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ORIGINAL ARTICLE

Systematic evaluation of a holmium: yttrium-aluminum-garnet laser lithotripsy device with variable pulse peak power and pulse duration

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Abstract *Objective:* The Holmium:yttrium-aluminum-garnet (Ho:YAG) laser is the standard lithotrite for ureteroscopy. This paper is to evaluate a Ho:YAG laser with a novel effect function *in vitro*, which allows a real-time variation of pulse duration and pulse peak power.
Methods: Two types of phantom calculi with four degrees of hardness were made for fragmentation and retropulsion experiments. Fragmentation was analysed at 5 (0.5 J/10 Hz), 10 (1 J/10 Hz), and 20 (2 J/10 Hz) W in non-floating phantom calculi, retropulsion in an ureteral model at 10 (1 J/10 Hz) and 20 (2 J/10 Hz) W using floating phantom calculi. The effect function was set to 25%, 50%, 75%, and 100% of the maximum possible effect function at each power setting. Primary outcomes: fragmentation (mm^3), the distance of retropulsion (cm); $\geq$5 measurements for each trial.
Results: An increase of the effect feature (25% *vs.* 100%), i.e., an increase of pulse peak power and decrease of pulse duration, improved Ho:YAG laser fragmentation. This effect was remarkable in soft stone composition, while there was a trend for improved fragmentation with an increase of the effect feature in hard stone composition. Retropulsion increased with increasing effect function, independently of stone composition. The major limitations of the study are the use of artificial stones and the *in vitro* setup.
Conclusion: Changes in pulse duration and pulse peak power may lead to improved stone fragmentation, most prominently in soft stones, but also lead to increased retropulsion. This new

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effect function may enhance Ho:YAG laser fragmentation when maximum power output is limited or retropulsion is excluded.

1. Introduction

Holmium:yttrium-aluminum-garnet (Ho:YAG) laser has been demonstrated to yield smaller fragments than lithoclast, pulsed dye laser, or electrohydraulic lithotripsy, fragmenting all compositions of urinary calculi with low risk of injury to the urothelium [1–6]. Fragmentation efficiency and retropulsion during Ho:YAG laser lithotripsy depend on power settings, pulse duration, fibre type, and stone composition [7–12]. The pulse duration is usually fixed between 250 and 350 μs in most of the Ho:YAG lasers available, while in some Ho:YAG devices pulse duration can be set freely between 150 and 800 μs [13] or set at 350 or 750 μs [8–11]. Wezel et al. [11] demonstrated an improvement of fragmentation efficiency by reducing the pulse duration from 700 to 350 μs in Ho:YAG laser lithotripsy. We systematically evaluated a new commercially available Ho:YAG laser device with a novel effect function *in vitro*, which allows a real-time variation of pulse duration and pulse peak power, on fragmentation efficiency and retropulsion of phantom calculi.

2. Methods

The Ho:YAG laser has a wave-length of 2.1 μm, a maximum power output of 30 W, a pulse energy ranging from 0.5 to 3.5 J and a pulse rate ranging from 1 to 20 Hz (Sphinx jr.®, Lisa Laser, Katlenburg, Germany), respectively. It possesses a novel effect feature (range: 0–100%), which allows a simultaneous real-time variation of pulse duration (range: 700–900 μs) and pulse peak power (range: 4.6–18 kW). Once the settings are made, a real-time oscillogram at the display of the laser informs at glance about pulse energy, pulse rate, pulse peak power and pulse duration. A 365 μm optical core bare-ended, re-usable laser fibre (PercuFib®, Lisa Laser) was used for the experiments.

According to Wezel et al. [11], artificial stones with four different degrees of hardness (DH) were produced: Dr Kühns® dental stone (DH 1, concentration 3:1 [*w*/*v* in H_2O] in water, Ernst Hinrichs, Germany) and Plaster of Paris (DH 2, concentration 2:1 [*w*/*v* in H_2O]) were used to simulate soft stone composition, while Laborit® (DH 3, concentration 10:3 [*w*/*v* in H_2O], Ernst Hinrichs) and Fujirock® type 4 dental stone (DH 4, concentration 5:1 [*w*/*v* in H_2O], GC Europe, Belgium) were used as hard stone composition. For testing fragmentation efficiency, standardized cone-shaped stones were poured according to Wezel et al. [11]. Test tubes with a standardized volume of 1.5 mL were used to produce standardized cones for testing retropulsion (Fig. 1). The treatment of the artificial stones before and after the lithotripsy and retropulsion experiments (including measurements of the volume of the craters after lithotripsy experiments) was done according to Wezel et al. [11].

Fragmentation efficiency was compared at 5 (0.5 J/10 Hz), 10 (1 J/10 Hz), and 20 (2 J/10 Hz) W using variable adjustments of maximum pulse peak power and pulse duration by choosing four different settings of the effect feature (25%, 50%, 75%, and 100%) applied to the four different stone compositions. According to Wezel et al. [11], the lithotripsy experiments were done in a water basin with the cone-shaped stones inside. 1000 J were applied in contact mode (hand-assisted) at each calculus on a surface area of 5 mm × 5 mm. Stones were fixed at their bottom to exclude retropulsion [11].

In a second step, designed to analyze retropulsion, an ureteral model according to Finley et al. [10] was used. Retropulsion was tested at 10 (1 J/10 Hz) and 20 (2 J/10 Hz) W using variable adjustments of maximum pulse peak power and pulse duration by choosing four different settings of the effect feature (25%, 50%, 75%, and 100%) applied to the four different stone compositions, respectively. The experimental set-up was according to Finley et al. [10] as follows: the phantom stones were placed inside an 8-cm clear polymer tube (inner diameter 12 mm), open on each end, and inscribed with distance markings. The tube was secured to the base of a water basin [10]. As Finley et al. [10] described, a stone phantom was placed into the tube at a starting point marked as zero for each trial. After each pulse, the stone was pushed

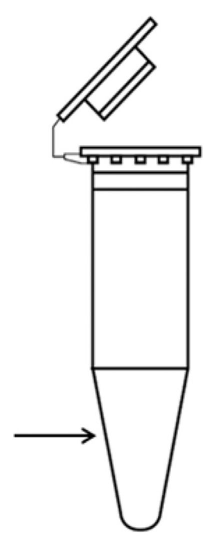

Figure 1 Test tubes with a standardized volume of 1.5 mL (black arrow) were used to produce standardized cones for testing retropulsion.

Table 1 Fragmentation efficiency at variable effect feature settings (variation of pulse peak power and pulse length) (in mm^3) at 5 W (0.5 J/10 Hz).

Effect feature (%)	25	50	75	100	p-value	Increase (%)
Pulse peak power (kW, range)	4.6–5.2	5.2–6.5	5.2–6.8	6.9–7.4	(25% *vs.* 100%)	(25% *vs.* 100%)
Pulse length (μs)	90	90	90	80		
Stone composition[a]						
DH 1	112.6 (74.1–148.6)	174.0 (110–238.5)	258.2 (208.7–360.4)	274.0 (189.2–359.7)	≤0.019	143.3
DH 2	106.8 (87.7–122.8)	145.8 (101.9–178.7)	174.8 (137.1–196.2)	207.0 (142.6–238.0)	≤0.023	93.8
DH 3	50.0 (43.6–57.6)	55.2 (43.2–64.0)	64.8 (48.7–77.4)	65.2 (40.2–96.3)	0.329	30.4
DH 4	45.2 (37.1–49.6)	46.8 (41.7–50.2)	54.8 (38.0–85.1)	59.4 (40.9–71.4)	0.104	31.4

[a] Data indicated as median (interquartile range); DH, degree of hardness.

distally, and the laser fibre was advanced until a total of 100 J were administered onto the stone in contact mode (hand-assisted). The maximum distance to the zero line was recorded (in cm). Each stone was used for one trial only.

Primary outcomes were the measurements of the volume of the craters (mm^3) and the distance of retropulsion (cm) after Ho:YAG laser lithotripsy. A minimum of five measurements were carried out for all Ho:YAG laser settings and all types of artificial stones. As pulse duration and pulse peak power show slight variations at each laser pulse, the range of pulse duration and pulse peak power during each trial at each power setting was recorded from the display of the laser device (Tables 1–5). Statistical analysis was performed using SPSS v11.5.1 (SPSS Inc., Chicago, IL, USA). Statistical data are presented as median (interquartile range). The data were analyzed using unpaired t-tests. A p-value < 0.05 was considered statistically significant.

3. Results

3.1. Stone fragmentation

An increase of the effect feature (25% *vs.* 100%) improved stone fragmentation significantly especially in soft artificial calculi (DH 1/2, $p \leq 0.023$) at 5 W, while there was a trend in hard stone composition (DH 3/4) for improved fragmentation efficiency with an increase of the effect feature at 5 W (Table 1). These results for soft and hard stone composition could be confirmed at 10 and 20 W, respectively (Tables 2 and 3).

3.2. Retropulsion

In the ureteral model, an increase of the effect feature (25% *vs.* 100%) resulted in significant greater retropulsion in hard stone composition (DH 3/4, $p \leq 0.016$) at 10 and 20 W, indicated by a longer distance measured after application of 100 J (Tables 4 and 5). A very similar pattern was observed for soft stone composition (DH 1, $p \leq 0.003$) at 10 (1 J/10 Hz) and 20 (2 J/10 Hz) W (Tables 4 and 5).

4. Discussion

The Ho:YAG laser has become the standard lithotrite for ureteroscopy (URS) during the past two decades. Fragmentation efficiency and stone retropulsion during Ho:YAG laser lithotripsy depend on power settings, pulse length, fibre type, and stone composition [7–11]. Sea et al. [12] found that increased pulse energy settings produce increased total fragmentation but also increased

Table 2 Fragmentation efficiency at variable effect feature settings (variation of pulse peak power and pulse length) (in mm^3) at 10 W (1 J/10 Hz).

Effect feature (%)	25	50	75	100	p-value	Increase (%)
Pulse peak power (kW, range)	6.2–6.8	7.7–8.6	9.2–10.2	11.1–12.9	(25% *vs.* 100%)	(25% *vs.* 100%)
Pulse length (μs, range)	150–170	120–130	90–110	90–100		
Stone composition[a]						
DH 1	54.4 (42.8–72.4)	57.0 (53.7–69.9)	87.2 (72.5–137.7)	107.4 (102.2–146.4)	≤0.012	97.4
DH 2	50.3 (44.5–57.9)	55.3 (49.6–70.6)	77.9 (58.8–85.8)	83.3 (65.6–87.0)	≤0.013	65.6
DH 3	26.8 (24.4–29.2)	28.1 (25.7–30.7)	34.5 (33.0–41.8)	48.2 (30.8–68.2)	0.085	79.9
DH 4	19.6 (14.9–24.0)	22.0 (19.2–28.7)	22.5 (20.6–24.45)	29.0 (24.2–39.2)	0.100	48.0

[a] Data indicated as median (interquartile range); DH, degree of hardness.

Table 3 Fragmentation efficiency at variable effect feature settings (variation of pulse peak power and pulse length) (in mm^3) at 20 W (2 J/10 Hz).

Effect feature (%)	25	50	75	100	*p*-value	Increase (%)
Pulse peak power (kW, range)	7.5–7.8	9.9–10.4	12.3–12.9	14.6–15.2	(25% *vs.* 100%)	(25% *vs.* 100%)
Pulse length (μs, range)	290–300	190–230	160–180	140–150		
Stone composition[a]						
DH 1	54.1 (43.2–77.2)	94.9 (62.2–105.2)	118.0 (89.2–129.6)	131.1 (109.6–147.1)	≤0.004	142.3
DH 2	94.4 (72.2–118.4)	104.8 (80.8–138.0)	111.2 (104.0–120.1)	113.5 (111.0–130.8)	0.150	20.2
DH 3	36.6 (31.0–42.0)	41.7 (40.5–48.1)	48.4 (38.9–57.4)	53.4 (51.2–56.3)	≤0.004	45.8
DH 4	42.8 (36.0–50.0)	44.6 (34.1–53.6)	46.3 (41.6–54.9)	50.1 (39.7–64.9)	0.346	17.1

[a] Data indicated as median (interquartile range); DH, degree of hardness.

retropulsion. However, since maximum energy settings during Ho:YAG laser lithotripsy are limited by laser and fibre construction [14–16], and stone composition is predetermined by the patient, modification of pulse duration may be one determinant to improve Ho:YAG laser fragmentation efficiency. We evaluated the *in vitro* performance of a Ho:YAG laser device featuring a novel effect function, which allows a real-time modification of pulse duration and pulse peak power. No studies up to date have specifically addressed the impact of this feature on fragmentation efficiency and retropulsion during Ho:YAG laser lithotripsy.

In this series, an increase of the effect feature (25% *vs.* 100%), i.e., a relative increase of pulse peak power and decrease of pulse duration, improved Ho:YAG laser fragmentation efficiency at 5 (0.5 J/10 Hz), 10 (1 J/10 Hz), and 20 (2 J/10 Hz) W. However, the variation of pulse duration using the effect feature does not directly allow to predict the level of the expected pulse peak power and vice versa. The effect of increasing the effect feature improved stone fragmentation especially in soft artificial stones, while there was a trend in hard artificial stones for improved fragmentation efficiency with an increase of the effect feature. Our findings, an improved fragmentation efficiency with relatively shorter pulse durations and higher pulse peak power at different power settings, are in accordance with those of Wezel et al. [11], although their results were more pronounced than in our study. These differences in fragmentation efficiency might be due to lower differences of the pulse durations (maximum difference 140 *vs.* 300 μs) at the 25% and 100% setting of the effect feature in this series when compared to Wezel et al. [11] (700 *vs.* 350 μs).

In contrast, Lee et al. [8] and Finley et al. [10] found in an *in vitro* ureteral model that retropulsion can be reduced in Ho:YAG lithotripsy using longer pulse durations (700 *vs.* 350 μs) without compromising fragmentation efficiency. The maximum efficiency of fragmentation in their ureteral model was seen using the 200 μm fibre at a 700 μs pulse length [8]. In a second experiment that mimiced intracaliceal stones, they found that there were no differences in fragmentation efficiency at both pulse lengths using the 200 μm fibre, while fragmentation efficiency at 700 μs pulse length was significantly higher compared to a 350 μs pulse length using the 400 μm fibre [10]. Although the energy density (J/cm^2) determines Ho:YAG fragmentation efficiency [7], these results confirm that an increase of the laser fibre diameter is not necessarily associated with improved fragmentation efficiency [8,10,11]. These different results were presumably also caused by differences between manufacturer's laser and fibre construction, which has not been tested in our study using only one laser fibre. In addition, Lee et al. [8] and Finley et al. [10] did not fully exclude retropulsion when testing fragmentation efficiency at different pulse durations: retropulsion was limited but still possible within a range of few millimetres as Wezel et al. [11] observed. In this series, larger phantom stones were fixed to exclude retropulsion using an established experimental set-up [11]. Finally, the use of a 400 μm fibre in a caliceal model may have practical limitations: thinner laser fibers are preferred affecting the

Table 4 Effect of variation of maximum pulse peak power and pulse length on retropulsion (in cm) at 10 W (1 J/10 Hz).

Effect feature (%)	25	50	75	100	*p*-value
Pulse peak power (kW, range)	6.2–6.8	7.7–8.6	9.2–10.2	11.1–12.9	(25% *vs.* 100%)
Pulse length (μs, range)	150–170	120–130	90–110	90–100	
Stone composition[a]					
DH 1	1.6 (1.4–2.0)	1.7 (1.5–2.1)	2.0 (2.0–2.3)	2.4 (2.2–2.5)	≤0.001
DH 2	1.5 (1.2–1.8)	1.7 (1.6–1.8)	1.5 (1.4–1.6)	1.7 (1.6–1.7)	0.306
DH 3	1.6 (1.4–1.8)	1.7 (1.6–2.1)	1.7 (1.6–2.7)	2.0 (1.8–2.2)	≤0.016
DH 4	1.0 (1.0–1.2)	1.2 (1.0–1.2)	1.5 (1.4–1.6)	1.7 (1.6–1.8)	≤0.001

[a] Data indicated as median (interquartile range); DH, degree of hardness.

Table 5 Effect of variation of maximum pulse peak power and pulse length on retropulsion (in cm) at 20 W (10 Hz/2 J).

Effect feature (%)	25	50	75	100	*p*-value
Pulse peak power (kW, range)	7.5–7.8	9.9–10.4	12.3–12.9	14.6–15.2	(25% *vs.* 100%)
Pulse length (μs, range)	290–300	190–230	160–180	140–150	
Stone composition[a]					
DH 1	1.9 (1.7–2.0)	2.0 (2.0–2.2)	2.1 (2.0–2.2)	2.3 (2.3–2.4)	≤0.003
DH 2	2.0 (1.7–2.4)	2.2 (2.1–2.4)	2.2 (2.0–2.6)	3.0 (2.6–3.4)	≤0.017
DH 3	1.2 (1.0–1.2)	1.5 (1.2–1.8)	1.7 (1.4–2.1)	3.0 (2.5–4.4)	≤0.007
DH 4	1.1 (1.0–1.2)	1.3 (1.1–1.3)	1.4 (1.3–1.5)	1.7 (1.6–2.0)	≤0.005

[a] Data indicated as median (interquartile range); DH, degree of hardness.

deflectability of flexible renoscopes only minimally as Michel et al. [14] stated.

One disadvantage during Ho:YAG laser lithotripsy is retropulsion [10], which has been demonstrated to depend on total pulse energy output and fibre diameter [17,18]. In our ureteral model, an increase of the effect feature, i.e. a relative increase of pulse peak power and decrease of pulse length, resulted in significant greater retropulsion in hard and in soft stone composition. Our studies confirmed prior findings that shorter pulse durations induced higher retropulsion than longer pulse durations [8,10,17,18]. Theoretically, retropulsion increases continuously during Ho:YAG laser lithotripsy due to concomitant loss of stone mass in our ureteral model and *in vivo*. In this series, the loss of stone mass observed during the retropulsion experiments was insignificant, since the transmitted energy was limited to 100 J and each stone was only used for one trial. In addition, cone stones were used to reduce retropulsion due to an increased dynamic and static friction when compared to spheric stones [8,10].

One limitation of this study was the difference of composition of phantom stones compared to urinary calculi. Human calculi might differ with regard to stone density, size, mass and stone composition within one stone and between different stones in the urinary tract. On the other hand, phantom stones can be easily reproduced with uniform charcteristics (i.e. defined mass, size, and density), and these invariable characteristics qualify them as an adequate model to study Ho:YAG laser lithotripsy as previously stated [8,10,11,19]. Our study confirms the findings by Teichman et al. [4] and Wezel et al. [11] that Ho:YAG fragmentation efficiency varies with stone composition, since stone disintegration has been increased from hard to soft artificial calculi using DH 1/2 and DH 3/4 stones as a proxy for soft and hard stone composition, respectively. These differences in fragmentation efficiency of different stone composition have been currently shown by analysing single pulse ablation crater volumes of urinary acid, calcium oxalate monohydrate and magnesium ammonium phosphate hexahydrate stones at 0.2, 0.5, 1, and 2 J [12]. Sea et al. [12] recommended to use higher pulse energy settings (higher than 0.2 J) in hard stone composition. However, despite the difficulties to define a subthreshold radiant exposure for pulse energy in hard stone composition (DH 3/4), pulse energy settings higher than 1 J resulted in an appropriate fragmentation efficiency in this series. We could confirm the results of Wezel et al. [11], that an increase of fragmentation efficiency due to the use of relatively higher pulse peak power and shorter pulse durations could be validated independently of stone composition, although this increase was more pronounced in soft than in hard stones.

The novel effect function of the tested Ho:YAG laser device may enhance Ho:YAG laser fragmentation efficiency, when the maximum power output is limited due to the ureteroscopic approach or the used laser fibre. The urologist may then adapt the Ho:YAG laser by modifying the effect function specifically to intraoperative findings: i.e. a relative increase of pulse peak power and reduction of pulse duration can be used to enhance fragmentation efficiency by raising the effect function in cases of large stone burden, a relative reduction of pulse peak power and an increase of pulse duration may be helpful in small, floating stones to minimize retropulsion by decreasing the effect function, respectively [11]. On the other hand, ureteral retrieval and ureteral occlusion devices have been shown to eliminate retropulsion and to improve fragmentation across all pulse widths and fibre sizes [8,12].

5. Conclusion

An increase of the effect function, a decrease of pulse duration and an increase of pulse peak power, leads to increased stone fragmentation in non-floating stones, most prominently in soft stone composition. On the other hand, an increased retropulsion can be observed by raising the effect function *in vitro*. This novel effect function of the Ho:YAG device may enhance Ho:YAG laser fragmentation efficiency when maximum power output is limited or retropulsion is excluded.

Conflicts of interest

The authors declare no conflict of interest.

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