https://doi.org/10.48193/revistamexicanadeurologa.v83i1.1013
Review article

Thulium Fiber Laser: game changer or marketing hype?

Láser de fibra de tulio: ¿revolucionario o frenesí mediático?

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Abstract

Description: The Holmium: yttrium-aluminum-garnet (Ho:-YAG) laser has become the gold-standard intracorporeal lithotripsy device since it was first introduced in the 1980's. More recently, the Thulium Fiber Laser (TFL) was introduced into the clinical setting, with the potential to address some of the inherent limitations with Ho:YAG devices. In particular, early experience suggested the TFL provided enhanced dusting and fragmenting capabilities, less retropulsion and better stone free rates compared to the Ho:YAG laser.

Relevance: Should the initial claims of the TFL's better dusting properties be confirmed, this would be a significant advancement in the field. The ability to dust larger stones more rapidly could enhance the role of ureteroscopy and reduce the need for more invasive procedures.

Conclusion: The initial experience with the TFL is promising and suggests an advantage over Ho:YAG laser lithotripsy. Properly conducted prospective randomized trials are required to further delineate the advantages, disadvantages and to optimize patient outcomes.

Keywords:
Thulium, solid-state lasers, laser lithotripsy, urolithiasis, Holmiun-YAG laser

Citation: Gonzalez-Cuenca E. Razvi H. *Thulium Fiber Laser: game changer or marketing hype? Rev Mex Urol.* 2023;83(1):pp. 1-11

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Received: February 10, 2023.
Accepted: February 20, 2023.

Resumen

Descripción: El láser de holmio: itrio-aluminio-granate (Ho:YAG) se ha convertido en el dispositivo de litotripsia intra-corpórea de referencia desde que se utilizó por primera vez en la década de 1980. Recientemente, el láser de fibra de tulio (TFL) se introdujo en el entorno clínico, con el potencial de abordar algunas de las limitaciones inherentes de los dispositivos Ho:YAG. En particular, los primeros estudios sugirieron que el TFL proporciona una mayor capacidad de pulverización y fragmentación, menor retropulsión y una mayor tasa libre de litiasis en comparación con el láser Ho:YAG.

Relevancia: Si se confirman las afirmaciones iniciales sobre las ventajas de pulverización del TFL, esto sería un avance significativo en el campo de endourología. La capacidad de pulverizar litos de mayor tamaño en un menor tiempo quirúrgico, podría extender las aplicaciones de la ureteroscopía y reducir la necesidad de procedimientos más invasivos.

Conclusión: La experiencia inicial con el TFL es prometedora y sugiere una ventaja sobre la litotripsia con láser Ho:YAG. Se requieren ensayos clínicos prospectivos y aleatorizados, con un diseño adecuado, para delinear las ventajas, desventajas y optimizar los resultados clíncos de los pacientes.

Palabras clave: Tulio, láseres de estado sólido, litotricia láser, urolitiasis, láser Holmiun-YAG

Introduction

Since the initial introduction of lasers as tools for intracorporeal stone fragmentation thirty-five years ago, there have been a number of innovations in this technology that have revolutionized the field of endourology.[1,2] The development of the pulsed holmium:yttrium-aluminum-garnet (Ho:YAG), in particular was a major milestone in the evolution of safe and effective intracorporeal lithotripsy.[3,4] As experience with the Ho:YAG laser grew, it ultimately emerged as the gold-standard laser. With energy avidly absorbed in water enhancing its safety profile, an ability to fragment stones of all compositions and the availability of fibres of varying sizes, the Ho:YAG laser was a significant upgrade from electrohydraulic and pneumatic intracorporeal lithotripters.

The widespread availability of the Ho:YAG laser ushered in the era of modern day flexible ureteroscopy and improved patient outcomes.

In this review article, the mechanisms behind laser fragmentation will be discussed. Features of the Ho:YAG laser and the newest device the Thulium Fiber Laser (TFL) will be compared.

Laser fragmentation process

Stone fragmentation using pulsed lasers such as the Ho:YAG and TFL occur via two mechanisms:

- Photo-thermal Effect: involves the conversion of laser energy into heat by absorption of the laser light. The energy is absorbed by the water molecules within the stone contributing to fragmentation. The heat accumulates during the laser pulse and produces local destruction before being conducted to surrounding tissues with an end-effect of melting, carbonization or chemical decomposition of the calculus.[5–7]
- Photo-acoustic/Mechanical Effect: involves the generation of a shockwave as a primary mechanism to fragment or disrupt urinary tract stones. Laser energy is converted into mechanical energy in the form of stress waves that propagate at the speed of sound. Rapid formation of a spherical cavitation bubble expands symmetrically and then collapses violently, generating a strong shockwave or acoustic emission that can be directed to the stone.[5,6]

Features of the holmium: YAG laser

Although the Ho:YAG was not the first laser with clinical application for lithotripsy, soon after its introduction it became the tool of choice for intracorporeal ureteroscopic and cystoscopic lithotripsy. Initial devices were however, somewhat limited by the ability to manipulate only two parameters, pulse energy and frequency. While for many clinical scenarios this was not a major limitation, as more complex stone situations were encountered, having the ability to use higher settings and alter the pulse duration allowed for an expanded use of the laser especially with flexible ureteroscopy and intra-renal procedures. The incorporation of the “Moses effect” whereby an initial short, low energy pulse “parting the waters” then allowed the subsequent pulse to have a more efficient ablative effect was another important innovation.[8–10]

The Ho:YAG laser operates via a flashlamp-pumped (Xenon or Krypton) solid-state configured YAG crystal rod chemically doped with Holmium ions inside an optical cavity. The laser pulsation is the light emitted by the flashlamp interacting with the Holmium ions and produces new photons with an infrared wavelength of 2,120 nm. These photons are reflected inside the optical cavity mirrors (reflective mirrors at each end) and multiplied depending on the desired pulse energy. The pulsed laser energy is tightly focused or collimated to exit the cavity when the laser is activated.[8,11–13]

The Ho:YAG generator requires a water-cooling system, due to the heat produced inside the optical cavity. The maximal temperature range of the laser crystal cavity limits the power and frequency of each generator. The solution for high power Ho:YAG lasers is to use multiple optical cavities allowing generators to reach >50 watts.

The clinical advantages of the Ho:YAG laser include the ability to fragment urinary stones of all compositions, application with flexible endoscopes and minimal tissue penetration. The Ho:YAG laser also has multipurpose applications including the capacity to cut, coagulate, ablate, enucleate and vaporize soft tissues.[12–14]

Despite the incremental technological advances however, there have remained some inherent limitations with the Ho:YAG laser. These issues include:

- The generator is prone to misalignment of the mirrors inside the optical cavity due to external shocks or impacts that can permanently damage the generator.
- Large laser generator footprint due to necessary water-cooling system and a required power outlet of 220 volts.
- Smallest available laser fiber diameter limited to 200 µm, which can impact ureteroscope flexibility especially in the lower pole portion of the collecting system.
- Dusting capabilities with certain stone compositions are not ideal, leading to larger than desired stone fragments.
- Retropulsion of stones during laser application, necessitating the need to chase stones fragments.

As a result of some of these shortcomings, evaluations of other wavelengths continued with the hopes of further improving the safety and efficacy of laser lithotripsy.

Features of the thulium fiber laser

The Thulium Fiber Laser (TFL) was first described by Fried in 2005.(15) Several pre-clinical studies then followed providing some insight into its unique properties.(16–18) The TFL operates via an electronic modulated laser diode-pumped configuration, which allows for high and constant peak power levels. A long (10-30 meters), and very fine (10-20 µm) silica fiber chemically doped with Thulium ions, transmits the laser energy to the externally connected laser fiber.(8,11–13)

The TFL can operate in a continuous mode or adopt a super-pulsed mode (50 µs to 12000 µs pulse duration). The TFL is more efficient because the spectrum of emission (laser diode) matches the Thulium ions, producing less heat in comparison to the Ho:YAG (flash-lamp produces a broad light spectrum emission). Due to less wasted energy, less heat is produced and the cooling can be performed by an air system (fan ventilation) inside the generator even at a high-power mode (>50 watts). This allows for a smaller laser box and is quieter to use. The fiber laser technology provides a simpler focusing of the beam and the ability to transmit the high energy via smaller fibers (150 microns).(8,11–13)

The infrared wavelength of 1,940 nm (closer to liquid water absorption peak than the Ho:YAG laser), produces a four-fold higher absorption coefficient, allowing for a higher ablation efficiency at equivalent pulse energies.(11,13,17,19–21)

The low pulse energy and high frequency capabilities of the TFL opened the door to a number of possibilities including better dusting mode, a reduction in stone retropulsion and better ablation efficacy of the stone.(11,17,19) Hardy et al. published preliminary results comparing the dusting mode between Ho:YAG and TLF lithotripsy, and showed the TLF demonstrated a higher stone ablation rate and smaller stone fragments under the same laser settings in an experimental model.(17)

During Ho:YAG laser lithotripsy applications, stone retropulsion is a common and annoying occurrence requiring the surgeon to chase the stone. With the TFL, the retropulsion threshold is up to four times higher when compared to Ho:YAG at equal pulse energies. Retropulsion is evident when using the Ho:YAG at 0.2 J, and with the TFL it is observed at higher energies above 1 J. This difference is thought to be due to the more constant, prolonged peak power and longer pulse duration with the TFL.[13,21,22] In contrast, Knudsen et. al documented an equivalent retropulsion of the TFL vs the Ho:YAG 120W with Moses mode.[22]

The higher pulse frequency, more variable pulse energy, pulse width and symmetrical pulse profile of the TFL energy could have significant benefits during lithotripsy.[8,11,12,17] Table 1 compares the features of the Ho:YAG and TFL.

Table 1. Comparison of Ho:YAG and TFL Features

	Holmium: YAG laser	*Thulium fiber laser*
Light emission	Flashlamp (Xenon / Krypton)	Laser Diodes
Solid-state	Yttrium-Aluminum-Garnet (YAG) Crystal + Holmium ions	10-20 µm Silica Fiber + Thulium ions
Wavelength	2,120 nm	1,940 nm
Optical penetration depth	0.314 mm	0.077 mm
Laser fiber diameter (µm)	>= 200	>=150
Cooling system	Water-cooling	Air-cooling
Power supply	High amperage outlet	Standard outlet
Pulse profile	Irregular + energy spikes	Symmetrical
Operation mode	Pulsed	Pulsed/Continuous
Pulse energy (j)	0.2 - 6.0	0.025 - 6.0
Pulse width (µs)	50-1,300	200-12,000
Maximum power (w)	120	50-60
Manufacturers	Lumenis Olympus Quanta EMS	Urolase SP IPG Olympus (Soltive) Quanta Fiber dust TFL EMS LaserClast Thulium Coloplast TFL Drive

Clinical experience with the TFL

The first clinic experience with the TFL was a retrospective series reported by Martov *et al*. in 2018.[23] Fifty-six patients were included with upper and lower urinary tract stones. Twenty-four patients underwent treatment by retrograde intrarenal surgery (RIRS) and the size of the upper urinary tract stones was 0.6-1.8 cm. The authors reported 100% stone fragmentation with 47.7% requiring additional stone removal techniques. The mean stone disruption time was 19 minutes and at follow-up (4-6 weeks), one patient was found to have a residual symptomatic stone. The first TFL case series in North America was a retrospective study by Carrera et. al, and included 118 treated urinary stones most commonly treated by

RIRS (76.3%).[24] The mean operative time was 59.4±31.6 minutes and a ureteral access sheath was used in 71.1% of procedures. Dusting technique was the preferred treatment (67.1%) with mean total laser-on-time of 10.8±14.1 minutes, mean frequency of 228±299 Hz and mean pulse energy of 0.2 ± 0.3 J. No signs of ureteral thermal injuries were observed. They concluded the TFL was able to ablate various stone compositions with a safety profile comparable to the Ho:YAG.

Corrales *et. al.* reported an initial clinical experience in the first 50 patients from Tenon hospital in Paris.[25] Forty-one patients were treated for renal stones. The median renal stone volume was 1800 (IQR 682-2760) mm^3 with a median stone density of 1200 (IQR 750-1300) HU. The median pulse energy was 0.3 (IQR 0.2-0.6) J with a median pulse frequency of 100 (IQR 50-180) Hz. The median laser-on-time was 23 (IQR 14.2-38.7) minutes. Two complications were noted in the group of renal stones but none related to the TFL. The authors concluded the TFL was a safe and effective modality for lithotripsy during RIRS, and suggested keeping the settings to less than 15-30 Watts. Their experience with dusting was similar to the findings of Enikeev *et. al.*, in that higher dusting efficiency was observed with higher frequencies.[26]

Ulvik *et al.* documented the results of the first prospective randomized clinical trial of TFL (60W) versus Ho:YAG (30W) for ureteroscopy lithotripsy.[27] After a single procedure, the renal stone-free rate at 3 months was 49% and 86% for Ho:YAG and TFL respectively (p =0 .001). The operative time was shorter for the TFL (49 compared to 57 minutes, p = 0.008) but the mean laser-on-time time was similar 13 (IQR 6-17) minutes for the TFL and 13 (IQR 4-19) for the Ho:YAG (p = 0.9) with a mean total energy of 3.5 (IQR 0.9-5.1) vs 4.2 (IQR 0.6-6) KJ (p = 0.4).

Haas *et al.* recently reported a single center prospective randomized trial comparing the high-power super-pulsed Ho:YAG with “Moses 2.0” technology versus the TFL.[28] One hundred and eight patients were randomized with ureteric and kidney stones measuring 3-20 mm. No difference in ureteroscopy time was noted when subdivided based on stone size, >1,023 HU or <1,023 HU or stone location. A comparable stone-free rate was noted for both lasers at 4-8 weeks using different imaging modalities (X-ray, ultrasound and CT scan). Median Laser-on-time was similar (Ho:YAG 4.8 VS TFL 5.1 minutes, p = 0.3) and less energy (Ho:YAG 3.1 VS 4.3 kJ, p = 0.046) was noted for disruption as well as ablation efficiency in favor of the Ho:YAG laser (p = 0.009). The authors describe that similar starting laser settings and modifications were left at each surgeon’s discretion, which may have influenced results given the optimal TFL settings are still not entirely known.

Various laser settings have been proposed based on stone location and whether dusting or fragmentation is the intention.[29,30] At this time, the general advice has been to keep the total energy to under 50 watts in the bladder, 25 watts in the kidney and less than 10 watts in the ureter.[30–32] Suggested settings for dusting and fragmentation are listed in Table 2.

Table 2. Reported TFL settings

Authors	**Energy (J)**	*Frequency (Hz)*	*Laser Power (W)*	*Modality*
		RIRS		
Enikeev et. al.[26]	0.5 0.15	30 200	15 30	Dusting Dusting
Kronenberg et. al.[13]	0.1- 0.2	150	15- 30	Dusting
Corrales et. al.[25]	0.2-0.6	50-180	10-100	Dusting
Ulvik et. al.[27]	0.4 0.8	6 20	2 16	*Fragmenting* Dusting
Hass et. al.[28]	0.8 0.3	8 80	3 24	*Fragmenting* Dusting
SJHC Experience	0.2 2	60 10	12 20	Dusting *Fragmenting*
		Ureter		
Dymov et. al.[30]	0.2 0.5	50 30	10 15	Dusting *Fragmenting*
Corrales et. al.[25]	0.4	40	16	Dusting
Ulvik et al.[27]	0.4	6	2	*Fragmenting*
		Bladder		
Dymov et. al.[30]	2-5	5-10	20-50	*Fragmenting*

Safety cosiderations with the TFL

Both the Ho:YAG and TFL generate heat during the process of intracorporeal lithotripsy. Both wavelengths are highly absorbed in water, however which helps to minimize collateral damage to surrounding tissues. The wavelength of the TFL is closer to the liquid water absorption coefficient than that of the Ho:YAG, resulting in a lower optical penetration in tissue in favor to the TFL (0.077 VS 0.314 mm), providing a high safety profile due to four times less tissue depth penetration.[8,12]

Despite the theoretical safety margin, concerns have been raised with respect to potential thermal effects of the TFL, although this is a subject of some controversy. With the higher TFL water absorption, it has been theorized that higher temperatures may still be generated and the potential for thermal injury to nearby tissues. Andreeva and colleagues demonstrated in an in-vitro ablation model comparing the Ho:YAG and TFL that there were no temperature differences at equivalent power settings.[21] An ex vivo study by Molina et. al comparing the two wavelengths noted equivalent temperatures rises during dusting but higher temperatures during TFL fragmentation.[33] None of the recorded temperatures in their experiments reached the threshold for thermal injury, however. With the TFL capable of much higher frequency settings, the operator much ensure precise laser fiber placement on the stone as fiber movement may be more difficult to control and lead to inadvertent contact with surrounding tissues.

Summary

The development and availability of TFL lithotripsy for clinical use is another quiver in the endourologist's armamentarium for the treatment of complex stones. Clinical experience to date would suggest this wavelength provides improved dusting capabilities. This feature maybe especially advantageous when tackling larger renal stones, obviating the need for more invasive percutaneous procedures. The reduced retropulsion during laser activation may allow for more efficient and quicker stone disruption. The smaller diameter fiber may allow for more consistent access to the lower pole when treating stones in this challenging location.

Although initial clinical experience is encouraging, further work is needed to identify optimal settings based on stone location, composition and therapeutic goals (dusting vs fragmentation). As this work continues we must also remain cognizant of producing optimal lithotripsy effect while minimizing the potential for tissue injury. It is an exciting time in endourology!

CRediT Taxonomy

Eduardo Gonzalez-Cuenca: Investigation, methodology, Project administration, software, visualization, writing (original draft, review & editing).

Hassan Razvi: Investigation, methodology, Project administration, software, visualization, writing (original draft, review & editing).

Financing

No sponsorship was received to write this article.

Conflict of interest

The authors declare no conflicts of interest.

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