Published in final edited form as:

J Pediatr Urol. 2020 October ; 16(5): 626.e1–626.e8. doi:10.1016/j.jpuro.2020.07.014.

A Simulated Model for Fluid and Tissue Heating During Pediatric Laser Lithotripsy

Jonathan S Ellison, MD¹, Brian MacConaghy², Timothy L. Hall³, William W. Roberts^{3,4}, Adam D. Maxwell^{2,5}

¹Department of Urology, Medical College of Wisconsin

²Center for Industrial and Medical Ultrasound, Applied Physics Laboratory, University of Washington

³Department of Biomedical Engineering, University of Michigan

⁴Department of Urology, University of Michigan

⁵Department of Urology, University of Washington School of Medicine

Summary

Background: Laser lithotripsy (LL) is a common modality for treatment of children and adolescents with nephrolithiasis. Recent introduction of higher-powered lasers may result in more efficacious “dusting” of urinary calculi. However, *in vivo* animal studies and computational simulations have demonstrated rapid and sustained rise of fluid temperatures with LL, possibly resulting in irreversible tissue damage. How fluid and tissue heating during LL vary with pediatric urinary tract development, however, is unknown. We hypothesize that kidneys of younger children will be more susceptible to changes in fluid temperature and therefore tissue damage than those of older children.

Methods: Computational simulations were developed for LL in children utilizing COMSOL Multiphysics finite-element modeling software. Simulation parameters were varied, including the child’s age (3, 8, and 12 years), flow of irrigation fluid (gravity – 5 mL/min or continuous pressure flow – 40 mL/min), treatment location (renal pelvis, ureter, calyx), and power settings (5W–40W). Using a simplified axisymmetric geometry to represent the collecting space, the model accounted for heat transfer via diffusion, convection, perfusion, and heat sourcing as well as tissue properties and blood flow of the urothelium and renal parenchyma. Laminar and heat-induced convection flow were simulated, assuming room-temperature ureteroscopic irrigation. Renal size was varied by age, based on normative values. The maximum fluid temperature after 60 seconds of simulated

Corresponding Author: Jonathan S Ellison, jellison@chw.org, 414-337-7316, 999 N 92nd St, Suite 330, Milwaukee WI 53226, Twitter: @jon_ellison.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Conflict of Interest Statement: JSE and TH have no relevant conflicts of interest. WWR is a consultant for Boston Scientific. BM and AM have equity and consulting arrangements with SonoMotion, Inc. None of the authors has any conflicts of interest related to this work to disclose.

LL was captured. Thermal dose was calculated using the t_{43} equivalence of 240 minutes as a threshold for tissue damage, as was tissue volume at risk for irreversible cellular damage.

Results: Simulation with gravity flow irrigation revealed generation of thermal doses sufficient to cause tissue injury for all ages at 20W and 40W power settings. Higher temperatures were seen in younger ages across all power settings. Temperature increases were dampened with intermittent laser activity and continuous pressure flow irrigation..

Conclusions: Smaller renal size is more susceptible to thermal changes induced by LL. However, power settings equal to or greater than 20 W can result in temperatures high enough for tissue damage at any age. Continuous pressure flow and intermittent laser activity may mitigate the potential thermal damage from high power LL.

Graphical Abstract

Summary Figure: Max temperature (°C) at 5 mL/min flow in the ureter (A), renal pelvis (B), and renal calyx (C)

Keywords

holmium laser; temperature; lithotripsy; ureteroscopy; pediatrics

Introduction:

Ureteroscopy is the most common modality for treatment of upper tract urinary calculi in the pediatric population.[1, 2] Benefits of ureteroscopic lithotripsy include direct visualization of the calculus, which can then be fragmented and removed or treated to sub-clinical fragments with higher-powered “dusting” or “pop-dusting” techniques.[3] Additionally, the holmium laser delivers energy directly to the calculus, as opposed to shock wave lithotripsy which transmits across the renal parenchyma. [4] Thus, laser lithotripsy is believed to place

the kidney at low risk for direct injury, provided direct contact to the urothelium is avoided during treatment.

However, recent *in vitro*, *in vivo*, and simulation studies have shown dramatic rises in intra-renal temperature during laser lithotripsy.[5, 6] The mechanism for this rapid temperature rise is based in the physical characteristics of the holmium energy source. The 2100 nm wavelength of the holmium laser is readily absorbed by water, resulting in local vaporization and creation of vapor bubbles.[7] While this bubble creation is important to the mechanism of lithotripsy, the by-product of this absorption is heat generation in adjacent fluid, stone, or tissue, which results in a temperature rise that could place the renal tissues at risk for thermal injury.[8] Importantly, this fluid absorption occurs even during treatment of the stone itself, a phenomenon which is the basis for the MOSES™ laser system. [9] As such, fluid heating from the application of the holmium laser would be expected to occur even while the stone itself is being treated.

The thermal effect of laser lithotripsy has yet to be characterized across the range of renal sizes naturally occurring during normal renal growth during childhood and adolescence. As ureteroscopic laser lithotripsy becomes more common in even the youngest patient populations, it is important to assess the impact of this technology within smaller intraluminal spaces, where heat dissipation may be restricted. We created a computational model for thermal energy dissipation during laser lithotripsy based on prior *in vitro* studies, simulating clinical scenarios varying by age-adjusted renal size, laser energy settings, and irrigation flow. We hypothesized that the model would show kidneys of younger children to be more susceptible to changes in fluid temperature and therefore tissue damage than those of older children and that this modeled effect could be mitigated by fluid irrigation and intermittent laser activity.

Methods

This study is not human research; no institutional review board approval was necessary.

Model Assumptions

We utilized COMSOL Multiphysics finite-element modeling software (COMSOL, Burlington, MA) to develop computational simulations for laser lithotripsy in children. The model uses a simplified axisymmetric geometry to represent the ureter, renal pelvis, and renal calyx. The model simulates bioheat transfer through physical interactions including diffusion, convection, perfusion, and heat sourcing as well as tissue properties and blood flow of the urothelium and renal parenchyma. This simulation has been previously validated against *in vitro* and *in vivo* experiments.[5, 10] Laminar, heat-induced convective flow are simulated by the model, assuming room-temperature irrigation through the working channel of a ureteroscope. Thermal properties of the holmium laser and urothelial tissue were acquired from literature data and included in Table 1.

Model Variables

Age-based renal size (3, 8, 12 years), irrigation flow rates (0, 5, 40 mL/min), anatomic location of lithotripsy (renal pelvis, ureter, calyx), and holmium laser energy settings (5 –

40W) were adjusted between simulations. The renal pelvis was shaped in simulation as a spherical fluid-filled chamber with cylindrical tube extending from one side to model the ureter. The urinary tract was lined with a 1-mm wall of urothelium. Kidney parenchymal tissue surrounded the collecting system and ureter wall. For renal pelvic calculi, the laser and irrigation were modeled to be located at the ureteropelvic junction. For ureteral calculi, the model was simulated in the same geometric configuration as the renal pelvis. However, for the ureteral simulation, the laser location was modeled 3.5 cm distal to the ureteropelvic junction and the irrigation source modeled 5 mm distal to the laser. The calyx was modeled as a cylinder with a thin urothelial wall which terminated with a hemispherical end rather than a larger spherical end as was modeled in the renal pelvis simulation.

To account for changes in renal size with age, physical dimensions for kidneys were approximated from published literature measurements in children and adults captured by urography, ultrasound, CT or MRI.[11–13]. The renal length-age relationship is relatively linear for children 3 years of age or greater. Accordingly, dimensions of the ureter, renal pelvis, and renal calyx were linearly scaled using adult measured dimensions as a reference. (Supplemental Table).[12, 14, 15]

Simulation of Laser Lithotripsy

The simulation was initiated at standard body temperature of 37°C, with room-temperature (22° C) irrigation introduced for 20 seconds prior to continuous lithotripsy. Laser activation was continued for 60 seconds followed by an additional 40 seconds of room-temperature irrigation. Intra-luminal and tissue temperature were recorded throughout the model every tenth of a second at each spatial location within the model.

Prior *in vitro* work has established irrigation flow rates of 5 mL/min to be equivalent to 40 cm H₂O (i.e. a saline bag elevated to 40 cm above the patient flowing by gravity) and 40 mL/min to be equivalent to 300 cm H₂O (i.e. a pressurized irrigation bag) which was simulated in a continuous (as opposed to intermittent) fashion.[16] Holmium laser settings were chosen to represent a range of typical settings for laser lithotripsy, including higher energy settings to represent “dusting” and “pop-dusting” energy ranges.

Acknowledging that continuous firing of the laser for a full 60 seconds is unrealistic in clinical care, simulations to reflect more realistic treatment parameters were also undertaken. The pattern of laser activation during lithotripsy has been termed the “operator duty cycle” and reflects a ratio of the time for laser activation on the stone and the time the laser is at rest throughout the treatment course. Aldoukhi et al prospectively measured the operator duty cycle for the highest laser activation to be 72%, indicating that over a 60 second period of time, the laser would be activated for 43 seconds.[17] Anticipating some variation on operator duty cycle across surgeons, we chose a more conservative operator duty cycle for 50% over a 60 second period with a 5 seconds “on”/5 seconds “off” pattern of laser activity to assess the impact of intermittent laser firing on thermal energy distributions during laser lithotripsy.[18] This cycle was modeled using the 3 year old, 5 mL/min, 40W power settings to demonstrate the impact of operator duty cycle on situations with the greatest potential for thermal injury.

Estimation of Thermal Injury

Thermal dose was calculated using the t_{43} equivalence as a metric for tissue damage, which is commonly used for tissue viability in evaluation of hyperthermal or ablative effects.[19, 20] This metric provides a comparative equivalency for tissues exposed to varying temperature for differing lengths of time. The time interval to tissue injury based on thermal dose is reduced by half for each degree increase in temperature.[21] For example, kidney parenchyma is estimated to show initial signs of injury when elevated to 43°C for between 20 to 70 minutes, but would require only ~1 – 4 seconds at 53 °C.[22] For this study, we chose a conservative thermal dose threshold of $t_{43} = 240$ minutes, above which most tissues are considered to undergo irreversible thermal injury.[19] Based on this definition, tissue volume at risk for irreversible cellular damage was also calculated. Maximum temperature and thermal dose were approximated in the geometric models of the collecting system, as shown by example in Supplemental Figure.

Results:

Using a model assuming 5 mL/min of room temperature irrigation, maximum temperatures were predicted to be consistently higher with higher power settings. This trend was observed irrespective of location of treatment or patient age. Maximum temperature did not vary substantially across age groups within the ureteral location. For instance, at 40W power settings and 5 mL/min of irrigation, maximum temperatures were calculated to be 70.4° C for age 3 and 67.7° C for age 12 (Table 2). However, for both renal pelvis and calyceal locations, maximum temperature trended higher in the smaller kidneys within the model, especially at higher power settings. Within the calyx at 40W power settings and 5 mL/min of irrigation, maximum temperatures were calculated to be 110.5° C for age 3 and 95.1° C for age 12. Notably, treatment within renal pelvis and calyceal locations consistently displayed higher maximum temperatures as compared to the ureter. Maximum temperatures in the renal pelvis and calyces varied by age and laser settings, with the largest variation noted in the younger age group and highest power settings.

Thermal dose also varied in a similar fashion to maximum temperature for clinically-modified parameters within the model. Higher thermal dose was noted in renal pelvis and calyx, younger age groups, and higher power settings. When utilizing a t_{43} of greater than 240 minutes as a threshold to consider tissue at risk, all parameters with gravity flow (5 mL/min irrigation) and power settings ≥ 20 W resulted in thermal dose substantial enough to result in tissue damage (Table 2). Additionally, with 10W power settings within the renal calyx for the 3 and 8 year old models, the thermal dose was estimated to cross the threshold capable of inducing thermal injury. The calculated volume of tissue injury followed similar trends. The largest lesion volumes were noted in the 3 and 8 year old renal pelvis models at 40W, estimated at 2.71 cm³ and 2.72 cm³ respectively (Table 2).

When pressurized irrigation at 40 mL/min was introduced into the model, the heating effects of laser lithotripsy were predicted to be mitigated across all power settings, locations, and age ranges. For the renal pelvis and calyx, these predicted effects were more pronounced than the ureter, with maximum temperatures not exceeding 37 °C even at 40W, reducing maximum predicted temperature by up to 73° C as compared to the model with gravity flow

irrigation. Using pressurized irrigation, none of the simulated situations resulted in maximum predicted temperatures greater than 37° C. (Figure 1)

A 50% operator duty cycle also demonstrated mitigation of overall thermal parameters. Maximum temperature during intermittent laser activation was 63.5° C and oscillated in a saw-like pattern with nadir temperature of 54.1 °C until treatment cessation. Temperatures greater than 60 °C were noted after 25 seconds of intermittent laser activation. Calculated tissue at risk for intermittent laser activity was 1.2 cm³, which represents a 54% reduction in potential lesion volume as compared to continuous laser activity.(Figure 2)

Discussion

Herein we present a computational simulation modeling the effects and implications of fluid heat transfer during laser lithotripsy within the pediatric urinary tract. Our findings have several key themes. First, irrespective of location or patient age, higher power settings result in incrementally higher maximum temperatures, thereby exposing surrounding tissue to potential thermal damage. Second, while patient age appears to minimally impact the heat transfer within the ureter, there can be a substantial increase in maximum temperature and corresponding thermal dose to both the renal pelvis and calyx with younger age ranges in the model. This insight could have important implications as advanced dusting techniques and higher-powered laser models permeate the pediatric landscape.[23] Assessment of multiple mitigation strategies revealed opportunities to minimize risk of thermal damage even during settings which pose the greatest potential for thermal injury. Using pressurized room temperature irrigation appears to mitigate all thermal effects and throughout our models resulted in theoretically safe temperature profiles even at the highest power settings. Furthermore, models of an intermittent laser activation pattern, reflective of typical clinical practice, showed reduced maximum temperature exposure, though overall thermal parameters were not diminished to the degree of pressurized irrigation. As focus has shifted recently within the endourologic community to decreasing intra-renal pressure during ureteroscopy, defining the appropriate balance between pressurized flow and intra-renal pressure will be an important aspect of future study.

The introduction of higher-powered laser technology into the surgical marketplace has reinvigorated interest in the thermal exposure from these instruments within the renal collecting system. Recent *in vitro* and *in vivo* studies have revealed the risks of unchecked fluid heating during high-powered laser lithotripsy as well as the potential mitigating effects of pressurized irrigation on thermal parameters.[5, 6] Our study adds to this literature by demonstrating the influence of age and therefore renal size on thermal profiles during laser lithotripsy. Assessment of differential thermal effects throughout the urinary tract and within varying age ranges will be important for defining optimal treatment settings across age ranges. Interestingly, while greater thermal dose was noted in younger age ranges and different locations, the overall volume of tissue at risk did not necessarily increase in our model in a similar linear fashion. In fact, while the renal calyx model had the highest estimated thermal dose exposures across all parameters, the calculated volume of tissue damage associated with each of these models was less than the corresponding model in the renal pelvis. One potential reason for this result is the smaller overall surface area for tissue

considered at-risk within the smaller renal collecting system (for younger ages) or within a smaller portion of the renal collection system (for the renal calyx models). Conversely, however, it should be noted that a greater proportion of renal tissue (as indicated by percentage of volume at risk) may be exposed to higher thermal dose in younger patients. The variability in thermal dose based on treatment location is also notable within our study. The ureter was consistently exposed to lower thermal dose across age and power settings as compared to the renal pelvis and calyceal models. This effect could be due to heat diffusion along the ureter within the model.

Our study has several limitations worth discussing. First, these results represent computational modeling, as direct measurement of heating effects and subsequent tissue damage would be difficult if not impossible to replicate during actual laser lithotripsy. However, these models are based off of detailed information gained from *in vivo* and *in vitro* simulations, and thus are consistent with and validated by empiric observations. Additionally, those prior studies showed higher, rather than lower, renal temperatures in the *in vivo* settings.[5] One further consideration in our modeling is the maximum temperatures in extreme situations, such as the smallest renal model where temperatures exceeded 100° C. Our models do not simulate evaporation or condensation processes. As a result, additional heat beyond 100° C increases the temperature of the fluid via conservation of energy principles. While this would not reflect a typical situation at 1 atmosphere, qualitatively this likely does not influence results as thermal damage simulated just prior to the temperature reaching 100° C remains substantial. Our primary models simulate a full 60 seconds of continuous laser firing, which is not representative of a typical clinical scenario. However, *in vitro* studies suggest that optimal popcorn-dusting parameters include *total* laser firing time of 4 minutes.[24] Using an operator duty cycle of 50%, we demonstrated mitigation of thermal parameters. As such, focus on duration of firing and rest during treatment may additionally improve the safety envelope during laser lithotripsy. However, even with intermittent activity maximum temperatures surpassed 60 °C, resulting in an estimated volume of tissue at risk of greater than 1 cm³. As cooling of the collecting system between laser activation depends upon the duration of rest periods, the collecting system fluid may not reach baseline temperatures during laser inactivation. Because thermal injury is a product of both intensity and duration of thermal energy exposure, this concept should be kept in mind during treatment. Lastly, current patterns of treatment for laser lithotripsy within the pediatric population are not well defined. Due to the relative infrequent nature of pediatric stone disease, as compared to adults, pediatric centers may not routinely perform a volume of ureteroscopy which warrants purchase of higher-powered laser lithotripters. However, given the close collaboration between pediatric and adult urologists especially at academic medical centers as well as the increased interest in dusting within all age groups, it is likely that dissemination of this technology to the pediatric realm is quickly forthcoming. [3, 23]

These limitations notwithstanding, our work has several important implications. Our prime objective was to select clinical scenarios that warrant further investigation with higher-fidelity simulations when indicated. To this end, we have identified several important situations wherein tissue may be at risk during laser lithotripsy. Acknowledging the limitations of our computational model, a logical next step would be to investigate these

specific scenarios with *in vitro* experiments in tissue phantoms of varying sizes. Future work will need to focus on efforts to mitigate thermal effects, such as utilization of pressurized irrigation. Within the pediatric population, striking the balance between flow and pressure is even more challenging, as ureteral access sheaths are not without risk and may be challenging to place in the smallest of kidneys (i.e. those at highest risk for potential thermal injury).[27, 28] Finally, in identifying the importance of various power settings on thermal exposure, it will be important to further define practice patterns for pediatric laser lithotripsy. This information could help to guide further simulation and education regarding optimal laser settings within the pediatric population, especially as newer technologies such as “Moses” technology and thulium lasers enter the marketplace.[16, 26]

In conclusion, we have simulated the thermal conditions of the renal and ureteral collecting systems during laser lithotripsy in children. Power settings greater than 20W in any location or age-range pose a risk of thermally-induced tissue damage at low-flow irrigation. Additionally, younger and therefore smaller kidneys appear to be at higher risk of exposure to maximum temperatures during laser lithotripsy, which could translate into a higher risk of thermal damage. Finally, pressurized irrigation appears to mitigate these heating effects, thereby introducing at least one mechanism to reduce the risk of thermal damage. Ultimately, future studies are needed to validate these simulations in *in vitro* or *in vivo* situations as well as to explore current practices of surgeons who treat children with nephrolithiasis.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Funding Source:

This study was supported in part by NIDDK K01 DK104854.

References

- [1]. Ellison JS, Shnorhavorian M, Oron A, Kieran K, Lendvay TS, Merguerian PA. Risk factors for repeat surgical intervention in pediatric nephrolithiasis: A Pediatric Health Information System database study. *J Pediatr Urol.* 2018;14:245 e1–e6. [PubMed: 29580730]
- [2]. Wang H-HS, Huang L, Routh JC, Nelson CP. Shock wave lithotripsy vs ureteroscopy: variation in surgical management of kidney stones at freestanding children’s hospitals. *The Journal of urology.* 2012;187:1402–7. [PubMed: 22341283]
- [3]. Matlaga BR, Chew B, Eisner B, Humphreys M, Knudsen B, Krambeck A, et al. Ureteroscopic Laser Lithotripsy: A Review of Dusting vs Fragmentation with Extraction. *J Endourol.* 2018;32:1–6. [PubMed: 29061070]
- [4]. Razvi HA, Denstedt JD, Chun SS, Sales JL. Intracorporeal lithotripsy with the holmium:YAG laser. *J Urol.* 1996;156:912–4. [PubMed: 8709362]
- [5]. Aldoukhi AH, Hall TL, Ghani KR, Maxwell AD, MacConaghy B, Roberts WW. Calyceal Fluid Temperature During High-Power Holmium Laser Lithotripsy in an In Vivo Porcine Model. *Journal of Endourology.* 2018.
- [6]. Wollin DA, Carlos EC, Tom WR, Simmons WN, Preminger GM, Lipkin ME. Effect of Laser Settings and Irrigation Rates on Ureteral Temperature During Holmium Laser Lithotripsy, an In Vitro Model. *J Endourol.* 2018;32:59–63. [PubMed: 29048226]

- [7]. Jansen ED, Asshauer T, Frenz M, Motamedi M, Delacretaz G, Welch AJ. Effect of pulse duration on bubble formation and laser-induced pressure waves during holmium laser ablation. *Lasers Surg Med.* 1996;18:278–93. [PubMed: 8778524]
- [8]. Kronenberg P, Somani B. Advances in Lasers for the Treatment of Stones—a Systematic Review. *Current urology reports.* 2018;19:45. [PubMed: 29774438]
- [9]. Ventimiglia E, Traxer O. What Is Moses Effect: A Historical Perspective. *Journal of Endourology.* 2019;33:353–7. [PubMed: 30892062]
- [10]. Maxwell AD, MacConaghy B, Harper JD, Aldoukhi AH, Hall TL, Roberts WW. Simulation of Laser Lithotripsy-Induced Heating in the Urinary Tract. *J Endourol.* 2019;33:113–9. [PubMed: 30585741]
- [11]. Zelenko N, Coll D, Rosenfeld AT, Smith RC. Normal ureter size on unenhanced helical CT. *AJR American journal of roentgenology.* 2004;182:1039–41. [PubMed: 15039184]
- [12]. Wadekar P, Pundge S, Gangane S. The impact of lower infundibular length and lower infundibular width on renal stone formation. *International J of Healthcare and Biomedical Research.* 2014;2:158–63.
- [13]. Schaeffer AJ, Kurtz MP, Logvinenko T, McCartin MT, Prabhu SP, Nelson CP, et al. MRI-based reference range for the renal pelvis anterior-posterior diameter in children ages 0–19 years. *The British journal of radiology.* 2016;89:20160211. [PubMed: 27610649]
- [14]. Zelenko N, Coll D, Rosenfeld AT, Smith RC. Normal ureter size on unenhanced helical CT. *American Journal of Roentgenology.* 2004;182:1039–41. [PubMed: 15039184]
- [15]. Rosenbaum DM, Korngold E, Teele RL. Sonographic assessment of renal length in normal children. *AJR American journal of roentgenology.* 1984;142:467–9. [PubMed: 6607625]
- [16]. Aldoukhi A, Ghani K. Ureteroscopic holmium laser lithotripsy using the Moses technology. *European Urology Supplements.* 2018;17:e1918.
- [17]. Aldoukhi AH, Black KM, Hall TL, Ghani KR, Maxwell AD, MacConaghy B, et al. Defining Thermally Safe Laser Lithotripsy Power and Irrigation Parameters: In Vitro Model. *J Endourol.* 2020;34:76–81. [PubMed: 31608654]
- [18]. Aldoukhi A, Hall TL, Ghani K, Hollingsworth JM, Ambani S, Dauw C, et al. “Operator Duty-Cycle”: Analysis of Laser Activation Patterns During Holmium Lithotripsy. *Engineering and Urology Society Chicago, IL* 2019.
- [19]. Yarmolenko PS, Moon EJ, Landon C, Manzoor A, Hochman DW, Viglianti BL, et al. Thresholds for thermal damage to normal tissues: an update. *Int J Hyperthermia.* 2011;27:320–43. [PubMed: 21591897]
- [20]. Sapareto SA, Dewey WC. Thermal dose determination in cancer therapy. *Int J Radiat Oncol Biol Phys.* 1984;10:787–800. [PubMed: 6547421]
- [21]. Dewhirst MW, Viglianti BL, Lora-Michiels M, Hanson M, Hoopes PJ. Basic principles of thermal dosimetry and thermal thresholds for tissue damage from hyperthermia. *Int J Hyperthermia.* 2003;19:267–94. [PubMed: 12745972]
- [22]. He X, Mcgee S, Coad JE, Schmidlin F, Iaizzo PA, Swanlund DJ, et al. Investigation of the thermal and tissue injury behaviour in microwave thermal therapy using a porcine kidney model. *International Journal of Hyperthermia.* 2004;20:567–93. [PubMed: 15370815]
- [23]. Silay MS, Ellison JS, Tailly T, Caione P. Update on Urinary Stones in Children: Current and Future Concepts in Surgical Treatment and Shockwave Lithotripsy. *European urology focus.* 2017.
- [24]. Emiliani E, Talso M, Cho SY, Baghdadi M, Mahmoud S, Pinheiro H, et al. Optimal Settings for the Noncontact Holmium:YAG Stone Fragmentation Popcorn Technique. *J Urol.* 2017;198:702–6. [PubMed: 28442384]
- [25]. Santiago JE, Hollander AB, Soni SD, Link RE, Mayer WA. To dust or not to dust: a systematic review of ureteroscopic laser lithotripsy techniques. *Current urology reports.* 2017;18:32. [PubMed: 28271355]
- [26]. Hardy LA, Gonzalez DA, Irby PB, Fried NM. Fragmentation and dusting of large kidney stones using compact, air-cooled, high peak power, 1940-nm, thulium fiber laser. *Therapeutics and Diagnostics in Urology 2018: International Society for Optics and Photonics;* 2018 p. 104680O.

- [27]. Wang HH, Huang L, Routh JC, Kokorowski P, Cilento BG Jr., Nelson CP. Use of the ureteral access sheath during ureteroscopy in children. *J Urol*. 2011;186:1728–33. [PubMed: 21855908]
- [28]. Traxer O, Thomas A. Prospective evaluation and classification of ureteral wall injuries resulting from insertion of a ureteral access sheath during retrograde intrarenal surgery. *J Urol*. 2013;189:580–4. [PubMed: 22982421]

Figure 1:
Temperature Curves at 5 mL/min (gravity flow) and 40 mL/min pressurized flow within the ureter (A) and renal pelvis (B)

Figure 2: Temperature (A) and thermal dose (B) within the renal collecting system for intermittent and continuous laser activity (3 year old, 40 W, 5 mL/min Gravity Flow, renal calyx)

Table 1:

Material and tissue parameters used for simulations of in vitro and in vivo conditions.

	Density (kg/m ³)	Specific Heat Capacity (J/kg-K)	Thermal Conductivity (W/m-K)	Perfusion Rate (L/min-kg)
Water	998	4184	0.608	-
Glass	2230	750	0.800	-
Urine	1023	4178	0.560	-
Blood	1049	3617	0.517	-
Urinary Tract Wall	1101	3306	0.462	0.19
Kidney Parenchyma	1049	3587	0.527	3.80

Table 2:

Thermal dose and tissue at risk (indicated by “Lesion Volume”) for the model across ages, power settings and treatment location, assuming treatment with gravity flow (5 mL/sec)

Ureter						
Power (W)	Thermal Dose (t43)			Lesion Volume (cm3)		
	3 years	8 years	12 years	3 years	8 years	12 years
5	1.1	0.7	0.6	0.0	0.0	0.0
10	26.5	14.3	8.1	0.2	0.1	0.1
20	19148.1	8566.8	3352.4	0.8	0.8	0.7
40	6.4×10^9	2.5×10^9	3.9×10^8	1.8	2.3	2.6
Renal Pelvis						
Power (W)	Thermal Dose (t43)			Lesion Volume (cm3)		
	3 years	8 years	12 years	3 years	8 years	12 years
5	0.5	0.5	0.5	0.0	0.0	0.0
10	86.2	16.5	5.4	0.1	0.1	0.1
20	4.8×10^6	1.1×10^6	4196.1	1.0	0.7	0.6
40	7.2×10^{15}	9.7×10^{11}	1.9×10^9	2.7	2.7	2.5
Renal Calyx						
Power (W)	Thermal Dose (t43)			Lesion Volume (cm3)		
	3 years	8 years	12 years	3 years	8 years	12 years
5	1.2	0.4	0.3	0.0	0.0	0.0
10	4163.7	609.5	235.2	0.2	0.2	0.1
20	2.2×10^{10}	3.7×10^8	5.2×10^7	0.8	0.9	0.9
40	6.1×10^{21}	2.4×10^{18}	1.1×10^{17}	1.6	2.0	2.2