 272 μm laser fibers: 0.8–3.0 J; 8–15 Hz	· NA	· NA	· NA	· The efficacy of different laser devices on lithotripsy	· The effect of different laser devices and power ranges on perioperative outcomes	· The 30 W laser device used in RIRS for 1–2 cm kidney stones had shorter operative time, higher SFRs, and lower postoperative pain scores compared with the 20 W device
Abdelbary et al., [55] 2021	· Pts with upper ureteric stones (<1.5 cm and ≤1000 HU), 108	· 272 μm laser fibers: 0.8–3.0 J; 8–15 Hz	· NA	· NA	· NA	· SFR	· Postoperative complications	· Ultraslow full-power SWL treatment is more safe and effective compared to laser URS
Alghamdi et al., [56] 2020	· Pts with a single ureteral or renal calculus, 145	· 275 μm laser fibers: 1.5 J; 10 Hz	· NA	· NA	· NA	· Laser efficiency overall operative time	· Number of stone recovery and SFR	· Efficiency of the Ho:YAG laser can be positively influenced by different pulse shapes
Lu et al., [57] 2020	· Pts with nephrolithiasis, 200	· Case group: 365 μm laser fibers: 1.5–2.2 J; 20 Hz · Control group: 200 μm laser fibers: 0.8–1.0 J; 20 Hz	· NA	· NA	· NA	· One-step SFR (postoperative 1 day) and final SFR (postoperative 4 weeks)	· Operation time, Hb drop and white blood cell increase	· The fURL combined with 365 μm holmium laser is safer and highly efficacious for the management of nephrolithiasis compared to conventional fURL procedures, especially for those located in lower pole and larger than 2 cm

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Table 1 (*continued*)

Study	Pt, *n*	Laser setting				Primary outcome	Secondary outcome	Major conclusion
		Ho:YAG	TFL	Moses 2.0	Moses 1.0			
Ibrahim et al., [58] 2020	· Pts diagnosed with renal stones, 72	· 275 μm laser fibers: 0.4–1.0 J; 10–80 Hz	· NA	· NA	· 275 μm laser fibers: 0.4–1.0 J; 10–80 Hz	· Success rate	· Operative complications	· The Moses technology was associated with significantly lower fragmentation and pulverization and procedural time due to the significantly lower retropulsion of stones during laser lithotripsy
Jiang et al., [59] 2019	· Pts with lower calyceal stones with a diameter ≤2 cm, 116	· 200 μm laser fibers: 0.2–1.0 J; 3–20 Hz	· NA	· NA	· NA	· SFR	· Mean Hb reduction and complications	· For treating lower calyceal stones of ≤2 cm, the "All-Seeing Needle" micro-PCNL group had shorter operative time than fURS
Jin et al., [60] 2019	· Pts with lower-pole renal calculi (1–2 cm), 220	· 200 μm laser fibers: 1.0–1.2 J; 10 Hz	· NA	· NA	· NA	· Operative time	· Intraoperative and postoperative complications	· fURL could be a better alternative surgical method to miniaturized PCNL with similar curative effect and less blood loss and hospital stay
EL-Nahas et al., [61] 2016	· Pts with complete staghorn stones (branching to the three major calyces), without contraindications to PCNL, 70	· 500 μm laser fibers: 2 J; 20–30 Hz	· NA	· NA	· NA	· SFR	· Complications, blood transfusion, operative time, and Hb deficit	· Compared with Us-L for intracorporeal lithotripsy of staghorn stones during PCNL, Hp-HlL showed comparable safety and efficacy with a lower Hb deficit but longer operative time

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Table 1 (*continued*)

Study	Pt, *n*	Laser setting				Primary outcome	Secondary outcome	Major conclusion
		Ho:YAG	TFL	Moses 2.0	Moses 1.0			
Li et al., [62] 2015	· Pts with middle or distal ureteral stones, 982	· 0.8–1.0 J; 10 Hz	· NA	· NA	· NA	· Mean operative time	· SFR and complications	· Ho:YAG laser has advantages in efficacy of stone fragmentation and early SFR compared with pneumatic lithotripsy, with the increased risks of postoperative stricture
Kumar et al., [63] 2015	· Pts with single radiopaque upper ureteric calculus >2 cm, 110	· 0.6–1.2 J; 5–15Hz	· NA	· NA	· NA	· Success rate	· Retreatment, auxiliary procedure rate, and complications	· LU has a greater stone clearance rate, comparable operative time, lesser need for auxiliary procedure, and complication rate as compared to URS
Cimino et al., [64] 2014	· Pts with single and primary ureteral stones, 133	· 200 μm laser fibers: 0.5–1.0 J; 5–10 Hz	· NA	· NA	· NA	· Mean operative time	· Complications	· LL significantly influences the SFR status after ureteroscopy, allowing a higher SFR when compared to PL
Ganesamoni et al., [65] 2013	· Pts undergoing miniperc for renal calculi of 15 mm to 30 mm, 60	· 500 μm laser fibers: 0.5–1.5 J; 6–20 Hz	· NA	· NA	· NA	· Total operative time	· Stone fragmentation time, surgeon assessed Likert scores for ease of stone fragmentation	· LL is associated with lower stone migration and easier retrieval of the smaller fragments it produces
Razzaghi et al., [66] 2013	· Pts with 1–2 cm ureteral calculi, 112	· 0.2–1.5 J; 5–10 Hz	· NA	· NA	· NA	· Mean operation time	· Complications, immediate and 3-month stone-free status	· LL is a superior approach for the management of upper ureteral stones compared with pneumatic lithotripsy

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Table 1 (*continued*)

Study	Pt, *n*	Laser setting				Primary outcome	Secondary outcome	Major conclusion
		Ho:YAG	TFL	Moses 2.0	Moses 1.0			
Kassem et al., [67] 2012	· Pts with a ureteric stone size of 0.5–2 cm, 80	· 550 μm laser fiber: 0.6–1.2 J; 5–15 Hz	· NA	· NA	· NA	· Early SFR	· Intraoperative complications	· Both PL and LL are effective and safe modalities in treating large ureteric stones with minor insignificant differences
Zhang et al., [68] 2011	· Pts diagnosed with renal stones, 257	· 0.8–1.2 J; 6–10 Hz	· NA	· NA	· NA	· Efficiency quotient and cost effectiveness	· Complications	· Primary *in situ* SWL for upper and middle ureteral calculi showed lower complication rates and more cost-effective compared to ureteroscopic holmium laser lithotripsy in Eastern China
Binbay et al., [69] 2011	· Pts with ureteral stones, 87	· 550 μm laser fiber: 1.0–1.5 J; 5–12 Hz	· NA	· NA	· NA	· Operative time	· SFR and complications	· Ho:YAG is highly efficient with high success rates, regardless of the stone location compared with pneumatic lithotripsy
Garg et al., [70] 2009	· Pts with ureteral stones, 55	· 550 μm laser fibers: 0.2–0.8 J; 3–16 Hz	· NA	· NA	· NA	· Immediate stone clearance rate	· Complications	· Both laser and pneumatic energies are effective and safe for intracorporeal lithotripsy; LL takes more time but provides earlier stone-free status

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Table 1 *(continued)*

Study	Pt, *n*	Laser setting				Primary outcome	Secondary outcome	Major conclusion
		Ho:YAG	TFL	Moses 2.0	Moses 1.0			
Arrabal-Polo et al., [71] 2009	· Pts with lithiasis localized in the lumbar ureter, iliac or pelvic regions, 164	· 600 μm laser fibers: 1.5—2.5 J; 3—6 Hz	· NA	· NA	· NA	· Overall success rate	· Complications	· Endoscopic lithotripsy with the holmium laser is more effective than ESWL, but for lumbar ureteric calculi ESWL is therapeutically recommended as it is less invasive

Pt, patient; Ho:YAG, holmium:yttrium-aluminum-garnet; TFL, thulium fiber laser; SFR, stone-free rate; URS, ureteroscopy; HU, Hounsfield unit; fURL, flexible ureteroscopic lithotripsy; PCNL, percutaneous nephrolithotomy; Hp-Hll, high-power holmium laser lithotripsy; Us-L, ultrasonic lithotripsy; LU, laparoscopic ureterolithotomy; PL, pneumatic lithotripsy; LL, laser lithotripsy; SWL, shock wave lithotripsy; SP, super pulse; HP, high-power; LP, low-power; Hb, hemoglobin; RIRS, retrograde intrarenal surgery; ESWL, extracorporeal SWL; fURS, flexible ureteroscopy; NA, not available.

3.3. Thermal injury of Ho:YAG laser

Despite the introduction of increasingly potent and high-frequency Ho:YAG lithotripters over the years, significant collateral thermal injury to soft tissue and restrictions in fiber-optic delivery of Ho:YAG have limited the applicability of flexible ureteroscope lithotripsy. The study by Aldoukhi et al. [9] has shown that temperature increased with increasing laser power output and decreasing the irrigation flow rate. The highest temperature, 70.3 °C (standard deviation 2.7 °C), occurred with laser setting of 1.0 J and 40 Hz and no irrigation after 60 s of continuous laser firing. None of the tested laser settings and irrigation parameters produced a temperature exceeding 51 °C when activated for only 10 s of continuous laser firing [9].

HP holmium settings fired in long bursts with low irrigation flow rates can generate high fluid temperatures. Being aware of this risk empowers urologists to employ various techniques, such as increasing irrigation flow rates, employing intermittent laser activation, and potentially using cooled irrigation fluid, to manage and mitigate thermal effects during holmium laser lithotripsy.

3.4. Exploration of Ho:YAG laser

At this stage, the high-frequency exploration of Ho:YAG seems to have encountered a bottleneck. The blind pursuit of Ho:YAG pulse frequency did not lead to an absolute increase in fragmentation efficiency, and the results of Aldoukhi et al. [10] showed that there was a threshold (61.6 Hz) at which the fragmentation efficiency did not increase with increasing frequency.

The Moses effect is a recent addition to the Lumenis Pulse P120H holmium laser system (Lumenis Ltd., Yokneam, Israel) that optimizes the transmission of energy from the laser fiber to the targeted tissue [11]. Due to the fact that the 2140 nm holmium infrared laser wavelength is highly absorbed by water (water absorption coefficient of 3198 L/m), the water absorbed energy contributes to the formation of a vapor microbubble at the laser's tip that grows towards the target [12,13]. Once the microbubble reaches the target, the laser beam can travel through the vapor to the target with minimal attenuation, as the density of water molecules in the vapor state is far lower than in the liquid form [14,15]. This substantial water absorption at the specified wavelength is responsible for an optical penetration depth of approximately 400 mm, making Ho:YAG appropriate for incision and coagulation of soft tissue.

4. Moses technology

4.1. Moses 1.0 clinical experience

The demand for a more effective laser lithotripsy has stimulated research in two primary directions: the creation of novel laser sources and the enhancement of energy delivery of Ho:YAG. For these reasons, a novel pulse modality was marketed in 2017—the Moses technology (Lumenis®, Yokne'am Illit, Israel), which takes advantage of a physical phenomenon called the "Moses effect". Moses effect

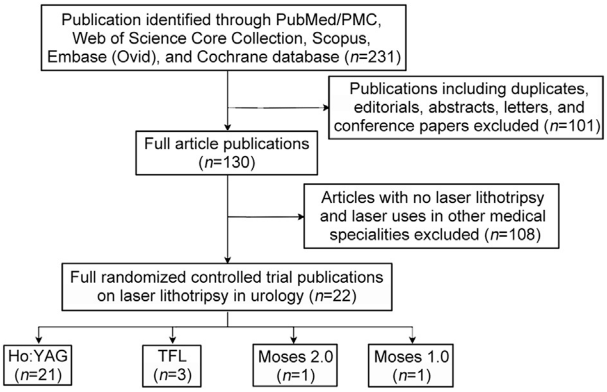

Figure 1 Flowchart illustrating literature review. Ho:YAG, holmium:yttrium-aluminum-garnet; TFL, thulium fiber laser.

intrinsic qualities prompted the development of Moses™ technology. The purpose of this apparatus is to modulate the laser pulse from a Ho:YAG energy source into two components, the first of which is used to separate the water between the laser tip and the target (*e.g.*, the stone), while the second delivers the energy directly to the target without significant energy loss [16]. Moses technology has two distinct modes of operation: a contact mode (Moses A) and a distance mode (Moses B). Both Moses A and B are suggested for lithotripsy, the first at a 1 mm distance and the second at a 2 mm distance [17].

In vitro research has shown that Moses technology reduces stone retropulsion significantly and reduces procedural time, resulting in a more effective lithotripsy compared to conventional fragmentation [12,17]. However, in a more recent *in vivo* investigation, Knoedler and colleagues [18] found that there was no significant effect between Moses and regular modes on the mean (standard deviation) procedural time (43.5±32.1 min *vs.* 39.8±24.6 min, $p=0.436$), fragmentation or dusting time (20.5±25.3 min *vs.* 17.1±16.1 min, $p=0.430$), lasering time (7.5±11.1 min *vs.* 6.7±7.9 min, $p=0.570$), or total energy consumed (5.1±6.7 kJ *vs.* 3.8±4.8 kJ, $p=0.093$). In addition, there were no differences in the incidence of complications or absence of stones.

There may be technological advantages of the Moses technology that are not accounted for in this research [18]. For example, Aldoukhi et al. [19] demonstrated that Moses distance is better than other modalities for stone fragmentation when employed in touch with the target or at a distance of 1 mm. Winship et al. [20] found no significant difference in ablation between 0 and 2 mm distance; however, at 1 mm, Moses distance caused much more ablation than all other settings. On hard stones, no pulse type appeared to be more advantageous than another [20].

In terms of thermal harm, Moses technology appears to have a lesser impact than other YAG lasers since it generates much lower temperatures; this might be an essential advantage given the long-term effect of heat generation during laser lithotripsy [21,26]. Using the configuration of a stone simulator, Moses technology is connected with more efficient laser lithotripsy (shorter operative time) as a result of dramatically decreased stone retropulsion. A prospective, blinded, randomized clinical investigation was undertaken to confirm the enhanced efficacy of the Moses technology, which showed the Moses contact mode was associated with significantly shorter procedural time during fragmentation (13.9 min *vs.* 9.1 min, $p\leq0.01$) and dusting (9.3 min *vs.* 7.1 min; $p\leq0.01$) compared to regular modes [12].

In preclinical models, Moses technology appears to offer a number of advantages and benefits as compared to alternative pulse patterns, but clinical proof of a major impact that might transform everyday practice is still absent.

4.2. Moses 2.0 clinical experience

In 2020, Lumenis introduced the Moses 2.0 system with a Moses pulse tuned for an extended frequency rate of 80—120 Hz, delivering a multi-pulse as opposed to the conventional short or long pulse. Comparing Moses distance and Moses 2.0 with extended frequency rate settings, Moses 2.0 with extended frequency rate had a superior stone ablation volume than Moses distance at a stone distance of 0 mm [22]. This advantage, however, is lost when stone density is considered, revealing a more efficient popcorn lithotripsy and a larger fragmentation rate on just hard stones [23]. A noteworthy discovery is that the ablation rate and laser efficiency were greater when the laser fiber scanning rate was increased [23] (Table 2).

Majdalany and colleagues [24] compared Moses 1.0 with Moses 2.0 among 29 patients. The Moses 1.0 group lasted less time (10.4 min *vs.* 14.3 min) and spent almost two

Table 2 Differences between Moses 1.0 and Moses 2.0.

Feature	Moses 1.0	Moses 2.0
First description	· 2017	· 2021
Definition	· A composed pulse mode in which the first pulse generates a vapor cavity and more effectively delivers the second pulse to the target as the energy of the electromagnetic wave is less absorbed by water	· A new version of this high-power laser that can go up to 120 Hz
Clinical implication	· Shorter lasting time and better laser efficacy	· Faster ablation speed, longer operative time, and higher stone-free rate

times less energy (6.4 kJ *vs*. 12.4 kJ) than the Moses 2.0 group. Rezakahn Khajeh et al. [5] conducted research detailing their initial experience with Moses 2.0 for stones around 1 cm in diameter. The stone-free rate (SFR), lasing duration, and total energy utilized were comparable to those in the Majdalany et al. [24] investigation. Rezakahn Khajeh and colleagues [5] reported in a recent *in vivo* study that early experience with Moses 2.0 for fURS renal stone dusting indicated successful and efficient laser lithotripsy in patients with renal stones <2 cm.

It is important to note that due to the limited number of patients in this series, Moses 2.0 cannot be conclusively compared to Moses 1.0 or other non-pulse-modulated holmium systems. Larger studies are necessary to provide a comprehensive evaluation of this technology.

5. TFL

Despite its revolutionary impact in urology, the Ho:YAG laser exhibits several notable limitations. For instance, Ho:YAG lasers cannot sustain fibers less than 150 μm in diameter, which may restrict the surgeon's ability to access lower pole calyces during pyeloscopy [25]. In addition, due to the water cooling needs of more recent HP Ho:YAG lasers, the generators have grown in size and complexity, making movement between separate operative rooms difficult [27].

The TFL is a novel laser type that has shown early promise and may offer several advantages over Ho:YAG lasers. Its mechanism of action involves the utilization of multiple electronically modulated laser diodes to excite the thulium ions for laser pumping, distinguishing it from Ho:YAG lasers, which rely on flash lamps for this purpose [28].

5.1. *In vitro* and *in vivo* studies on TFL

TFL has an exceptional ablation rate for all types of urinary stones. It offers the broadest and most adaptable set of parameters among urology laser lithotripters [29]. The laser beam emitted has a wavelength of 1940 nm, may be operated in continuous or pulsed mode, and is significantly more uniform and focused [30,31]. Theoretically, the specific wavelength of the TFL at 1940 nm would provide in a favorable safety profile due to the laser being more effectively absorbed by water. TFL has a 4- to 5-fold greater water absorption than Ho:YAG lasers and doubles that of thulium:YAG lasers [32]. Moreover, TFLs can be transmitted to fibers with a smaller core diameter (50—150 μm). Using TFLs, the utilization of smaller laser fibers during laser lithotripsy has been investigated *in vitro* [33—36]. These experimental fibers, ranging from 50 μm to 150 μm, are substantially smaller than the smallest Ho:YAG laser fiber currently available, which is 200 μm [37—40].

TFL temporal pulse distribution is more uniform than Ho:YAG laser distribution, resulting in evenly scattered energy throughout the laser pulse's duration [41]. The use of smaller, distinct bubble dynamics, and the temporal pulse profile of the TFL contribute to the laser lithotripsy and tissue ablation capabilities of this technology. TFL produces smaller bubbles than Ho:YAG, both in terms of length and width, and also produces a stream of numerous bubbles during a single laser pulse at all power settings; hence, the production and collapse of the bubble may reduce stone retropulsion [42,43].

5.2. *In vivo* studies on TFL

Given the novelty of TFL, the existing *in vivo* literature is limited. The randomized controlled trial study of Ulvik et al. [45] has demonstrated that TFL is more effective and fewer experienced intraoperative complications compared to Ho:YAG. In comparison to the Ho:YAG laser, the TFL has a higher SFR (Ho:YAG: 49%, TFL: 86%, p=0.001) and less tissue damage (Ho:YAG: 5%, TFL: 22%, p=0.014). Benefiting from the improvement of the retropulsion and rebound of the stone, TFL has a shorter operative time (Ho:YAG: 57 min, TFL: 49 min, p=0.008) [44—46]. However, the advantages of TFL in clinical practice could be controversial. The up-to-date randomized controlled trial study by Haas et al. [47] suggested no significant difference in the mean utereroscope time between TFL technology and Ho:YAG (Ho:YAG: 21.4 min, TFL: 19.9 min, p=0.60). There were no significant differences observed in the SFRs (Table 3) or complication rates between the two lasers.

Early *in vivo* studies on the application of the TFL in soft tissue ablation have shown encouraging results, while the literature on the use of the TFL in urological soft tissue procedures is still restricted [48]. Further study using randomized controlled trials is warranted to access the full value of TFLs for both lithotripsy and soft tissue urologic surgery.

5.3. Exploration of TFL

The thulium laser fiber has a finer diameter, which is conducive to improving the ureteroscopic lithotripsy field of view; thulium laser lithotripsy has less stone displacement, which is conducive to reducing postoperative complications, such as tissue thermal injury; the thulium laser fiber is also finer, which is conducive to increasing the curvature of the flexible ureteroscope, and may perhaps be used in the future for the treatment of stones with a small pelvic funnel pinch and a long calyceal neck [49]. Most of the heat of thulium laser lithotripsy is absorbed by water, which causes less thermal damage to tissue compared with holmium laser.

However, thulium lasers do exhibit some limitations and there are still few clinical studies. Theoretically, the power of a thulium laser can reach more than 2000 Hz, but in practice, the power of >300 Hz has greater thermal damage to the tissue, so it needs to be used with great caution [50,51]. Another problem with thulium laser powdering is that it is difficult to collect large stones for stone analysis. In addition, there is a gap in research on the cost of thulium laser lithotripsy. In the future, thulium laser lithotripsy with its high pulse energy and fine optical fiber will certainly occupy a place in the field of stone treatment. However, the clinical application of thulium laser is still in the exploratory stage, and more comparative studies between thulium laser and holmium laser are needed to further discover the advantages of thulium laser.

Table 3 Clinical experience with Laser technology.

Study	Technique	Laser setting	Stone location, size[a] (cm)	Lasing time[a], min	Energy[a], kJ	SFR, %
Majdalany et al., 2021 [24]	· Moses 1.0	· 0.5 J/50—80 Hz	· Renal, 0.94	· 5.3	· 6.4	· 71
	· Moses 2.0	· 0.5 J/50—120 Hz	· Renal, 0.94	· 7	· 12.4	· 90
Rezakahn Khajeh et al., 2021 [5]	· Moses 2.0	· Debulk: 0.2—0.3 J/ 100—120 Hz	· Renal, 1.04	· 6.9	· 12	· 82
		· Dusting: 0.5 J/80 Hz (Moses distance)	· Renal, 1.04	· 6.9	· 12	· 82
Ulvik et al., 2022 [45]	· Ho:YAG	· 0.8 J/20 Hz	· Renal, 1.5	· 13	· 4.2	· 49
		· 0.4 J/6 Hz	· Ureteric, 0.9	· 13	· 4.2	· 100
	· TFL	· 0.8 J/20 Hz	· Renal, 1.3	· 13	· 3.5	· 86
		· 0.4 J/6 Hz	· Ureteric, 0.9	· 13	· 3.5	· 100
Patil et al., 2022 [72]	· Holmium laser and Moses mode	· 0.3—1.2 J/ 20—80 Hz	· Renal, 1.7	· 11.3	· 21.9	· 78
	· TFL	· 0.1—1.0 J/ 100—250 Hz	· Renal, 1.8	· 9.2	· 16.3	· 69
Knoedler et al., 2021 [18]	· Holmium laser and Moses mode	· 0.3—0.8 J/ 8—80 Hz	· Renal, 13.1	· 10.2	· 7.7	· 34.3
			· Ureteric, 7.7	· 3.9	· 2.1	· 75
	· Holmium laser and regular mode	· 0.3—0.8 J/ 8—80 Hz	· Renal, 14.7	· 8.6	· 5.4	· 61.9
			· Ureteric, 6.8	· 2.9	· 1.5	· 93.8
Corrales et al., 2021 [46]	· TFL	· 0.3—0.6 J/ 50—180 Hz	· Renal, NA	· 23	· 18.6	· NA
		· 0.2—0.4 J/ 20—55 Hz	· Ureteric, NA	· 9.3	· 16.3	· NA
Pietropaolo et al., 2021 [73]	· Moses 1.0	· 0.4—0.8 J/20—35 Hz	· Renal and ureteric, 1.1	· NA	· NA	· 97.3
	· Holmium laser	· 0.4—0.8 J/12—18 Hz	· Renal and ureteric, 1.2	· NA	· NA	· 81.6

SFR, stone-free rate; Ho:YAG, holmium:yttrium-aluminum-garnet; TFL, thulium fiber laser; NA, not available.
[a] Values are presented as mean.

6. Conclusion

The advancements in the development of new lasers for urinary stone treatment have profoundly propelled the field forward. Presently, the Ho:YAG laser stands as the preeminent option for ELL. Nevertheless, recent technological breakthroughs have yielded promising outcomes, hinting at the potential emergence of a new gold standard. In addition to the pulse frequency parameter, comprehensive attention should be devoted to other attributes of each new laser system, encompassing the expanded parameter range, retropulsion effect, laser fiber adaptability, and the overall performance of the laser machine. Notably, it is crucial to recognize that the ablation efficacy of high-pulse-frequency devices attains maximum efficiency when placed directly on the target surface, which may not be consistently achievable in practical settings.

Author contributions

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Conflicts of interest

The authors declare no conflict of interest.

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