ORIGINAL PAPER

Investigation of irrigation fluid temperature variations caused by thulium fiber laser with various settings and comparison with Ho:YAG laser: an *in vitro* experimental study

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Introduction Our experimental *in vitro* study aimed to evaluate the impact of four power settings with different energy and frequency combinations on the irrigation fluid temperature using the thulium fiber laser (TFL). In addition, we aimed to identify the differences between the Ho: YAG laser and TFL by direct comparison of the same power settings.

Material and methods All measurements were performed with a fluid volume fixed at 10 ml and an outflow rate at 10 ml/min. The laser was fired continuously for 30 seconds with total power settings of 10 W, 20 W, 40 W, and 60 W with different power settings (energy × frequency) and various pulse combinations using TFL and Ho: YAG laser (Quanta System, Samarate, Italy).

Results Higher temperatures were recorded when the power was increased from 10 W, 20 W, 40 W, to 60 W. The temperature exceeded the threshold of 43°C when power settings of ≥ 40 W were applied regardless of frequency (15–120 Hz) and energy (0.5–4 J). Similar temperature increase patterns were reported with different peak power settings. No major differences were found when the same power settings were applied using TFL and Ho: YAG lasers.

Conclusions Based on our results temperatures >43°C were recorded for power settings ≥ 40 W after continuous laser firing of 30 seconds using TFL. Modifying the frequency and energy settings, as well as firing with Ho:YAG laser under the same power setting did not affect the patterns of temperature increase. Generally, the TFL shows more regular thermal behavior in comparison with the Ho:YAG laser.

Key Words: urolithiasis ‹› thulium fiber laser ‹› temperature ‹› experimental study

INTRODUCTION

The recent evolution of management options for urolithiasis has presented a unique dilemma for modern urologists [1]. On one hand, the capability of applying higher powers for lithotripsy is very intriguing, and it is associated with shorter surgical time [2]. On the other hand, the high powers have been associated with an increased risk of complications due to intrarenal temperature rise [3, 4].

Since its first introduction, endoscopic nephrolithotripsy has gained wide popularity and nowadays constitutes the gold standard method for the treatment of upper tract urinary stones ≤2 cm [1]. The recent advances in laser technology, along with the established practices of retrograde intra renal surgery (RIRS), have significantly contributed to the development and wider adoption of endoscopic combined intrarenal surgery (ECIRS), enabling the effective treatment of larger and more complex kidney stones [3, 4]. Among these advancements, the introduction of the thulium fiber laser (TFL) offers a wide variety of configurations of pulse energy, frequency and length [5, 6].

The gold standard for lithotripsy is the Holmium:YAG laser (Ho:YAG), which is the recommended treatment because of its demonstrated safety and efficacy [5]. The TFL has emerged as a promising alternative to the Ho:YAG laser. It offers a wide range of settings (from 0.025 to 6 J and from 5 to 2,400 Hz), providing greater flexibility during the lithotripsy procedure [3, 4].

With these benefits, the TFL is positioned as a strong and viable alternative to the conventional Ho:YAG laser lithotripsy, potentially revolutionizing the approach to treating urinary stones with enhanced precision and outcomes. Studies in TFL have advanced from preclinical trials into clinical practice, and there has been a notable decrease in retropulsion, or the backward movement of stones during fragmentation, which can complicate the process and lengthen the treatment time [6–8].

The use of TFL laser in lithotripsy is widely expanded and safety concerns were arisen due to pulse generation. In comparison to the Ho:YAG laser, the generation of the pulse is significantly different. A major difference is that with increasing energy the peak power stays the same as opposed to Ho:YAG [5]. Thus, it can be hypothesized that changing the energy within the same power settings may affect temperature generation. Further investigations may provide more detailed information regarding the safety and functional characteristics of this laser device. In this study, we evaluated the impact of four power settings with different energy and frequency combinations on the irrigation fluid temperature using the TFL. In addition, we aimed to identify the differences between the Ho:YAG laser and TFL by direct comparison of the same power settings.

MATERIAL AND METHODS

Experimental set-up

For the evaluation of the different power settings, an *in vitro* experimental study was conducted. The experimental setting was constructed in a 20 ml syringe immersed in the water bath (temperature ranging from 34–37°C degrees) using a dual lumen ureteral catheter (Cook Medical Cook Ireland Ltd., Limerick, Ireland) and a 12/14Fr ureteral access sheath (UAS) (Flexor® Ureteral Access Sheath with AQ® Hydrophilic Coating, COOK Medical, Cook Ireland Ltd., Limerick, Ireland). The irrigation inflow was connected to the side channel of the dual-lumen catheter, whereas the central channel was used to insert a laser fiber. For the lasering, an optical performance 365 μm laser (Quanta System, Samarate, Italy) was utilized. It was stabilized from the outside with a "Luer-lock" (Tuohy-Borst

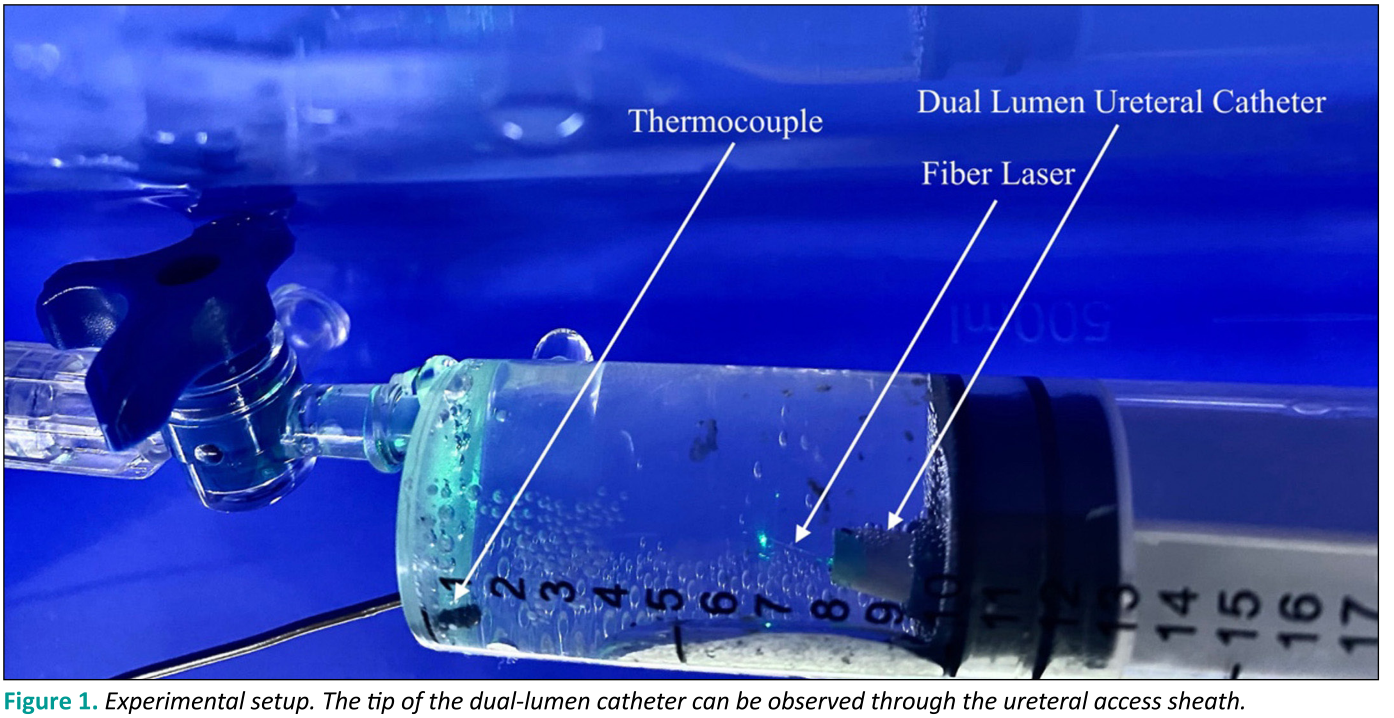

Figure 1. *Experimental setup. The tip of the dual-lumen catheter can be observed through the ureteral access sheath.*

Adapter, Cook Medical, Cook Ireland Ltd., Limerick, Ireland) which also ensured the absence of any fluid leakage from the channel.

The dual lumen catheter was then inserted in the 12/14 Fr UAS, which was prior introduced into the syringe and fixed at the level of the black rubber. To have an adequate volume chamber, the piston of the syringe was set at the 10 ml marking and fixed to prevent any inadvertent movement of the piston due to laser-firing or irrigation flow. For measuring the intrafluid temperatures, a K-type thermocouple (SE001, Pico Technologies, Cambridgeshire, UK) was inserted through a separate hole made on the front side of the syringe (Figure 1).

For irrigation, two saline 3 l bags set at 1 meter above the working table were used. A 10 ml/min continuous irrigation flow rate, calculated every 15_{th} minute, was set for all trials. To achieve fluid outflow only from the UAS, the tip of the syringe, that were usually designed to connect the needle, was connected with a 3-way connected system, and it was closed as shown in Figure 1. The laser was activated for 30 seconds, followed by deactivation till the return of the irrigation fluid temperatures to normal baselines.

Utilized laser devices

The experiment was conducted using a Fiber Dust® Thulium Fiber Laser (Quanta System, Samarate, Italy) and a high-power Ho:YAG Quanta Ho150 laser (Quanta System, Samarate, Italy).

Power settings

The temperature changes were documented with laser firing at the total power of 10 W, 20 W, 40 W and 60 W. We tested 4 variations of energy (0.5 J, 1 J, 2 J and 4 J) with the corresponding frequencies ranging from 5–120 Hz as shown in (Table 1). We also investigated the effect of the peak power of the TFL device stabilizing the energy on the 1 J with the corresponding frequencies for each power setting (10 W, 20 W, 40 W, 60 W).

Firing time

In all of each settings in the two devices we were firing the laser just for 30 seconds.

Comparison of Ho:YAG and thulium fiber laser devices

A further comparison between TFL and Ho: YAG laser using the latter settings was performed. The same 10 W, 20 W, 40 W and 60 W (energy = 1 J, frequency = 10–60 Hz) and firing for 30 seconds to see how evaluate were used for comparing the TFL and high-power Ho:YAG lasers in each device.

We also conducted a statistical analysis using the SPSS program, starting with a descriptive analysis (Table 2), correlation, and threshold statistics.

Table 1. *Temperature response of the irrigation fluid at various power settings over 30 seconds, comparing TFL and Ho:YAG*

	HPP	TFL		Ho:YAG
		LPP		
Power (W)	Energy (J) × Frequency (Hz)	$T_{30}s$ (°C)		
10	0.5 × 20	30.4	–	–
	1 × 10	30.1	29.55	31.3
	2 × 5	29.2	–	–
20	0.5 × 40	35.5	–	–
	1 × 20	35	36.3	36.2
	2 × 10	32.6	–	–
	4 × 5	34.2	–	–
40	0.5 × 80	43.3	–	–
	1 × 40	45.8	47.5	45.3
	2 × 20	46.4	–	–
	4 × 10	46	–	–
60	0.5 × 120	53.8	–	–
	1 × 60	56.7	57.9	59.3
	2 × 30	55.8	–	–
	4 × 15	56.6	–	–

HPP – high peak power; LPP – low peak power; TFL – thulium fiber laser

Table 2. *Descriptive statistics for laser temperatures*

Laser	Power	Mean	SD	Min	Max
Ho:YAG	10	31.3	–	31.3	31.3
	20	36.2	–	36.2	36.2
	40	45.3	–	45.3	45.3
	60	59.3	–	59.3	59.3
TFL (HPP)	10	29.9	0.6	29.2	30.4
	20	34.3	1.3	32.6	35.5
	40	45.4	1.4	43.3	46.4
	60	55.7	1.3	53.8	56.7
TFL (LPP)	10	29.5	–	29.5	29.5
	20	36.3	–	36.3	36.3
	40	47.5	–	47.5	47.5
	60	57.9	–	57.9	57.9

HPP – high peak power; LPP – low peak power; SD – standard deviation; TFL – thulium fiber laser

Bioethical standards

This study was conducted entirely *in vitro* and does not involve human subjects, human material, human data, or in vivo experiments on animals. The ethical approval was not required.

RESULTS

Temperature with various power settings of thulim fiber laser

The temperature of the irrigation fluid increased in a linear manner as the power increased from 10 W to 60 W. For power settings 10 W, 20 W, and 40 W, the temperatures remained below 46°C. However, at a power setting of 60 W, a significantly higher temperature of approximately 55°C was observed. When the frequencies and energies were varied while keeping the power settings constant, no significant differences were found. This indicates that changing the frequencies and energies does not affect the maximum temperature or the profile of temperature rise. The recorded maximum temperatures were as following, at 10 W was from ~29°C to ~30°C, at 20 W was from ~32°C to ~35°C, at 40 W was from ~43°C to ~46°C and at 60W was from ~54°C to ~57°C, as shown in the (Figure 2), and with no significant difference were was detectible when the laser was fired with low or high peak power, as shown in the (Figure 3).

In the correlation study for all laser types, showed that power and the temperature were strongly linked in a good way. The Pearson correlation coefficient for the Ho:YAG laser was r = 0.994 (p = 0.006). The correlation coefficients for the TFL (HPP) and LPP were r = 0.994 (p <0.001) and r = 0.999 (p = 0.001) respectively. This shows that power is a strong predictor of temperature increase for all laser types.

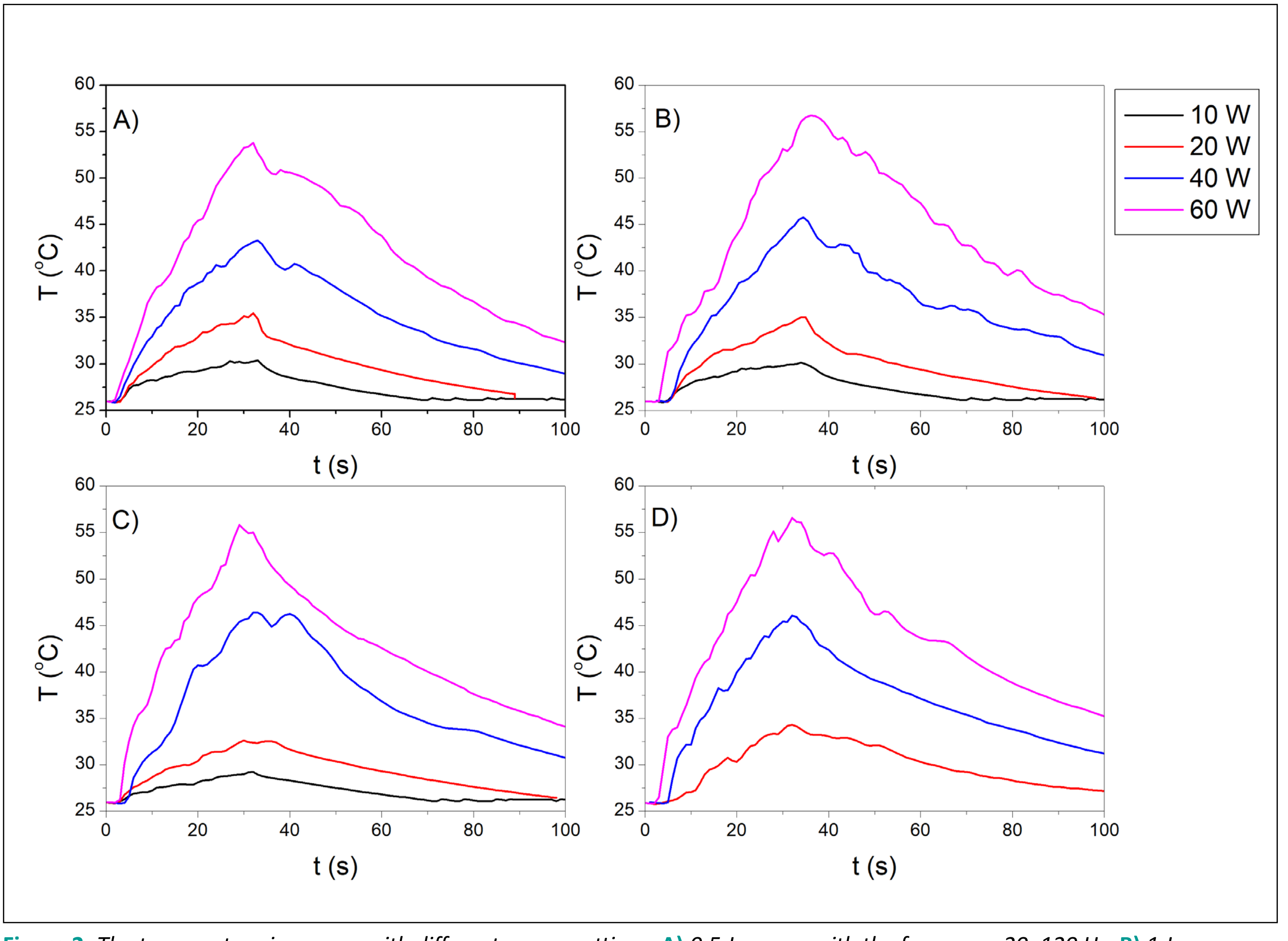

Figure 2. *The temperature increases with different power settings:* **A)** *0.5 J energy with the frequency 20–120 Hz;* **B)** *1 J energy with the frequency 10–60 Hz;* **C)** *2 J energy with the frequency 5–30 Hz;* **D)** *4 J energy with the frequency 5–15 Hz.*

Comparison of Ho:YAG and thulium fiber laser devices

The comparison of the temperature response of irrigation fluid at various power settings over a 30-second period is the main focus of the TFL and Ho:YAG lasers. We investigate 10 W, 20 W, 40 W, and 60 W power settings with different energy and frequency combinations.

At 10 W, Ho:YAG recorded 29.55°C and 31.3°C for the same (1 J × 10 Hz) setting, while TFL recorded 30.4°C (0.5 J × 20 Hz), 30.1°C (1 J × 10 Hz), and 29.2°C (2 J × 5 Hz). Ho:YAG recorded slightly higher temperatures of 36.2°C and 36.3°C for (1 J × 20 Hz), while TFL results at 20 W ranged from 32.6°C to 35.5°C across various energy-frequency combinations. On the other hand, Ho:YAG gave the reading of 45.3°C and 47.5°C for (1 J × 40 Hz), whereas the TFL was within the range of 43.3°C to 46.4°C at 40 W. At the highest power setting of 60 W, TFL touched maximum temperature ranging from 53.8°C to 56.7°C; however, Ho:YAG recorded relatively higher values of 57.9°C and 59.3°C for (1 J × 60 Hz).

Based on available data of this experimental study, TFL might raise temperature more subtly than Ho:YAG, which seems to reach higher temperatures at similar power levels. (Figure 4). But for further investigation to find out if these lasers can be safe to use, a threshold analysis was done to see how often temperatures went above 43°C, which could be harmful to the tissue. The Ho:YAG laser exceeded this limit in 50% of the settings, which means there is a moderate risk of overheating. TFL (HPP) and TFL (LPP), on the other hand, exceeded 43°C in 53.3% and 50% of settings, respectively. This shows that Ho:YAG and TFL lasers are less likely to reach temperatures that can damage tissue.

DISCUSSION

The rapid development of laser technologies introduces a need for deeper investigations of the safety profiles of different laser devices and settings. Temperature rise during laser lithotripsy is an important concern because temperatures above 43°C might induce tissue thermal damage [7]. Our team had previously determined the safety of high-power

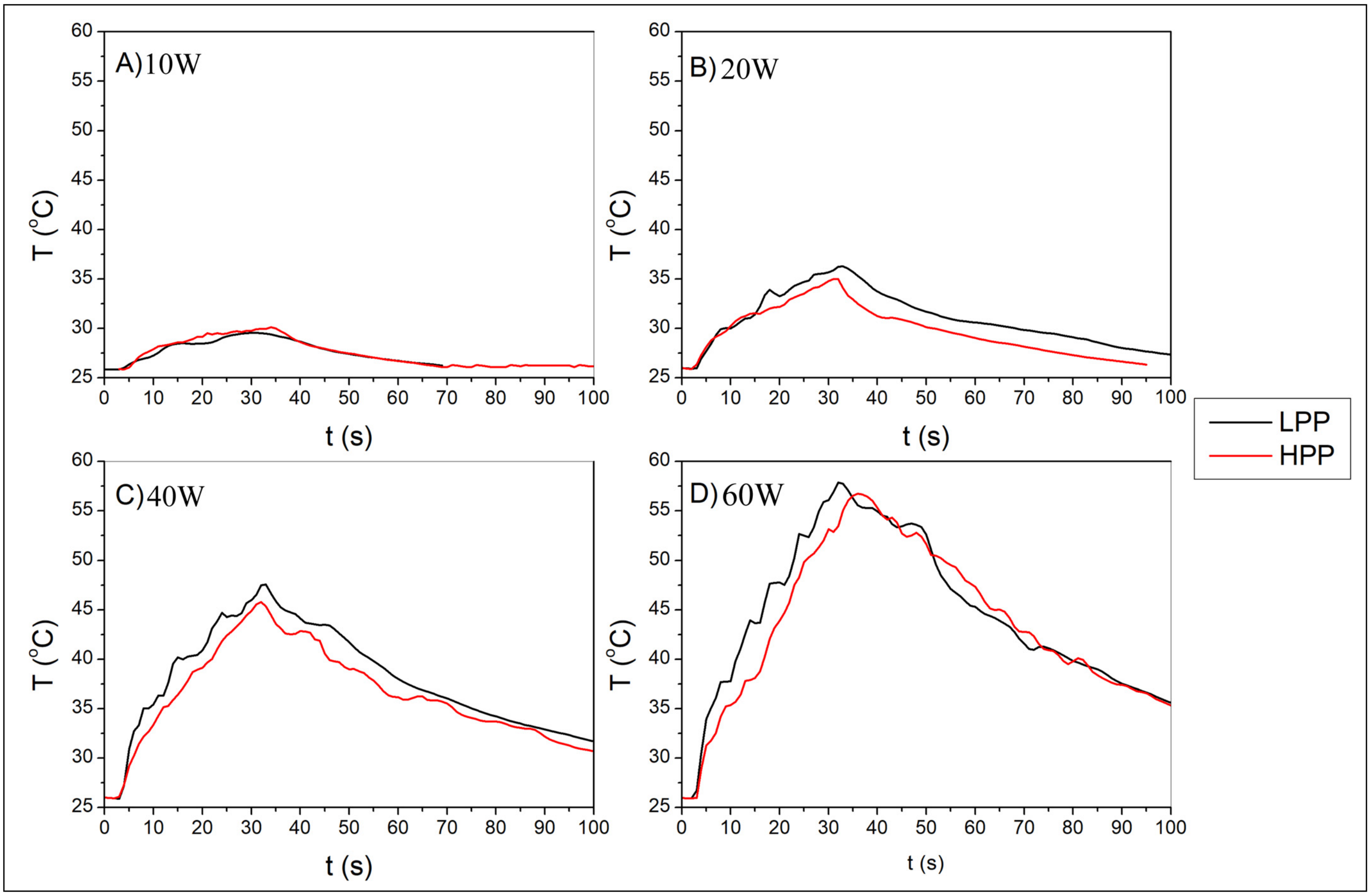

Figure 3. *Temperature increases with high and low peak power settings.*

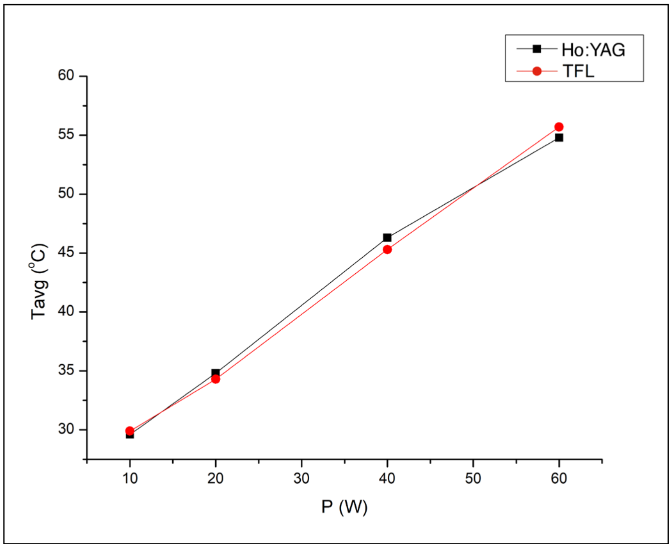

Figure 4. *Temperature increases with TFL and Ho:YAG lasers.*

lithotripsy utilizing the Ho:YAG laser [8, 9]. However, the process of heat generation by the TFL is still a matter of debate in the literature [10], since this laser has several different features that might influence temperature when compared to the Ho:YAG laser [11]. Firstly, the TFL has a wavelength of 1940 mm, which provides a 3–4 times higher water absorption coefficient [12]. Additionally, the TFL pulse is continuous as opposed to the peak power seen in the Ho:YAG laser pulse [11]. The continuous pulse allows uniform heating of the stone, with the vaporization of interstitial water inside the stone. Whether these features of the TFL significantly impact temperatures is still not clear.

This investigation evaluated the thermal generation of both the Fiber Dust® Quanta Thulium Fiber Laser and the Ho:YAG Quanta Ho150 laser, by escalating power levels from 10 W to 60 W, altering energy and frequency parameters, yet holding all other variables constant. We have shown that using the same settings, the TFL and Ho:YAG laser did not show any differences in saline temperature increase. These results are in line with other studies, which also found equal temperature when using the two lasers with the same power settings. Andreeva et al. [13] performed an *in vitro* ablation study using artificial stones inside water cuvettes. The authors evaluated the Ho:YAG and TFL at the same power settings (8 W, 16 W and 40 W) and they reported similar temperature increases with both lasers (4.9°C, 9.8°C and 14.6°C). Using a similar model without the use of artificial stones, Taratkin et al. [14] evaluated the temperature increase with a single setting (0.2 J × 40 Hz = 8 W) and found that after the 60 s of laser firing, both Ho:YAG and TFL presented a similar temperature increase (14.9°C for Ho:YAG and 15.4°C for TFL) and similar energy introduced into the experimental system (447.3 J for Ho:YAG and 459.8 J for TFL). Hardy et al. [15] reported higher temperatures while using the TFL at 500 Hz. However, the power settings used in the TFL did not match the ones used for Ho:YAG, so no direct comparison can be derived from this study. Molina et al. [16] performed an *ex vivo* experimental study using porcine kidneys and inserting artificial stones inside. The authors investigated dusting settings (0.3 J × 70 Hz = 21 W for Ho:YAG and 0.1 J × 200 Hz = 20 W for TFL) and fragmentation settings (0.8 J × 8 Hz = 6.4 W for both Ho:YAG and TFL). They found an equal temperature increase using dusting settings but a higher temperature increase in the TFL when fragmentation settings were being used (29.30°C for Ho:YAG and 31.87°C for TFL). No ureteral lesions were found in the histological examination.

A study conducted by Okhunov et al. [17] outlined methods for reducing the increase in intrarenal temperature during laser lithotripsy such using ureteral access sheaths to be helpful in preserving lower temperatures, most likely through improved flow rates. Moreover, Peng et al.'s [18] research reaffirmed the importance of irrigation rate in temperature regulation. According to their research, even at a lower power of 15 W, the lack of irrigation could cause dangerous temperature thresholds to be quickly reached after just 20 seconds of laser activation. On the other hand, even when using greater power settings for longer periods of time, it has been demonstrated that maintaining an irrigation rate of 25 ml/min will keep temperatures within acceptable limits [18]. These insights were taken into account in our experiment, where we consistently applied a fixed outflow rate of 10 ml/min across all trials to manage thermal effects.

In 2021, Belle et al. [19] performed an experiment with a 3D printed ureter to compare the evaluation of fluid temperature between TFL and Ho:YAG. The maximum temperature for the TFL was higher than the Ho:YAG at all power settings tested and the TFL exceeded the threshold for tissue damage at 30 W with at 43°C. Oppositely, as already stated, in our study, a similar temperature increase for the same power settings was detected. Our findings support the thermodynamical concept that 1 J always produces the same temperature increase, regardless of the energy source [10, 14]. Moreover, we have also found that none of the parameters (frequency, energy and pulse length) had any significant association with the temperature rise. Therefore, only the total amount of energy delivered in a specific period of time (power) has an impact on temperature, for both Ho:YAG laser and TFL.

Currently, there is no clear understanding and recommendation on which laser settings are the best for effective and safe lithotripsy. A recent interesting study on TFL settings using experts' Tweets showed great differences in the proposed settings, with most experts recommending dusting settings [20]. In light of the divergent views on optimal power settings, it has been observed that operating at lower power levels, specifically below 40 W, is a common approach to mitigate the potential risk of thermal injury. This practice is typically coupled with adequate fluid irrigation as well as appropriate intervals for laser firing and flushing, to maintain a balance between efficacy and safety [21].

Several limitations are still associated with our study. As with every *in vitro* model, a complete, realistic replication of different clinical scenarios is not possible. In particular, several factors, including anatomical and physiological variations, blood circulation, and baseline body temperature, presence, and composition, may affect the outcomes in clinical practices. In addition, working parameters such as the use of UAS, the diameter of the flexible ureteroscope, and the volume of the pelvicalyceal system may influence the irrigation flow rate, thus affecting the temperature changes. In addition, the presence of artificial stones or real renal calculi might alter the fluid dynamics and the temperature patterns observed. The addition of stones would be a great idea for a future experimental study. Nonetheless, by maintaining constancy in the surrounding factors, our model serves as a beacon, illuminating the typical patterns of activity within the system. Also there were no diagram for the 10 W with the sittings using below the 5 Hz. It was not acceptable from the device to decrease the frequency below the 5 Hz.

CONCLUSIONS

Reflecting on the conclusions of our analysis temperatures >43°C were recorded for power settings ≥40 W after continuous laser firing of 30 seconds using TFL. Changing the frequency, energy and peak power, as well as firing with the same power setting with Ho:YAG laser did not affect the patterns of temperature increase.

Generally, the TFL shows more regular thermal behavior in comparison with the Ho:YAG laser. This indicates that it may be used safely in clinical settings. This regular thermal behavior decreases the heat impact and improves both efficacy and safety. More research is necessary to confirm the benefits of TFL in different surgical contexts and to investigate the clinical implications of these findings.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research received no external funding.

ETHICS APPROVAL STATEMENT

The ethical approval was not required.

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