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When Long Pulse Is Not Enough: Inferior Dusting Efficiency of Pulsed Thulium:YAG Compared with Ho:YAG and Thulium Fiber Laser in a Standardized In Vitro Renal Model

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Abstract

Endoscopic laser lithotripsy is the standard treatment for urolithiasis. While thulium-based technologies have gained increasing popularity, differences in pulse architecture among platforms may influence fragmentation efficiency beyond wavelength alone. We aimed to evaluate whether long-pulse pulsed thulium:YAG (p-Tm:YAG) achieves comparable ablation efficiency and thermal behavior to holmium:YAG (Ho:YAG) and thulium fiber laser (TFL) under standardized low-power dusting settings.

An in vitro renal collecting system model using Begostone phantoms was employed. Fifty-four stones were equally distributed among Ho:YAG, TFL, and p-Tm:YAG (n = 18 each). Energy and frequency were standardized (0.8J / 25Hz). Ho:YAG and p-Tm:YAG were operated in long-pulse mode, while TFL was used in short-pulse mode. Ablation mass, ablation speed, energy efficiency, temperature evolution, and thermal dose (CEM43) were assessed.

Ho:YAG and TFL demonstrated similar ablation efficiency, while p-Tm:YAG showed a 30–40% reduction in ablation speed and energy efficiency ($p < 0.05$). p-Tm:YAG also exhibited earlier and higher temperature increases, with greater cumulative thermal dose. All systems remained below thresholds for significant thermal injury during the experimental period. Limitations include the in vitro design and use of synthetic stones.

Long-pulse p-Tm:YAG demonstrates inferior dusting efficiency compared with Ho:YAG and TFL under standardized conditions. These findings suggest that pulse architecture and peak power, rather than wavelength alone, are key determinants of laser performance. Extrapolation of outcomes across thulium platforms should be made with caution, and further studies are required before assuming equivalence among thulium-based technologies.

INTRODUCTION

Urolithiasis is a highly prevalent condition with a steadily increasing global incidence and recurrence rate (1, 2). Endoscopic laser lithotripsy has become the standard intracorporeal treatment due to its versatility, safety profile, and ability to fragment stones throughout the urinary tract (1–5).

For nearly three decades, the holmium:yttrium-aluminum-garnet (Ho:YAG) laser has served as the reference lithotripter. Its high absorption in water, shallow tissue penetration, and proven ability to fragment all stone compositions have supported its widespread adoption (3–5). Further technological refinements, including pulse modulation systems, have enhanced energy transmission and reduced retropulsion (3).

In recent years, thulium-based technologies have gained increasing interest, particularly the thulium fiber laser (TFL). Experimental and clinical evidence suggests improved ablation efficiency and favorable dusting characteristics, with pulse duration and peak power identified as key determinants of fragmentation dynamics (6–10).

Despite operating within similar wavelength ranges (~ 1940–2010 nm), thulium platforms are not technologically identical. TFL uses diode-pumped fiber architecture allowing precise short pulse durations, whereas pulsed thulium:YAG (p-Tm:YAG) systems rely on flashlamp excitation and may deliver broader temporal pulse profiles, particularly in long-pulse configurations (10, 11). Whether wavelength similarity translates into equivalent dusting performance across different pulse architectures remains insufficiently characterized.

Most comparative studies have focused on Ho:YAG versus TFL. Specific data evaluating long-pulse p-Tm:YAG under standardized dusting settings remain limited. We therefore designed a controlled in vitro study to determine whether long-pulse p-Tm:YAG achieves comparable ablation efficiency and thermal behavior to Ho:YAG and TFL under standardized low-power dusting parameters.

MATERIAL AND METHODS

We used an in vitro renal collecting system model where Begostone phantoms were located. Begostone phantoms were selected for their reproducibility and mechanical similarity to calcium oxalate monohydrate stones (12). Fifty-four phantoms were equally distributed among three laser systems (n = 18 per group): Ho:YAG and pulsed thulium:YAG were operated in long-pulse settings, and thulium fiber laser was used in short pulses. Energy and frequency parameters were standardized across groups (0.8 J / 25 Hz), representing commonly used low-power dusting parameters.

Pulse duration settings were selected according to each device's available configurations. Ho:YAG and pulsed thulium:YAG were used in long-pulse mode, while TFL was operated using short-pulse settings. Direct standardization of pulse duration across platforms was not feasible due to device-specific architecture.

Energy was delivered through a 200-µm fiber via a 7.5 Fr digital flexible ureteroscope under gravity irrigation maintained at 60 cm. Nine trained operators performed two five-minute activation runs per laser type. Operators were not blinded to the laser system.

Stone mass was recorded before and after activation. Ablation speed and energy efficiency were calculated. A thermocouple positioned 1 cm from the ablation site recorded temperature every 10 seconds. Thermal dose was calculated using the CEM43 model (13, 14).

Statistical analysis was performed using Kruskal–Wallis testing with Dunn–Bonferroni correction. Significance was set at $p < 0.05$.

RESULTS

The mean initial stone weight was 2.161g (± 0.19g), with no statistically significant baseline differences between groups.

After five minutes of activation at 20 W, mean mass ablated differed among systems, as detailed in Table 1. Ho:YAG removed a mean of 0.063 g, TFL 0.066 g, and long-pulse p-Tm:YAG 0.046 g. Post-hoc analysis confirmed that both Ho:YAG and TFL achieved significantly greater ablation than p-Tm:YAG ($p < 0.05$), while no significant difference was observed between Ho:YAG and TFL.

Table 1
Ablation speed and efficiency per laser

Laser Type	**Mass ablated (g) (mean)**	**Ablation speed (gs-1) (mean)**	**Efficiency (gkJ-1) (mean)**
Holmium: YAG	0.063	0.00049	0.025
Pulsed-Thulium: YAG	0.046	0.00035	0.018
Thulium Fiber	0.066	0.00048	0.024

Ablation speed demonstrated the same rank order. Ho:YAG achieved 0.00049 $g \cdot s^{-1}$ and TFL 0.00048 $g \cdot s^{-1}$, compared with 0.00035 $g \cdot s^{-1}$ for p-Tm:YAG. Energy efficiency followed a parallel pattern: 0.025 $g \cdot kJ^{-1}$ for Ho:YAG, 0.024 $g \cdot kJ^{-1}$ for TFL, and 0.018 $g \cdot kJ^{-1}$ for p-Tm:YAG (Table 1). These findings indicate an approximately 30–40% reduction in efficiency when long-pulse p-Tm:YAG was used under identical dusting conditions.

Thermal evolution over time is summarized in Table 2, while dispersion data are presented in Table 3. Ho:YAG exhibited a gradual temperature increase from 23.49°C at baseline to 36.26°C at five minutes. In contrast, p-Tm:YAG reached

41.7°C at five minutes, demonstrating earlier and steeper temperature rise. TFL displayed a similar thermal trajectory at later time points.

Table 2
Mean fluid temperature (°C) at successive time-points

Laser	Initial mean (°C)	1 min mean (°C)	2 min mean (°C)	3 min mean (°C)	4 min mean (°C)	5 min mean (°C)
Holmium:YAG	23.49	26.85	33.02	33.02	35.49	36.26
Pulsed-Thulium: YAG	22.93	32.46	40.07	40.07	41.53	41.7
Thulium Fiber	22.92	31.13	38.51	38.51	40.08	41.78

Table 3
Mean ± 1 Standard Deviation (SD) fluid temperature (°C) at initial time and each minute (0–5 min) for each laser

Laser	Initial mean (°C)	Initial SD (°C)	1 min mean (°C)	1 min SD (°C)	2 min mean (°C)	2 min SD (°C)	3 min mean (°C)	3 min SD (°C)	4 min mean (°C)	4 min SD (°C)	5 min mean (°C)	5 min SD (°C)
Holmium:YAG	23.49	1.46	26.85	3.61	33.02	4.47	33.02	4.47	35.49	4.34	36.26	4.79
Pulsed-Thulium:YAG	22.93	1.04	32.46	5.86	40.07	6.05	40.07	6.05	41.53	4.98	41.7	4.8
Thulium Fiber	22.92	0.96	31.13	4.84	38.51	5.18	38.51	5.18	40.08	5.22	41.78	5.47

CEM43 values calculated at five minutes were 0.014 minutes for Ho:YAG, 0.341 minutes for TFL, and 0.640 minutes for p-Tm:YAG. Although all remained below the traditional 10-minute threshold for minimal reversible injury (13, 14), extrapolated modeling suggested that p-Tm:YAG would approach moderate thermal exposure earlier during prolonged activation.

DISCUSSION

The present study demonstrates that, under identical low-power dusting settings, long-pulse pulsed thulium:YAG exhibits inferior ablation efficiency compared with both Ho:YAG and thulium fiber laser. While Ho:YAG and TFL showed comparable performance in terms of ablation speed and energy efficiency, p-Tm:YAG removed significantly less stone mass and required greater energy per gram ablated.

The comparable performance between Ho:YAG and TFL aligns with previous experimental and clinical data emphasizing the importance of pulse duration, peak power, and stone–laser interaction dynamics (9, 15, 16). Several meta-analyses and randomized trials have reported favorable outcomes with TFL, including higher stone-free rates and shorter operative times (15–17). However, pulse-modulated Ho:YAG systems have demonstrated equivalent results in prospective trials, suggesting that energy delivery profile, rather than wavelength alone, largely determines clinical efficiency (18). Our findings support this interpretation: at standardized parameters, Ho:YAG and TFL behaved similarly.

An additional consideration relates to the practical limitations in pulse duration standardization across platforms. In the present study, pulse settings were selected according to clinically available configurations for each device. While TFL systems technically allow adjustment of pulse duration, longer pulse settings have been associated with markedly

reduced fragmentation efficiency in dusting strategies, which limits their clinical applicability. This reinforces that device architecture and usable pulse profiles, rather than nominal wavelength alone, determine real-world performance.

In contrast, the inferior dusting efficiency observed with long-pulse p-Tm:YAG suggests that pulse architecture may critically influence performance within the same wavelength family. Although TFL and p-Tm:YAG operate within the thulium spectrum, their pulse generation mechanisms differ substantially (10, 11). In our experimental setup, Ho:YAG and p-Tm:YAG were used in long-pulse configurations, whereas TFL was operated using short-pulse settings, which are typically favored for dusting due to their higher peak power delivery and improved fragmentation efficiency.

Peak power has recently emerged as a critical determinant of laser–stone interaction, beyond total energy and frequency settings. Higher peak power is associated with more explosive vapor bubble formation, increased cavitation effects, and enhanced microfracture propagation within the stone matrix. In contrast, lower peak power delivered over longer pulse durations results in a more gradual energy deposition, potentially reducing fragmentation efficiency. Recent experimental work has emphasized that peak power, rather than wavelength alone, may better explain differences in dusting performance across laser platforms (9, 19). In this context, the inferior performance observed with long-pulse p-Tm:YAG may be partially explained by reduced peak power delivery compared with short-pulse configurations.

The approximately 30–40% reduction in ablation efficiency observed in Table 1 supports this mechanistic hypothesis. These findings indicate that wavelength similarity does not guarantee functional equivalence in dusting mode. This distinction is clinically relevant because thulium-based platforms are often discussed as a homogeneous technological category, despite important differences in pulse generation mechanisms and temporal energy delivery.

Thermal behavior followed a parallel pattern. p-Tm:YAG demonstrated earlier temperature elevation and higher cumulative thermal dose compared with Ho:YAG. Although all systems remained below the traditional CEM43 threshold for minimal reversible injury during the 5-minute experimental period (13, 14), extrapolated modeling suggested that prolonged activation with p-Tm:YAG could approach sublethal exposure ranges earlier than the other platforms. Previous studies have shown that both Ho:YAG and TFL can induce significant fluid heating under limited irrigation conditions (20–23), underscoring the importance of adequate coolant flow. Given the high water absorption coefficient of thulium wavelengths (6–8), careful control of activation time and irrigation is essential.

It must be acknowledged that CEM43 was originally developed for oncologic hyperthermia and does not fully capture the dynamic heat dissipation occurring in vivo (13, 14). Tissue perfusion and continuous irrigation rapidly modulate temperature accumulation. Therefore, the projected values presented here should be interpreted as relative indicators of thermal burden rather than precise predictors of clinical injury. Nevertheless, recent reassessment of renal thermal tolerance suggests that historically accepted safety margins may overestimate tissue resilience (23), reinforcing the need for cautious interpretation.

The use of Begostone phantoms represents a limitation, as these models do not reproduce the heterogeneity of human stones (12). However, their standardized mechanical properties allow controlled comparison of laser–pulse interactions and minimize compositional variability. Within this controlled environment, the consistent inferiority of long-pulse p-Tm:YAG across efficiency and thermal parameters supports a pulse-dependent explanation. Although multiple trained operators were used to simulate realistic endoscopic conditions, minor variability in laser handling cannot be completely excluded.

From a clinical perspective, these results suggest that long-pulse configurations of p-Tm:YAG may not be optimal for dusting strategies at low power. Therefore, extrapolation of performance expectations from TFL literature to other thulium-based platforms should be approached with caution until pulse-specific optimization studies are available.

Further studies evaluating short-pulse configurations and different energy–frequency combinations are warranted to determine whether performance equivalence can be achieved under alternative settings.

Future research should include longer activation times and experiments with human stones of diverse composition and density, as performed by other groups (11, 24). This would help validate whether differences in thermal dose and ablation persist under clinical conditions.

CONCLUSION

Under standardized low-power dusting conditions, long-pulse pulsed thulium:YAG demonstrated inferior ablation efficiency compared with Ho:YAG and TFL. Differences in pulse architecture among platforms likely contributed to these findings, highlighting that pulse architecture, rather than wavelength alone, plays a critical role in laser lithotripsy performance. Optimization of pulse configuration (particularly evaluation of shorter pulse profiles for p-Tm:YAG) should precede assumptions of equivalence among thulium-based laser technologies.

Declarations

Ethics declaration: Not applicable. This study did not involve human participants, animal subjects, or identifiable patient data. All analyses were performed using simulated in vitro calculations.

Competing interests: The authors declare that they have no competing interests.

Funding declaration: There was no funding for this study.

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Figures



Figure 1

Legend not included with this version



Figure 2

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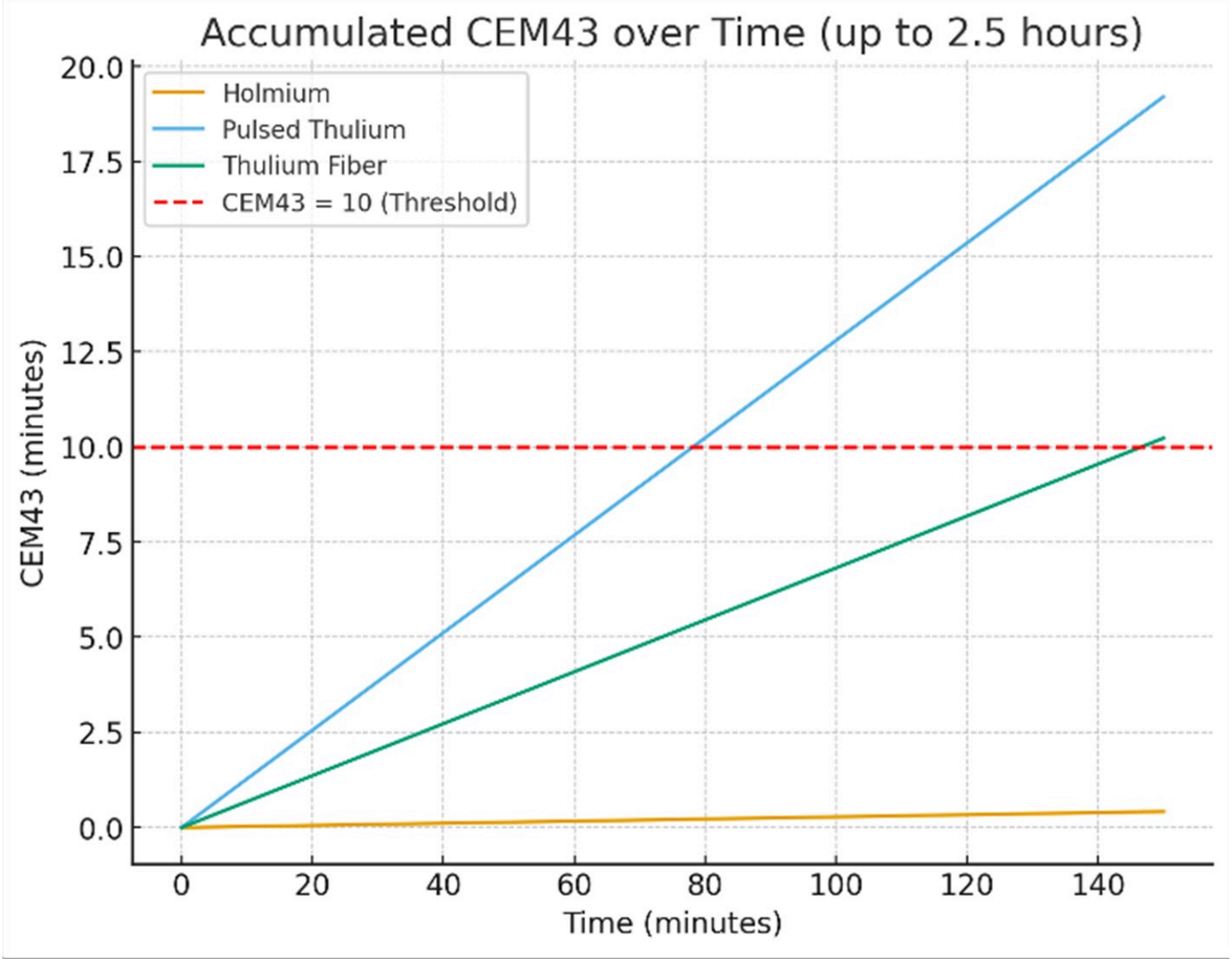


Figure 3

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