Mechanism of Pulse Modulated Holmium:YAG Lithotripsy

Jason B. King[1*], Nitesh Katta[1*], Austin B. McElroy[1], Sahar Alaei[1*], Sabish Shrestha[1], Bonnie Chan[1], Thomas E. Milner[1*], Joel M.H. Teichman[2]

1. The University of Texas at Austin | *Biomedical Engineering
2. University of British Columbia | Urological Sciences

Introduction

Pulse modulated Ho:YAG (λ=2.1 µm) laser lithotripsy (Moses) is a novel method where a first pulse creates a vapor bubble between fiber-tip and stone followed by a second pulse for fragmentation resulting in enhanced removal, reduced retropulsion and increased radiant energy delivery to the stone. Reported advantages include ability to work in non-contact mode and greater lithotripsy efficiency even in contact mode [1]. We evaluated the mechanisms of pulse modulated lithotripsy by monitoring stone fragmentation using a fast video camera, an optical hydrophone, and Optical Coherence Tomography (OCT).

Methods

1. BegoStone Preparation:
   - 5:1 power to water by weight
   - 2 mm thick
2. Ablation:
   - Lumenis P120 Ho:YAG laser
   - Single 1 J pulse per location
   - 1 mm separation fiber to stone
   - Moses-Distance, Moses-Contact and Non-Moses operating modes
   - Hydrated (wet) and dry stones
   - In air and in water
   - 12 total conditions
   - n=15 repetitions
3. Fast Video Recording:
   - Photron Fastcam Mini UX100
   - 50,000 frames per second
4. Optical Coherence Tomography
   - Crater volume measurements computed using edge detection
   - ANOVA test for statistical significance

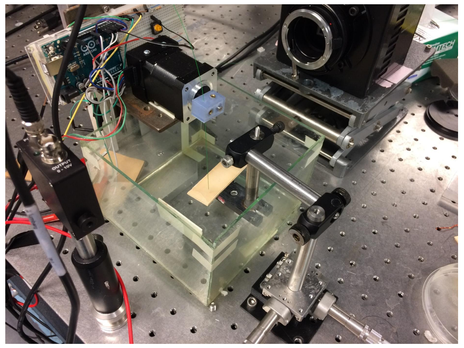

Figure 1. Photograph of ablation setup including linear actuator for ablation using a single pulse and a fast video camera.

Rotational Fiber Actuator

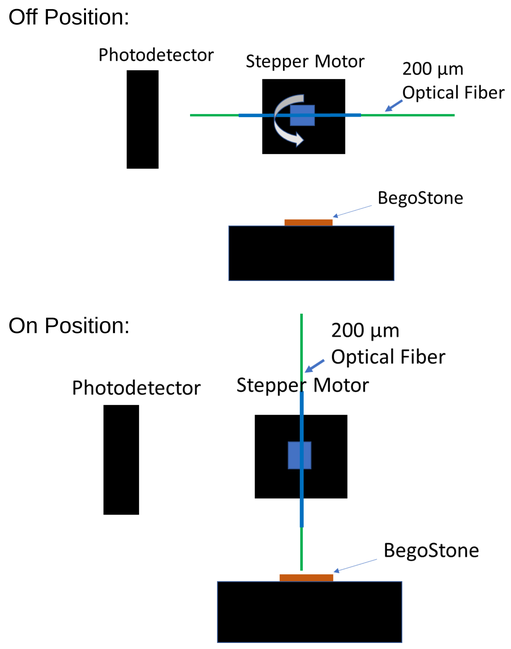

Figure 1. Rotational fiber actuator to select a single pulse. Laser is set to 5 Hz repetition rate. The photodetector detects the first pulse and after a delay the fiber is turned to be positioned 1 mm above the stone for a single pulse. After 200 ms the fiber is turned away from the stone and returns to its original position.

In Air Video Examples

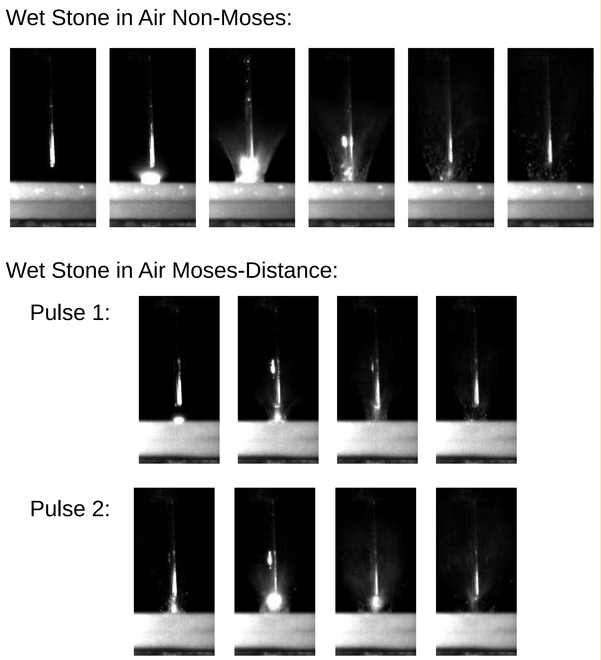

Figure 2. Example video from the fast camera for wet stones in air using Non-Moses and Moses-Distance Pulses. For each pulse, the time between frames shown is 60 µs. Ablation debris are observed in both pulses of the Moses-Distance pulse sequence, with more debris observed on the second pulse in the sequence.

OCT Image Examples

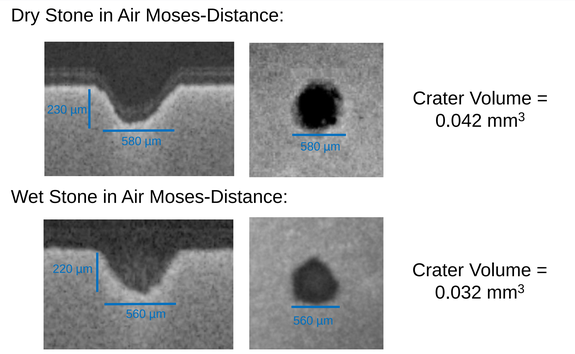

Figure 3. Example OCT B-scans (left) and en-face images (right). Stones were imaged with OCT after being dried in air. Crater volumes were calculated using edge detection across the 3D OCT volume of each crater.

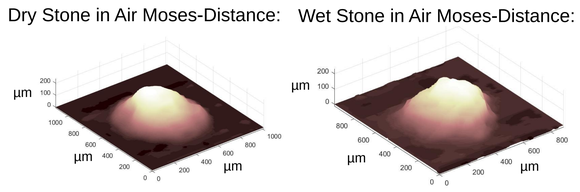

Figure 3. 3D reconstruction of the OCT volume using edge detection to find the surface of the stone from each b-scan.

In Water Video Examples

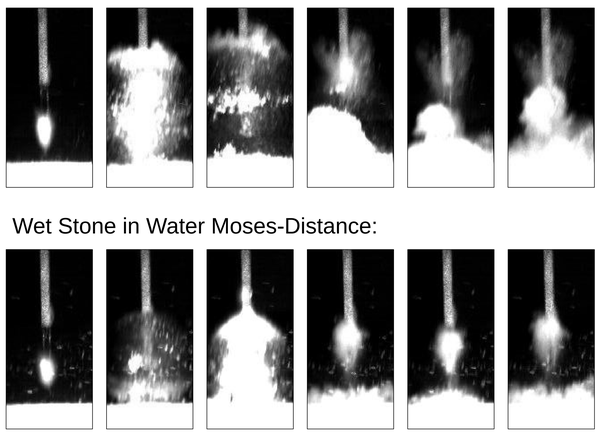

Figure 4. Example video from the fast camera for wet stones in water using Non-Moses and Moses-Distance Pulses showing vapor bubble formation and collapse. For each pulse, the time between frames shown is 200 µs. Previous studies have show increased ablation using Moses-Distance mode at a fiber distance of 1 mm [1]. The first pulse in the Moses-Distance pulse sequence forms a vapor bubble allowing the second pulse in the sequence a clear path to the stone.

Ablation Volume Comparison

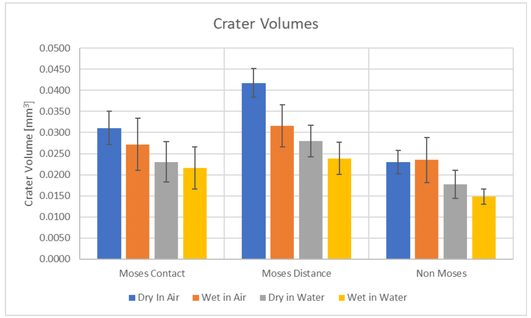

Figure 4. Mean crater volume for each ablation condition (n=15). Error bars represent ± 1 STD.

Table 1: Crater volume for each condition (mean ± STD), p-values calculated using ANOVA with Tukey's HSD (*p-value<0.05)

	Moses-Contact	Moses-Distance	Non-Moses	p-value MC vs MD	p-value MC vs NM	p-value MD vs NM
Dry in Air	0.031±0.004	0.042±0.003	0.023±0.003	2.3E-7*	1.5E-5*	2.2E-7*
Wet in Air	0.027±0.006	0.032±0.005	0.023±0.005	0.18	0.42	1.4E-5*
Dry in Water	0.023±0.005	0.028±0.004	0.018±0.003	0.065	0.032*	2.3E-7*
Wet in Water	0.022±0.005	0.024±0.004	0.015±0.002	0.96	7.7E-4*	6.5E-7*
p-value DA vs WA	0.35	2.3E-7*	1.0			
p-value DW vs WW	1.0	0.24	0.77			
p-value DA vs DW	1.6E-5*	2.2E-7*	0.034*			
p-value WA vs WW	0.017*	4.5E-5*	1.8E-6*			

Moses-Distance had larger ablation volumes compared to Non-Moses for all ablation conditions. Dry stones in air had larger ablation volumes compared to wet stones in air for Moses-Distance mode. Both wet and dry stones in air had larger ablation volumes than stones in water for all pulse modes. Each of these results are statistically significant with p-value <0.05.

Conclusions

Advantages of pulse modulation for lithotripsy are supported by a high ablation volume for in-water and in-air cases. However, increased crater volumes for Moses-Distance mode in air, where bubble formation does not occur, suggests mechanism of laser-stone interaction and fragmentation requires further study. Ablation conditions with less water had higher ablation volumes suggesting the primary ablation mechanism is photothermal. Monitoring BEGO stone phantoms and *ex vivo* human stones with a fast camera and OCT enhances understanding of Ho:YAG laser lithotripsy mechanisms.

References

1. J Endourol 2019 Feb;33(2):120-126. doi: 10.1089/end.2018.0572
2. J Urol. 2012 Mar;187(3):914-9. doi: 10.1016/j.juro.2011.10.147
3. J Endourol. 1999 Apr;13(3):181-90. doi: 10.1089/end.1999.13.181