Original Article

A Comparative Study of Holmium: Yttrium-aluminum-garnet Laser Modes for the Fragmentation of Kidney Stones

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ABSTRACT

Background: The problem of human kidney stones is currently a common disease. This is due to several variables, including nutrition, genetic factors, and geographic region. Kidney stones can be eliminated in several ways, including laser fragmentation, a safe and minimally harmful method because it does not require surgical intervention.

Objectives: This study compares hard stones and dusting modes of the Holmium: Yttrium-aluminum-garnet (Ho:YAG) laser used for fragmented kidney stones.

Methods: The Ho:YAG laser with a maximum power of 30 W, pulse duration 600 μs, wavelengths 2100 nm, the maximum energy level 5 J with maximum frequency level of 30 Hz, used for lithotripsy in Al-Sadr Medical City in Najaf City, Iraq, at different laser parameters energy pulse and pulse rate of 0.8 J/8 Hz and 1 J/10 Hz, respectively, for 17 samples of kidney stones. The laser is passed by the optical fiber through a thin tube (catheter) that is inserted into the ureter through the urethra to reach the stone.

Results: The calcium oxalate stones are ablated more than uric acid stones at different pulse rates. In addition, the samples that fragmented by Ho:YAG laser with hard stones mode with the energy of 0.8 J and pulse rate of 8 Hz have the highest ablation rates than dusting mode, and the dusting mode with energy 0.8 J and pulse rate 8 Hz have the highest ablation rates than dusting mode with energy 1 J and pulse rate 10 Hz for calcium oxalate stones.

Conclusion: Laser lithotripsy may be a more effective treatment option for calcium oxalate stones than uric acid stones.

Keywords: Ablation rates, Calcium oxalate stone, Holmium: Yttrium-aluminum-garnet (Ho:YAG) laser, Kidney stones, Uric acid stone

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Introduction

Kidney stone disease affects nearly 10% of the population in the United States and about 50 million people worldwide (Hardy et al., 2018). The prevalence of this condition is increasing, with approximately 7% of women and 12% of men experiencing its effects throughout their lifetimes (Frank et al., 2019). Multiple classifications of urinary tract stones exist, which are determined by the composition of crystals or chemicals comprising them (Awazli & Mahmood 2013). The three main components of laser lithotripsy laser, optical fiber, and ureteroscope have all progressed over the past decade, allowing the procedure to become increasingly common in clinical practice. The Holmium: Yttrium-aluminum-garnet (Ho:YAG) infrared laser, driven by a flashlamp and has a lengthy pulse duration, has been the gold standard for lithotripsy for almost 20 years (Johnson et al., 1992; Emiliani, 2019; Mahajan & Mahajan, 2022). While examining a specimen of erbium oxide in the year 1879, the Swedish scientist Per Theodor Cleve observed a brown substance. He named it Holmium (Holmia is a Latin name for Stockholm). Trivalent ions of Holmium are the most common form in nature and commercial applications, like lasers. Similar to other rare-earth ions, trivalent Holmium, and thulium ions exhibit a distinctive spectrum of emission wavelengths, especially in the near-infrared region. A laser beam made of Ho:YAG is generated within an optical cavity (Traxer & Keller 2020). A YAG crystal with Holmium ions added chemically forms the focal point of this void. A solid-state laser is an example of such a design (Sandhu et al., 2007). The Ho:YAG laser's architecture shifts depending on the power supply used to pump the crystal. Flashlamp light (usually xenon or krypton) is used to create laser pulses, and when it interacts with the Holmium ions, it causes them to generate new photons at a wavelength of 2120 nm (Traxer & Keller 2020).

Clinically, fragmentation and dusting ablation modes are two of the most frequently employed procedures in laser lithotripsy (Patel & Knudsen, 2014; Mullerad et al., 2017). High pulse energy (0.5–2.0 J) and low pulse rate (5–30 Hz) are hallmarks of the fragmentation mode. Larger pieces of stone are quickly broken off. Strong retropulsion effects are also generated by the fragmentation mode of operation. The dusting ablation mode uses high pulse rates (50-80 Hz) and low pulse energies (0.2-0.4 J). The patient may readily and naturally eliminate the dust-sized (0.5 mm) ablated particles. Due to the weaker retropulsion in the dusting mode, it may not be possible to ablate tougher stones without switching to the fragmentation mode or increasing the pulse intensity of the laser (Tracey et al., 2018; Hardy, Vinnichenko & Fried 2019). The delivery of Holmium laser energy occurs via a compact optical fiber, resulting in the fragmentation of the stone into numerous smaller pieces (Frank et al., 2019; Schatloff et al. 2010). These fragments can then be extracted individually using a stone basket. Alternatively, if the stone size is reduced to 2 mm or smaller, it can traverse the urinary tract without obstruction and be naturally expelled by the patient (Fried, 2018). The tiny, malleable optical fibers with diameters between 200 and 1000 µm are used (Kronenberg & Traxer 2014). Because of its adaptability, lithotripsy may be performed anywhere in the upper urinary system, including during flexible ureteroscopy and flexible nephroscopy (Emiliani, 2019; Somani et al., 2013; Nazif et al., 2004). Optical fibers are composed of multiple layers of transmission and protecting materials. This material permits linear reflection and transmission of photons (a property known as the beam's coherence) with minimal loss of thermal energy (Emiliani, 2019). The ablation rate is also material-specific, as hard calculi absorb electromagnetic radiation directly (Chan et al., 1999). Accordingly, this study opens research horizons for studying the development and obtaining the best results for breaking up kidney stones with the least harm.

Materials and Methods

A total of 17 samples that were collected from Al-Sader Medical City in the City of Najaf, Iraq, were fragmented by Ho:YAG laser with a maximum power of 30 W, pulse duration of 600 µs, wavelengths 2100 nm, the maximum energy level 5 J with maximum frequency level 30 Hz. This laser from Litho Company and brand Quanta System Italy with optical fiber from the REOSABLE Company were used with a diameter of 550 µm to insert the laser beams into the ureter and shine the rays on the stones. The patient was positioned on an exam table and the urethra was numbed with a local anesthetic. The laser is passed by the optical fiber through a thin tube (catheter) that is inserted into the ureter through the urethra. The laser fragments the stone into small pieces less than 4 mm that can be passed out of the body in the urine. According to Table 1, the samples were divided into several sections according to the modes of fragmentation, the type of stone, and the laser variables that were used to break the stones, so that a comparison between the laser modes and parameters.

Table 1. Classification of stones according to modes fragmentation and parameters for laser

Mode	Dusting			Hard Stones
Stone type	Calcium oxalate (n=6)	Calcium oxalate (n=3)	Uric acid (n=4)	Calcium oxalate (n=4)
Pulse energy (J)	0.8	1	0.8	0.8
Pulse rate (Hz)	8	10	8	8

Statistical analysis

In this study, the analytical results were put through a series of statistical tests to clarify the outputs and establish reliable relationships between the observed measurements. The SPSS software, version 26, was employed for this purpose. The Pearson correlation coefficient calculates the linear dependency (correlation) among two or more variables. It gives a number between -1 and +1, where -1 represents a negative correlation, while 0 represents no relationship between the variables, and +1 represents a positive correlation (Rennak et al., 2024; Adeleye et al., 2024). In this study, the correlation coefficient was employed to explain the interactions and relationships between the various factors. The independent t-test was used to compare the means of two independent groups. Independent groups mean that each individual belongs to one of the groups. Also, knowing the values of the observations in one group tells us nothing about the observations in the other group (Salavati et al., 2024; Rooshan et al., 2024).

Results

Holmium laser lithotripsy for ureteral calculi has shown consistently positive outcomes. The treatment time was calculated by multiplying the number of pulses by the pulse duration (600 µs) for the hard stones mode and (1500 µs) for the dusting mode, from which the ablation rates were calculated resulting from dividing the mass of stones by the treatment time as shown in Table 2. According to Table 2, the ablation rates of calcium oxalate and uric acid stones under different conditions. The ablation rate is the rate at which a stone is ablated, or destroyed, by laser energy. The results in Figure 1 show that the ablation rate of calcium oxalate stones is higher than the ablation rate of uric acid stones. Where the average ablation rate for calcium oxalate stones is 1.329 g/s, while the average ablation rate for uric acid stones is 0.653 g/s. Figure 2 explains the difference in ablation rates for calcium oxalate stones at pules energy 0.8 J and pulse rate 8 Hz for dusting and hard stones modes, where it has a higher value in hard stones than in dusting mode. Meanwhile, Figure 3 shows the variance in ablation rates for calcium oxalate stones for dusting mode at different pulse energy and pulse rate (0.8 J/8 Hz, 1J/10 Hz), it found the ablation rates with 0.8 J/8Hz faster compared to 1 J/10 Hz. These results are in line with (Chawla et al., 2008; Wezel et al., 2010). The statistical analysis shows that the mass of the stone has a moderate positive correlation with treatment time and pulse number with a $P<0.05$; accordingly, the results are statistically significant. The mass of the stone has a weak positive correlation with energy and pulse rate with a $P>0.05$, so the results are not statistically significant. The treatment time has a moderate positive correlation with energy with a $P<0.05$; hence, the results are statistically significant. The treatment time has a weak positive correlation with pulse rate with a $P>0.05$; therefore, the results are not statistically significant. The energy of pulse has a moderate positive correlation with pulse rate and pulse number with a $P<0.05$, this means the results are

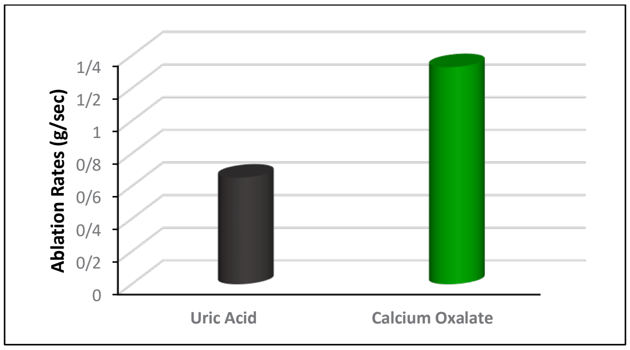

Figure 1. Ablation rates for calcium oxalate and uric acid stones at different pulse rate (P>0.5)

Table 2. Treatment and ablation rates for kidney stone samples

Sample	Mass of Stone (g)	Pulse Number	Treatment Time (s)	Ablation Rates (g/s)
Calcium oxalate (hard stones; 0.8 J/8 Hz)	1.282	1012	0.6072	2.1107
	1.599	5800	3.48	0.4596
	0.911	538	0.3228	2.8225
	0.344	124	0.0744	4.6243
Calcium oxalate (dusting; 0.8 J/8 Hz)	1.664	2366	3.549	0.469
	0.963	280	0.42	2.293
	2.5	1544	2.316	1.079
	2.642	804	1.206	2.191
	0.493	314	0.471	1.047
	0.697	516	0.774	0.9
Calcium oxalate (dusting; 1 J/10 Hz)	3.124	2680	4.02	0.777
	0.664	2270	3.405	0.195
	1.213	2536	3.804	0.319
Uric acid (dusting; 0.8 J/8 Hz)	8.926	4344	6.516	1.37
	0.288	1462	2.193	0.131
	0.183	390	0.585	0.313
	0.414	346	0.519	0.799

statistically significant. The pulse rate has a weak positive correlation with the pulse number with a P>0.05, hence, the results are not statistically significant. A t-test for the variables was tested to see if there were differences between the laser dusting and hard stones modes. The mass of the stone, treatment time, energy, and pulse rate have P>0.05 with dusting and hard stones modes, so the results are not statistically different.

Discussion

The use of laser technology in the treatment of urinary stones, particularly through laser lithotripsy, has emerged as a highly effective and minimally invasive approach in modern urology. Laser lithotripsy provides superior precision in fragmenting stones, allowing for targeted disintegration of calculi while minimizing trauma to the surrounding tissue (Hardy et al., 2018). This method has been confirmed effective across a wide range of stone types and sizes, including harder stones that are resistant to other treatments, thereby offering enhanced therapeutic outcomes. Moreover, the use of lasers significantly reduces postoperative complications, recovery time, and the need for more invasive surgical interventions, contributing to its high success rate in clinical practice. As such, laser lithotripsy represents a valuable advancement in the management of urolithiasis, offering both improved patient safety and efficacy in the treatment of urinary stones (Johnson et al., 1992).

There are a few factors that could explain the increase in the ablation rate of calcium oxalate stones in comparison with uric acid stones at different pulse rates. First, calcium oxalate stones are harder than uric acid stones, so they may require more laser energy to ablate. Second, calcium oxalate stones may be more porous than uric acid stones, which could allow the laser energy to penetrate more deeply into the stone. Therefore, the differences in composition, the texture of the surface, or the density of the stone play an important role in the results. The ablation rates in calcium oxalate in the dusting mode at (0.8 J/8 Hz) are faster than with (1 J/10 Hz) which may be because the dusting mode results in lower retropulsion for stone, as well as the error in aiming the

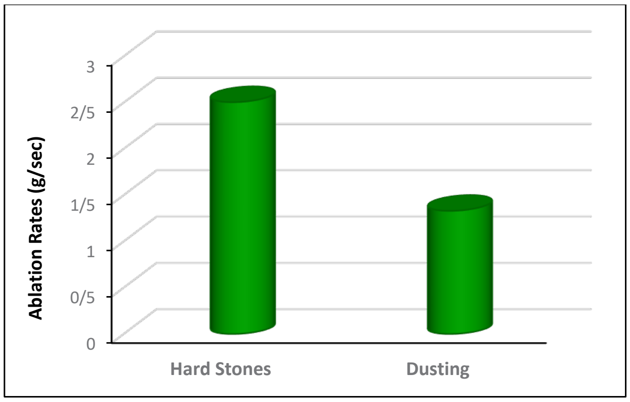

Figure 2. Ablation rates for calcium oxalate stones at 0.8 J/8 Hz for two modes (P>0.5)

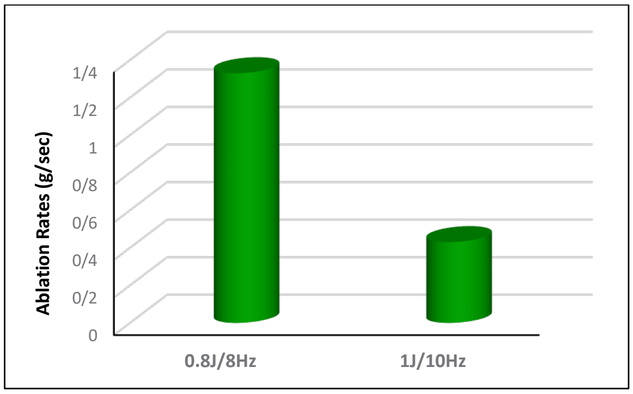

Figure 3. Ablation rates for calcium oxalate stones for dusting mode at 0.8 J/8 Hz and 1 J/10 Hz (P>0.5)

laser beam directly at the stone and the laser beam is not completely absorbed by the stone (Wei et al., 2024).

The findings of this study on Holmium laser lithotripsy for ureteral calculi align with and extend upon previous research in this field, particularly studies by Chawla et al. (2008) and Wezel et al. (2010), both of which reported positive outcomes for laser-based treatments of urinary stones. In line with those studies, our results demonstrated higher ablation rates for calcium oxalate stones compared to uric acid stones, with an average ablation rate of 1.329 g/s for calcium oxalate and 0.653 g/s for uric acid stones. This difference supports earlier observations of variability in laser efficacy depending on stone composition. Furthermore, consistent with prior research, our data indicated that the ablation rate was more efficient in the hard stones mode than the dusting mode, particularly for calcium oxalate stones, where pulse energy and rate variations (0.8 J/8 Hz vs 1 J/10 Hz) produced notable differences. Statistical analysis revealed that stone mass, treatment time, and pulse number exhibited a moderate positive correlation, with a $P<0.05$ indicating statistical significance, while energy and pulse rate correlations were weaker (Wriedt et al., 2023). This nuanced understanding of treatment parameters contributes to optimizing laser lithotripsy protocols. However, no significant differences were observed between dusting and hard stones modes for variables, such as stone mass, treatment time, and energy, suggesting that both modes may offer comparable outcomes under specific conditions, a conclusion supported by the t-test results ($P>0.05$). These insights build on the foundation of earlier studies, offering a deeper exploration of the relationships between laser parameters and stone ablation efficiency (Jiang et al., 2023).

Conclusion

Ho:YAG laser, demonstrated greater effectiveness in ablating calcium oxalate stones compared to uric acid stones across various parameters. The highest ablation rates were achieved using the hard stones mode with energy 0.8 J and a pulse rate of 8 Hz for calcium oxalate stones. These results suggest that laser lithotripsy may be more suitable for calcium oxalate stones, but additional research is required to optimize treatment conditions and validate these findings for both stone types.

Ethical Considerations

Compliance with ethical guidelines

The research did not involve any ethical considerations.

in this research.

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Authors' contributions

All authors contributed equally to the conception and design of the study, data collection and analysis, interpretation of the results, and drafting of the manuscript. Each author approved the final version of the manuscript for submission.

Conflict of interest

The authors declared no conflict of interest.

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