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Original Article

A method for reducing thermal injury during the ureteroscopic holmium laser lithotripsy

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Holmium laser;
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Thermal injury

Abstract *Objective:* Many studies have demonstrated the heat effect from the holmium laser lithotripsy can cause persistent thermal injury to the ureter. The purpose of this study was to elucidate the use of a modified ureteral catheter with appropriate firing and irrigation to reduce the thermal injury to the "ureter" during the ureteroscopic holmium laser lithotripsy *in vitro*.
Methods: An *in vitro* lithotripsy was performed using a modified catheter (5 Fr) as the entrance for the irrigation and the holmium laser fiber while using the remaining space in the ureteroscopic channel as an outlet. Different laser power settings (10 W, 20 W, and 30 W) with various firing times (3 s, 5 s, and 10 s) and rates of irrigation (15 mL/min, 20 mL/min, and 30 mL/min) were applied in the experiment. Temperature changes in the "ureter" were recorded with a thermometer during and after the lithotripsy.
Results: During the lithotripsy, the local highest mean temperature was 60.3 °C and the lowest mean temperature was 26.7 °C. When the power was set to 10 w, the temperature was maintained below 43 °C regardless of laser firing time or irrigation flow. Regardless of the power or firing time selected, the temperature was below 43 °C at the rate of 30 mL/min. There was a significant difference in temperature decrease when continuous 3 s drainage after continuous firing (3 s, 5 s, or 10 s) compared to with not drainage ($p<0.05$) except for two conditions of 0.5 J×20 Hz, 30 mL/min, firing 5 s, and 1.0 J×10 Hz, 30 mL/min, firing 5 s.
Conclusion: Our modified catheter with timely drainage reducing hot irrigation may significantly reduce the local thermal injury effect, especially along with the special interrupted-time firing setting during the simulated holmium laser procedure.

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1. Introduction

Although the current popular ureteroscopic holmium laser lithotripsy has become an important method for the clinical treatment of ureteral calculi, it can also result in many problems to patients. It has been reported that holmium laser lithotripsy is more likely to lead to ureteral stricture than pneumatic lithotripsy [1]. The holmium laser is a pulsed laser with a wavelength of 2.1 μm. The energy vaporizes the water between the end of the fiber and the stone, forming tiny vacuoles that transmit the energy to the stone and shatter it [2]. Although the depth of holmium laser radiation is from 0.5 mm to 1.0 mm, the local heat generated by the holmium laser can still cause thermal damage to the ureteral mucosa and submucosa. Local temperature can lead to protein or enzyme degeneration to tissue necrosis, especially local fibrosis and stenosis formation [3]. Using an experimental model *in vitro*, Liang et al. [4] described that different operating parameters would generate different temperatures in the ureter during ureteroscopic holmium lithotripsy and proposed low-power lithotripsy to reduce thermal damage. Winship et al. [5] demonstrated judicious use of irrigation, limited activation time, and adequate laser activation intervals can reduce the risk of thermal injury when performing laser lithotripsy during high-energy mode setting. However, the lack of an effective reflux mechanism when using semi-rigid ureteroscopic lithotripsy alone has been a problem for urologists. Thus, using the same experimental model as Liang's team, we performed 8/9.8 Fr semi-rigid ureteroscopic holmium laser lithotripsy using a modified catheter to see if it could reduce the temperature in the ureter and thus reduce the occurrence of thermal injury.

2. Materials and methods

2.1. Materials

Our modified ureteral catheter consisted of a 5 Fr ureteral catheter (Huamei Medical Instrument Company, Zhangjiagang, China), a needle of a 50 mL syringe, a spiral cap (Nitinol Tipless Stone Extractor, Bloomington, IN, America), and a medical three-way rotary valve (Becton Dickinson Company, Franklin Lake, NJ, America) (Figs. 1 and 2). By fixing the holmium laser fiber with the screw cap, we could easily and flexibly adjust the fiber to access stone during the procedure. After the completion of the *in vitro* simulation experiment, we conducted a preliminary clinical application. The principles of the Helsinki Declaration were followed in this study. The present study protocol was reviewed and approved by the Institutional Review Board of Taizhou Hospital of Zhejiang Province affiliated to Wenzhou Medical University (approval number: K20200801).

2.2. Steps and the flow diagram of irrigation

First, an *in vitro* model simulating ureteroscopic laser lithotripsy was established to monitor the changes in temperature in the ureter during and after laser lithotripsy (Fig. 3). A segment of ligated 20 Fr rubber tube was used to simulate human ureter with a stone. The stone was from a human pelvis cast stone (computed tomography value: 850 Hounsfield unit) which was roughly evenly divided into 12 small stones for our experimental testing. Next, the modified ureteral catheter was applied during the experiments

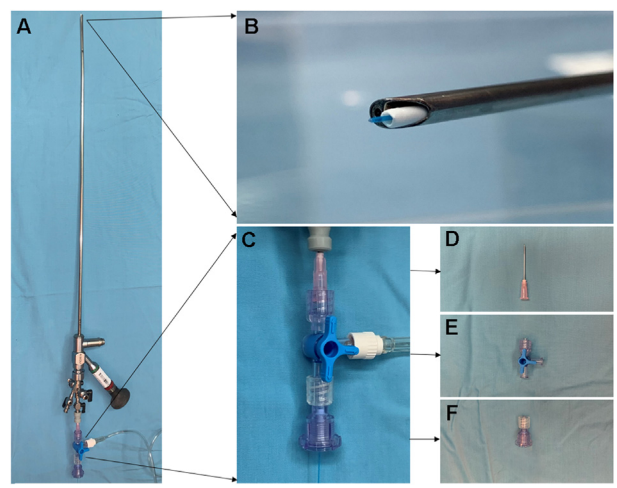

Figure 1 Flow chart of the assembly of a modified ureteral catheter. (A) The holmium laser fiber and the modified catheter in the ureteroscope; (B) Magnification of the modified catheter in the ureteroscope; (C) Magnification of the tail end of the modified catheter; (D) A 50 mL syringe needle; (E) A three-branch pipe; (F) A screw cap.

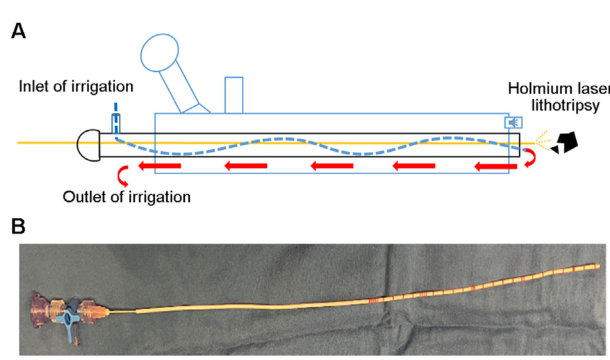

Figure 2 Schematic diagram of the flow of irrigation and the modified catheter in the ureteroscope. (A) The flow diagram of irrigation (the direction of the red arrows represented the outflow of hot irrigation); (B) The modified catheter.

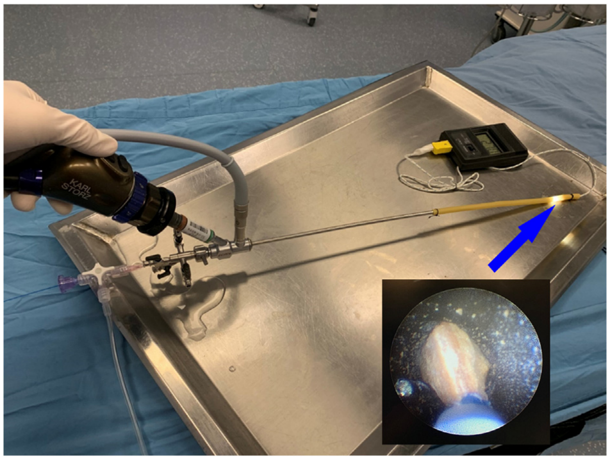

Figure 3 The ureteroscopic holmium laser lithotripsy performed using a 5 Fr modified catheter in a rubber tube. The region temperature was recorded by the thermocouple.

with the various power settings commonly used in our practice. Third, energy settings were at 0.5 J, 1.0 J, 1.5 J, and 2.0 J. Frequency settings of 10 Hz and 20 Hz were tested at different energy settings. Laser firing time was 3 s, 5 s, and 10 s. Fourth, a 200 μm holmium laser fiber and the flushing fluid (room temperature air conditioning around 26.6 °C) were passed through the modified catheter to the front head of the 8/9.8 Fr ureteroscope. The hot irrigation could be drained out through the remaining space in the operating channel (Fig. 2). The different irrigation flow rates (15 mL/min, 20 mL/min, and 30 mL/min) were employed by the peristaltic pump at room temperature. A local thermometer was placed on the side of the stone (5 mm from the bottom and approximately 2 mm lateral from the position of the laser tip) to record the local temperature.

2.3. Statistical analysis

The temperature for each power, flow rate, and firing time combination was recorded four times, and the mean values were calculated. Statistical software GraphPad Prism (version 8.0.2, GraphPad Software, CA, USA) was used for comparison between the drainage group and the not drainage group. The *t*-test was used for data of measurement. When *p*-value is less than 0.05, the difference was considered to be statistically significant.

3. Results

3.1. Temperature changes in the "ureter" during the ureteroscopic laser lithotripsy (firing 3 s, 5 s, and 10 s)

Through temperature monitoring, a large amount of heat energy was generated around the laser fiber tip during the ureteroscopic holmium lithotripsy process. The comparison of most sets of data showed that the ureter temperature presented the downward trend with the increase of the irrigation under a setting laser firing time and power. However, in a few data sets, the ureter temperature at first increased and then decreased with the increase of irrigation. Under the conditions of 2.0 J×10 Hz power and 15 mL/min irrigation flow, the laser was continuously fired for 10 s, and the peak temperature was 60.3 °C. Under the conditions of 1.0 J×10 Hz power and 30 mL/min irrigation flow, the lowest temperature was 26.7 °C after continuous firing for 10 s. When the power was set to 10 W (0.5 J×20 Hz or 1.0 J×10 Hz), the temperature was maintained below 43 °C regardless of laser firing time (3s, 5s, or 10s) or irrigation flow (15 mL/min, 20 mL/min, or 30 mL/min). Regardless of the power mode selected, the temperature measured at the irrigation of 30 mL/min was below 43 °C (firing 3 s, 5 s, and 10 s) (Table 1).

3.2. Temperature changes in the "ureter" when stopping the ureteroscopic laser lithotripsy

3.2.1. Drainage for 3 s and 5 s

All of the test results indicated that the temperature in the ureter is below 43 °C (safe temperature) after 3 s or 5 s of continuous drainage. Moreover, most results showed that the temperature in the ureter is close to or equal to room temperature after 5 s of continuous drainage. The maximum decline of temperature could reach 28.5 °C after 5 s of continuous drainage under the conditions of 2.0 J×10 Hz, 15 mL/min, and firing 10 s.

3.2.2. Drainage versus not drainage for 3 s

Under the conditions of 2.0 J×10 Hz, 20 mL/min, and firing 5 s, the maximum temperature difference was 0.7 °C when the valve was quickly closed to stop the drainage of the hot irrigation for 3 s. Under the conditions of 1.5 J×20 Hz, 15 mL/min, and firing 3 s, the maximum temperature difference was 22.0 °C when the valve was continually opened to drain the hot irrigation for 3 s. Further statistical analysis found that most of the results showed that the temperature difference between the drainage group and the not drainage group for 3 s was statistically significant regardless of the power, irrigation, or laser firing time ($p<0.05$) (Fig. 4). However, two special results showed that the temperature difference between the drainage group for 3 s and the not drainage group for 3 s was not statistically significant, respectively, under the conditions of 0.5 J×20 Hz, 30 mL/min, firing 5 s, and 1.0 J×10 Hz, 30 mL/min, firing 5 s (Fig. 4). The reason why there was no obvious difference in the intra-group comparison of results between these two groups was that we think the irrigation in this mode can keep the "ureter" at a relatively low temperature with less temperature variation during the tests.

3.3. Changes in vision during the ureteroscopic lithotripsy

In order to maintain a clear surgical vision, drainage of the irrigation could be performed by increasing the rate or stopping the lithotripsy intermittently.

Table 1 The local mean temperature varied with the laser working mode and irrigation flow rate.

Flow rate	Different power	Drainage situation	Change in temperature (°C)								
			3 s[a]	3s[b]	5s[b]	5 s[a]	3 s[b]	5s[b]	10 s[a]	3 s[b]	5 s[b]
15 mL/min	0.5 J×20 Hz	Drainage	36.5	26.6	26.6	31.2	28.7	26.8	32.3	28.9	28.0
		Not drainage		36.2	36.1		31.0	30.8		32.1	31.8
	1.0 J×10 Hz	Drainage	32.4	27.2	26.8	30.5	28.0	26.9	39.0	32.7	28.2
		Not drainage		32.3	31.9		30.0	29.8		38.5	38.2
	1.0 J×20 Hz	Drainage	36.7	29.8	26.8	45.0	32.6	27.9	43.7	32.7	28.6
		Not drainage		36.0	35.7		44.8	44.5		43.2	43.1
	2.0 J×10 Hz	Drainage	36.9	26.9	26.6	57.6	38.6	32.1	60.3	39.6	31.8
		Not drainage		36.6	36.3		57.4	57.3		60.1	60.1
	1.5 J×20 Hz	Drainage	55.6	33.6	31.9	58.2	39.2	31.8	59.9	39.1	32.3
		Not drainage		55.3	55.2		58.0	57.9		59.7	59.5
	3.0 J×10 Hz	Drainage	54.1	33.3	27.1	38.7	28.6	26.9	44.0	32.8	28.1
		Not drainage		53.9	53.7		38.5	38.4		43.9	43.8
20 mL/min	0.5 J×20 Hz	Drainage	34.7	32.1	28.9	36.9	31.6	29.4	37.0	32.7	30.1
		Not drainage		34.5	34.0		36.5	36.1		36.9	36.6
	1.0 J×10 Hz	Drainage	28.8	26.8	26.8	33.8	29.1	26.6	35.1	30.6	28.8
		Not drainage		28.6	28.2		33.3	33.1		34.7	34.2
	1.0 J×20 Hz	Drainage	38.9	31.2	28.2	35.6	28.7	26.8	41.7	33.1	28.1
		Not drainage		38.5	38.2		35.4	35.1		41.5	41.3
	2.0 J×10 Hz	Drainage	43.1	33.5	28.3	41.2	31.6	28.1	45.0	32.7	27.9
		Not drainage		43.0	42.8		40.5	39.9		45.0	44.8
	1.5 J×20 Hz	Drainage	44.7	30.7	27.2	48.2	36.7	31.2	52.3	37.8	31.5
		Not drainage		44.5	44.3		48.0	47.9		52.1	50.0
	3.0 J×10 Hz	Drainage	42.6	31.5	27.8	41.3	33.5	27.1	39.6	31.2	26.8
		Not drainage		42.4	42.1		41.0	40.8		39.4	39.1
30 mL/min	0.5 J×20 Hz	Drainage	27.8	26.8	26.8	27.1	26.9	26.6	26.7	26.6	26.6
		Not drainage		27.6	27.4		27.0	26.8		26.7	26.7
	1.0 J×10 Hz	Drainage	26.9	26.6	26.6	27.2	26.6	26.6	27.0	26.6	26.6
		Not drainage		26.9	26.7		26.7	26.7		27.0	26.8
	1.0 J×20 Hz	Drainage	35.4	29.1	26.7	36.5	27.9	27.0	36.1	28.2	27.3
		Not drainage		35.3	35.1		36.1	35.9		35.8	35.6
	2.0 J×10 Hz	Drainage	33.6	26.8	26.6	38.7	31.5	27.3	31.1	26.9	26.7
		Not drainage		33.5	33.1		38.4	38.2		30.7	30.5
	1.5 J×20 Hz	Drainage	34.5	28.1	26.9	37.4	31.6	28.6	38.8	30.4	26.9
		Not drainage		34.0	33.8		37.2	37.0		38.6	38.4
	3.0 J×10 Hz	Drainage	39.1	30.6	26.8	38.8	29.3	26.8	36.7	27.6	26.6
		Not drainage		39.0	38.8		38.6	38.4		36.5	36.3

[a] Firing time.
[b] Stop firing time.

4. Discussion

4.1. Ureteral stricture and thermal injury

The causes of ureteral stricture after ureteroscopy included duration of disease [6], stones' size and location [6,7], embedded stones [8,9], pneumatic ballistic lithotripsy [10], holmium laser lithotripsy [11], the flexible mirror sheath [12], and mechanical injury from ureteroscopic manipulation [13]. Many studies had shown that patients with impacted ureteral stones have a high incidence of ureteral stenosis [1,14]. The impacted ureteral stone was considered to be a major predictor of the development of stenosis. Postoperative scarring was usually caused by direct injury to the ureter during electrocoagulation, laser coagulation, or resection. Although the holmium laser had poor tissue penetration, there remained a risk of stricture from scarring of the ureter. A recent meta-analysis showed a relationship between a high incidence of ureteral stricture and the thermal effects of holmium laser [11]. The thermal injury stemmed from the holmium laser and was considered to be the overlooked etiology for ureteral stricture [4]. Perhaps the internal temperature change could not be directly observed during ureteroscopic holmium laser lithotripsy, we ignored its existence.

4.2. Analysis of temperature change and clinical implications

The principle of holmium laser lithotripsy suggests that a lot of heat is generated inevitably. The factors leading to the thermal effect of holmium laser lithotripsy include

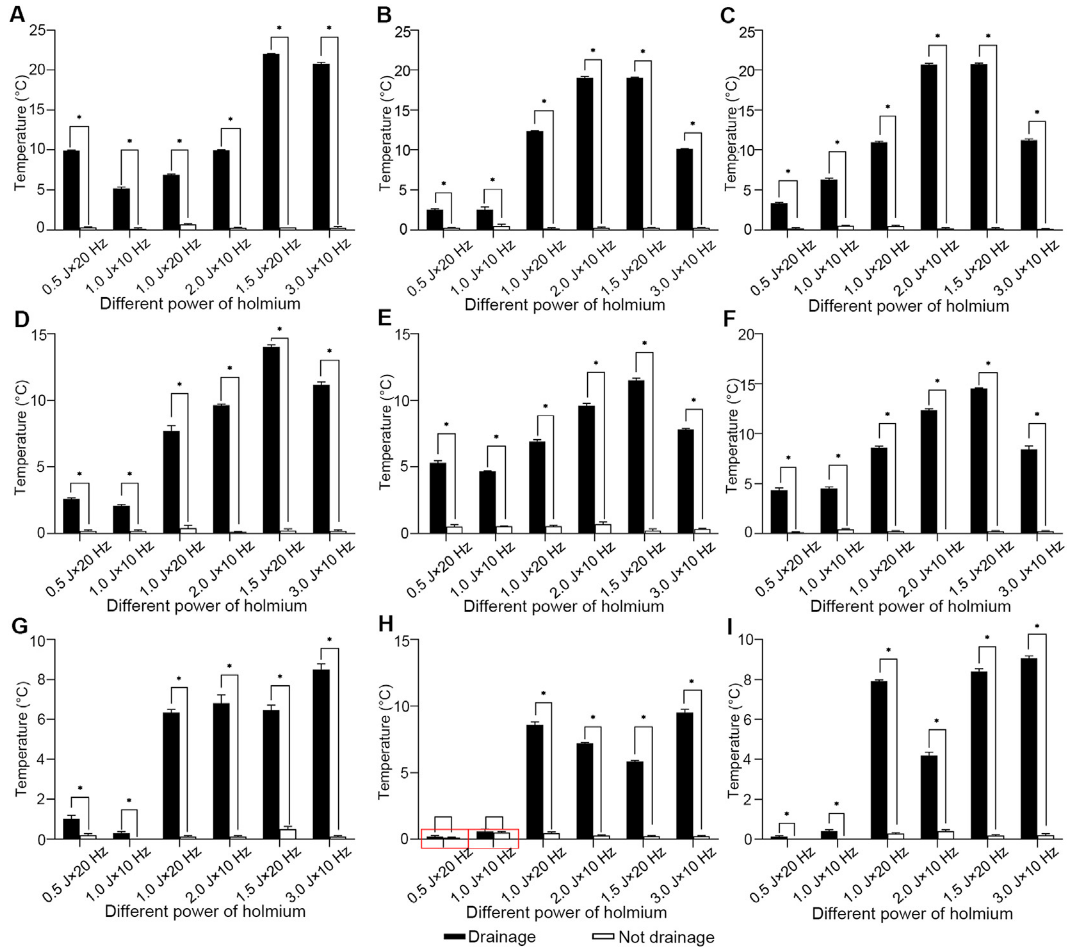

Figure 4 The temperature difference when stopping different power of ureteroscopic laser lithotripsy (stop firing 3 s) between drainage group and not drainage group. (A) Firing 3 s, and irrigation of 15 mL/min; (B) Firing 5 s, and irrigation of 15 mL/min; (C) Firing 10 s, and irrigation of 15 mL/min; (D) Firing 3 s, and irrigation of 20 mL/min; (E) Firing 5 s, and irrigation of 20 mL/min; (F) Firing 10 s, and irrigation of 20 mL/min; (G) Firing 3 s, and irrigation of 30 mL/min; (H) Firing 5 s, and irrigation of 30 mL/min, except for two conditions (red boxes, $p>0.05$, not significant); (I) Firing 10 s, and irrigation of 30 mL/min. * $p<0.05$.

energy and frequency, fiber diameter, infusion temperature, and lithotripsy mode. In order to reduce the ureteral temperature and the persistent occurrence of thermal injury, the remaining space in the ureteroscopy passage was used to drain the hot irrigation. The maximum temperature measured in our study was lower than that measured in the study of Liang's team [4], which might indicate that drainage of the hot irrigation is effective. When the power was set to 10 W, which is often used in clinical practice, the temperature was maintained below 43 °C regardless of laser firing time or irrigation flow. When further clinical research is needed, this power may give us a reference value for clinical practice. When the valve was closed to stop drainage of the hot irrigation, we found that the temperature in the ureter decreased slowly, which led to continuous thermal injury. It was already known that once the temperature exceeded the "threshold" (43 °C), it could lead to cell damage, protein coagulation, and tissue injury, which subsequentially progresses to scar formation and ureteral stricture [5]. When the valve was opened to drain the hot irrigation, the temperature around the laser fiber tip dropped rapidly. After 3 s or 5 s of continuous drainage, the temperature in almost all tests was below 43 °C. Especially after 5 s of continuous drainage, most of the measured temperature was very close to 26.6 °C (room temperature at that time). Perhaps an intermittent 3 s or 5 s lithotripsy approach would help to significantly reduce persistent thermal injury. Our results also indicated that the temperature of the "ureter" increases with the increasing energy. Starting with low power is a good and safe way for us in clinical practice. For the speed of irrigation, our study showed that in most cases, the faster speed of the irrigation, the more obvious the temperature decrease trend at the same power and the same firing time. However, the temperature did not always drop from the highest temperature, and there was a process of continuous temperature increase followed by a drop, which we speculated may be caused by the fact that the composition of the stones used in the study is not uniform. Since most of the stones encountered in clinical work are of inconsistent composition, intermittent lithotripsy and drainage of hot irrigation is a very good option when it is not possible to increase the rate of irrigation indefinitely.

4.3. Advantages of the modified catheter

The idea of lithotripsy along with the designed modified catheter was derived from flexible ureteroscopic lithotripsy assisted by the ureteral sheath. There was a space between the flexible ureteroscope and the sheath, which facilitates the flow of the flushing fluid. In our design, we utilized the remaining gap between the catheter and the ureteroscopic operation channel to drain the hot irrigation. It might not only solve the problem of the lack of an effective reflux mechanism when using ureteroscopic lithotripsy alone but also might improve the efficiency of lithotripsy. As we all known, the flexible ureteroscope had the disadvantages of high cost, easy wear, and high maintenance cost; and it also needed the assistance of soft sheath in practical application. In particular, the commonly used outer diameter of the sheath is 13 Fr or 15 Fr, while the outer diameter of the normal ureter is only 9 Fr or 10 Fr. The ureteroscope soft sheath should be carefully placed to avoid ureteral wall tearing, perforation, or even renal bleeding [15]. In contrast, the materials used in our study are commonly available, inexpensive, and easily assembled. During the procedure, the modified catheter was placed inside the ureteroscope with unoccupied ureter piping space.

For the catheter type selection, Wu et al. [16] demonstrated ureteroscopic lithotripsy under negative pressure with using a 5 Fr ureter catheter, which is a simple and safe method for the treatment of ureteral calculi. According to the formula (irrigation = flow rate × [inner diameter of pipeline × inner diameter of pipeline × π ÷ 4]), at the same irrigation and firing time, the larger the diameter of the catheter was, the more fluid it passed through. More irrigation would reduce holmium laser's thermal effect. The ureteroscope (8/9.8 Fr) instructions could operate through one 5 Fr device or two 3 Fr devices; therefore, the maximum operating space was usually limited to under 6 Fr in size. Therefore, when a 6 Fr or larger ureteral catheter was used, there was almost no space between the catheter and the operation channel of the ureteroscope, which was difficult for the hot irrigation to flow out from this space. In theory, the 5 Fr ureteral catheter we used had better irrigation than the 4 Fr ureteral catheter and better drainage than the 6 Fr ureteral catheter. During the lithotripsy, the endoscopic field of view was clear in using a 5 Fr ureteral catheter which could reduce the chance of injury to the ureter from the holmium laser.

4.4. The attempt of clinical application

The calculi may completely block the ureter in some cases of incarcerated ureteral calculi, which was difficult to push off from the original position. It was also difficult to pass through the margin space of the calculi to drain into the renal pelvis in conventional lithotripsy. We used intermittent firing holmium laser lithotripsy on the above condition (Supplementary Video 1). From the video, we could see that the hot irrigation, stone powder, bubbles, and bleeding produced during the lithotripsy can be easily discharged from the gap between the catheter and the ureteroscope. It improved the procedure efficiency by ensuring a clear view under the endoscope.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.ajur.2022.05.011

4.5. Limitations

Although the rubber catheter has the characteristics of corrosion resistance, heat resistance, and pressure resistance, it is relatively safe for us to use it for experiments *in vitro*. However, it could not simulate the real human ureter; therefore, our results were different from those of humans. The different types of thermometers may affect the results due to their different sensitivity and precision. In our study, we consistently used the same mode of thermometers with regular calibration. Regulating inside pressure of the ureter via negative pressure suction equipment may improve the irrigation during testing, we may investigate this strategy in future providing related specific irrigation parameters.

5. Conclusion

Our modified catheter with timely drainage reducing hot irrigation may significantly reduce the local thermal injury effect, especially along with the special interrupted-time firing setting during the simulated holmium laser procedure. We expect this strategy can reduce persistent thermal injury to the ureter during ureteroscopic laser lithotripsy. For these assembly materials, surgeons are easy to find in their daily work, simple to assemble, and easy to master.

Author contributions

Study concept and design: Xiaoliang Zhu, Haihong Jiang.
Data acquisition: Xiaoliang Zhu, Feiping Li, Haiping Li.
Data analysis: Xiaoliang Zhu, Xixi Hu, Haiping Li, Songjiang Wu.
Drafting of manuscript: Xiaoliang Zhu, Haihong Jiang.
Critical revision of the manuscript: Haihong Jiang.

Conflicts of interest

The authors declare no conflict of interest.

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