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Contribution of cavitation and photothermal effects in laser lithotripsy

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ABSTRACT

Recent studies suggest that cavitation effect following laser induced vapor bubble collapse is more dominant than the photothermal effect in stone ablation during laser lithotripsy. Our research aims to introduce an experimental study design that precisely measures each effect's contribution using gypsum phantom stones. To isolate the cavitation-only mechanism after the collapse of the laser-induced vapor bubble, a phantom stone was submerged in a dye solution. The dye solution absorbed all laser light, generating cavitation, with additional experiments confirming the absence of any photothermal effect when the dye was not used. The fiber was positioned both parallel to the stone surface and perpendicular at a 1mm distance, exposing it solely to cavitation. In another set of experiments, a phantom stone was submerged in water and 2µm light from a thulium yttrium aluminum garnet (Tm:YAG) laser was delivered via the same optical fiber positioned (this time) perpendicular to the stone surface. In this case, both optical absorption and cavitation effect from laser-induced vapor bubble collapses were observed but the measured pressure transients showed significantly lower peak pressures compared to the first set. In a final set of experiments, these conditions remained constant, except the fiber was positioned parallel to the stone surface, once again exposing it to only the cavitation from the collapse of the laser induced vapor bubble. Craters created by all methods were imaged using an optical coherence tomography (OCT) system. Measured volumes showed that stone ablation was dominated by photo-thermal, and not by cavitation from the vapor bubble collapse. In fact, in two of the three trials of stone experiments (n=5, each trial) that were subjected to cavitation-only, there was no observable ablation. One trial produced an average volume that was 50% smaller than the average resulting from a single photo-thermal-only case ($p = 0.0022 < 0.05$). Our results suggest that finetuning of lithotripsy procedures with focus on energy transmission to the stone can provide optimal results.

Keywords: cavitation, kidney stone, thulium, laser lithotripsy, OCT

1. INTRODUCTION

In the field of urology, laser lithotripsy is used to ablate kidney stones through a ureteroscope. There are two primary factors that are hypothesized to be dominant in ablating the stone. These factors are the photothermal effect[1][2][3][4] and the effect of cavitation[5][6][7][8] from the collapse of the laser induced vapor bubble. In the past few decades, the primary system used in the clinic is the holmium yttrium aluminum garnet (Ho:YAG) laser. Wavelength of the Ho:YAG laser is between 2.06um and 2.1um. The Ho:YAG laser has a high peak power (multi kW). Recently, semiconductor laser pumped fiber lasers like Thulium fiber laser (TFL) centered at 1.94um. 1.94um is close to the local maximum of water absorption.

Photothermal effect: It has been shown that the direct absorption of optical energy is what causes the ablation of a kidney stone. This has been tested by showing that the ablation of the stone occurs prior to the collapse of the vapor bubble, as it is related to the rise in temperature of the stone.

Cavitation effect: On the other end, for Ho:YAG lasers, given the high peak power, laser-water interaction results in production of cavitation effect given the pressure transients observed at short pulse durations, following the collapse of the laser induced vapor bubble, such as 70-78µs. The motivation of the current study is to assess the relative contributions of photothermal ablation and cavitation. In this experiment we decided to assess this by isolating the cavitation effect, following the collapse of the laser induced vapor bubble, and comparing the ablation of the stone to craters created by the photothermal effect with minimal cavitation.

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2. MATERIALS AND METHODS

2.1 Experimental Conditions

Two light sources were used in this study; a dye sensitive laser and a thulium yttrium aluminum garnet (Tm:YAG) laser. The Tm:YAG (DPM-100, Pantec Medical) had the following laser parameters: wavelength 2020nm, pulse length 500µs, energy per pulse 0.5J (max. 2J). The laser was controlled by an external controller on a Single-Pulse setting. The laser sources absorbed by the dye were tested to ensure similar pressure to other cavitation experiments [5], following the collapse of the laser induced vapor bubble, and therefore similar cavitation. The laser was also controlled by an external controller with a 100 pulse preset.

One phantom stone was subjected to 4 different stone experiments in different locations. The first experiment was performed by submerging the phantom stone in a dye solution (green), which absorbed all the light from the laser absorbed by the dye producing a laser induced vapor bubble and subsequent cavitation following the collapse of the laser induced vapor bubble. This was done to isolate cavitation. A cleaved optical fiber was positioned 1 mm away from the stone, and 100 laser pulses were delivered in 5 different locations. In the next experiment, all conditions remained constant, exposing the stone to cavitation only, except the fiber was positioned perpendicular to the stone. The following two experiments were performed using the thulium yttrium aluminum garnet (Tm:YAG) laser. In order to test the photothermal effect, the same phantom stone was submerged in water and a 2µm light from the thulium yttrium aluminum garnet (Tm:YAG) laser was delivered in 1 pulse at 5 different locations via the same optical fiber suspended 1mm from the surface. The fiber was positioned perpendicular to the surface of the stone this time. In this case, both optical absorption (photothermal) and cavitation (following vapor bubble collapse) were observed but the measured pressure transients showed significantly lower peak pressures compared to the first set. To maintain consistency in the experiments performed by the two different lasers, a final experiment was done using the Tm:YAG. The phantom remained submerged in water, but the optical fiber was positioned parallel to the surface at a distance of 1 mm, once again isolating cavitation following the collapse of the laser induced vapor bubble. The laser was pulsed 100 times in 5 different locations.

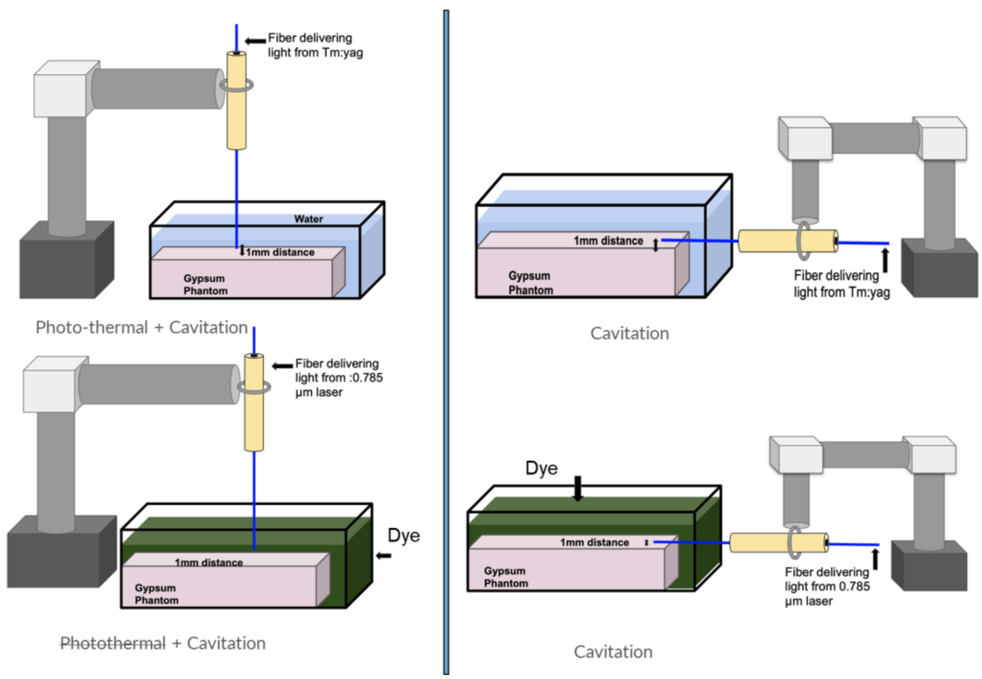

Figure 1: Different orientation and laser dosimetry for testing the effects of cavitation versus photothermal ablation of gypsum phantom stones. Two cases of laser and two cases of fiber orientation were studied. Tm:YAG stone experiment with photothermal effect and minimal cavitation(top left). Tm:YAG stone experiment with cavitation only(top right). Stone experiments with cavitation-only following the collapse of the laser induced vapor bubble - perpendicular and parallel fiber orientation (bottom left and right).

2.2 Stone Type and Preparation

A Gypsum Snap Stone was prepared to be used as a phantom stone. The stone was prepared using a 5:1 Gypsum powder to water ratio. After being mixed, the stone was left to rest and harden for 48 hours.

2.3 Pressure transients' measurement:

Measurement of pressure transients was conducted using a pressure sensor (112B21; 1000psi, PCB Piezotronics, Depew, NY) connected to a 200 MHz oscilloscope for each laser. The fiber was oriented toward the pressure sensor with a separation distance of 5 mm to avoid laser damage to the sensor surface. Subsequently, the pressure at a 1 mm separation distance was computed.

2.4 OCT Imaging after Ablation

After each set of experiments the stones were dried and imaged using a custom-made Optical Coherence Tomography (OCT) 3-D imaging system. Each crater's dimensions were measured and a conical volume equation was used to calculate the size of each ablation. An Anova: Single Factor test was done to compare the mean volumes of the measurable craters in each of the experiments. The OCT system utilized a single-mode optical fiber and a 1310 nm swept-source laser with a Mach-Zehnder fiber interferometer to record three-dimensional tomograms of the stone.

3. RESULTS AND DISCUSSION

In the first experiments, a dye absorbing laser was used and the stone was submerged in a dye solution, which absorbed all light, isolating the cavitation effect following the collapse of the laser induced vapor bubble. A pressure sensor was used to measure the pressure of the dye absorbing laser to confirm that it was similar to that of the Ho:YAG used in previous cavitation experiments [5]. Cavitation pressures of less than 20 bars were observed with the Tm:YAG laser following the collapse of the laser induced vapor bubble, whereas the dye absorbed to create strong cavitations greater than 60-100 bars following the collapse of the laser induced vapor bubble similar to that observed in previous experiments [5] with similar pulse durations of approx. 50µs with the Ho:YAG laser.

When the fiber was oriented parallel to the stone, measurable craters were created and measured. Meanwhile when the fiber was oriented perpendicular to the stone, ring-like imprints were created, but no ablations with a measurable depth were present. When cavitation, following the collapse of the laser induced vapor bubble, was isolated using the Tm:YAG laser by orienting the fiber parallel to the surface, no observable ablation was seen. The average volume of the craters created by the photothermal effect with minimal cavitation, created by a fiber suspended perpendicular to the phantom delivering light from the Tm:YAG was approximately 50% greater than that of the cavitation-only case with a significant p value ($p = 0.0022 < 0.05$). To further support the dominance of the photothermal effect, these values were achieved by firing 100 shots with cavitation-only case per crater, and 1 shot of the photothermal effect.

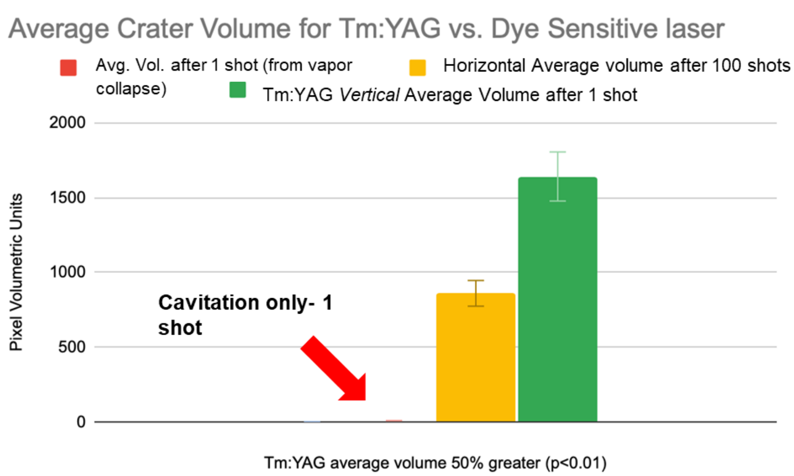

Figure 2: Results of stone volume removed (in units of voxels derived from OCT volume images., each voxel in OCT corresponds to a volume approximately 15e-6 mm^3). Orange bar shows the average volume measured after 100 shots of the horizontal setting with the dye sensitive laser on the bego stone. Green bar corresponds to volume of stone removed after just 1 shot of the Tm:YAG laser in vertical orientation facing the stone. Note: Vertical orientation of the dye sensitive laser and horizontal orientation of Tm:YAG experiments produced no measurable ablations

4. CONCLUSIONS

We have introduced a methodology to aid in studying relative contributions of photothermal versus cavitation following the collapse of the laser induced vapor bubble during laser lithotripsy of kidney stones. Using this methodology, the pressure amplitudes measured at the collapse of the vapor bubble are equivalent to previous literature. The results of this experiment suggest that the photothermal effect is dominant in stone ablation in laser lithotripsy. The photothermal effect created significantly larger ablations on the phantom stone, using 1 pulse as compared to the 100 pulses of the cavitation only effect. Our findings indicate that refining lithotripsy procedures, with a specific emphasis on optimizing energy transmission to the stone, can yield optimal outcomes. Pressure amplitudes from cavitation bubbles following the collapse of the vapor bubble may be additive and need further experimentation at higher laser repetition frequencies.

5. ACKNOWLEDGEMENTS

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