

# Journal of Biomedical Optics

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**Abstract.** Q-switched (QS) Tm:YAG laser ablation mechanisms on urinary calculi are still unclear to researchers. Here, dependence of water content in calculus phantom on calculus ablation performance was investigated. White gypsum cement was used as a calculus phantom model. The calculus phantoms were ablated by a total 3-J laser pulse exposure (20 mJ, 100 Hz, 1.5 s) and contact mode with  $N = 15$  sample size. Ablation volume was obtained on average 0.079, 0.122, and 0.391 mm<sup>3</sup> in dry calculus in air, wet calculus in air, and wet calculus in-water groups, respectively. There were three proposed ablation mechanisms that could explain the effect of water content in calculus phantom on calculus ablation performance, including shock wave due to laser pulse injection and bubble collapse, spallation, and microexplosion. Increased absorption coefficient of wet calculus can cause stronger spallation process compared with that caused by dry calculus; as a result, higher calculus ablation was observed in both wet calculus in air and wet calculus in water. The test result also indicates that the shock waves generated by short laser pulse under the in-water condition have great impact on the ablation volume by Tm:YAG QS laser. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JBO.20.12.128001]

Keywords: calculus; laser; lithotripsy; phantom; Q-switched; Tm:YAG; urology; water.

Paper 150487PRR received Jul. 20, 2015; accepted for publication Oct. 30, 2015; published online Dec. 10, 2015.

## 1 Introduction

Urinary calculi are crystalline deposits, also known as kidney/ureter/bladder/urethra stones or uroliths, which occur in the urinary system. The condition causes the individual severe discomfort and pain. Urinary calculus disease is the third largest area in urology after urinary tract infection and prostate disease. Calculi occur in urinary tract (kidney, ureter, bladder, and urethra) affecting 10% of the population with a high recurrence rate of ~50%.<sup>1-3</sup> The treatment of urinary calculi is currently achieved through either extracorporeal shock wave lithotripsy, percutaneous nephrolithotomy, ureteroscopy (URS), or other surgical approaches. Use of a laser to fragment calculus (laser lithotripsy) was first introduced in 1968 by Mulvaney and Beck<sup>4</sup> utilizing a ruby laser excited by a xenon lamp, which can produce a wavelength of 694 nm. After the flash-lamp-pumped Ho:YAG laser was introduced,<sup>5,6</sup> use of the Ho:YAG laser through URS has been the gold standard for laser lithotripsy from 1995 until present.

It is believed that detailed studies showed that the fragmentation process in Ho:YAG laser lithotripsy was predominantly photothermal secondary to a long pulse duration that significantly reduced the strength of acoustic emission.<sup>7</sup> The vapor bubble produced by the vaporization of the intervening fluid between the delivery fiber and the target stone produced an open channel that facilitated laser delivery to the calculus surface (Moses effect). Light absorption of the calculus caused a

rapid temperature rise above the threshold for chemical breakdown, resulting in calculus decomposition and fragmentation.<sup>7</sup> On the other hand, with a Q-switched (QS) laser, the laser pulse duration is normally in the nanosecond range and can lead to photomechanical effect that breaks up the calculus.<sup>8,9</sup> Rink et al.<sup>9</sup> was the first to study the physical basis of the fragmentation with nanosecond durations by Nd:YAG QS systems. This superheated area will generate a vaporized bubble that can create shock wave during the initial formation and collapse of the bubble. The shock wave fragments the calculus in its vicinity. However, it is still unclear to researchers what factors can affect the ablation mechanism of the QS laser. The objective of this study was to investigate the effect of water content in calculus phantom on ablation performance by three sample conditions: dry, wet (damp), and submerged in water. This can reveal how much the water content contributes to fragmentation in the form of spallation, or microexplosion, shock wave, and bubble collapse under the QS Tm:YAG laser ablation condition. A previous study by the same group of authors as this paper revealed the water content did have some effect to enhance the ablation volume with limited sample size and total laser pulse energy on each sample.<sup>10</sup> In this study, a sample size of 15 is used as well as a pulse train of total 3-J exposure on each sample, resulting in substantial increase in statistical significance and measurement reliability.

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## 2 Materials and Methodology

### 2.1 Calculus Phantom

Calculus phantom was made of white gypsum cement used as tissue phantom for human kidney stone (UtralCal<sup>®</sup>30, United States Gypsum Company, Chicago, Illinois), which was widely used for laser lithotripsy studies by other researchers.<sup>11</sup> Cuboid tissue phantoms sized 5 mm on each face were made by mixing gypsum cement (500 g) with distilled water (0.23 L) and allowing curing for at least 3 h (overnight curing preferred). The cement was molded to have a size of 5 × 5 × 5 mm as shown in Fig. 1. The calculus phantom has its tensile strength of 2 MPa, which is comparable with tensile strength of human struvite (0.1 to 3.4 MPa).<sup>12</sup>

### 2.2 Laser System

A custom-made QS Tm:YAG laser (2.01 μm) was employed for this study, as shown in Fig. 2. The laser crystal Tm:YAG is pumped by a diode laser beam from a laser diode stack through a beam shaping and delivery optics system. A lens is used to overcome the strong thermal lens of Tm:YAG crystal to

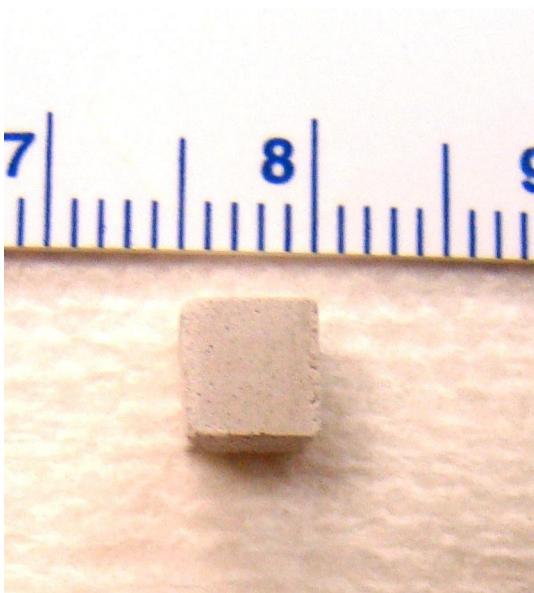


Fig. 1 5 × 5 × 5 mm calculus phantom.

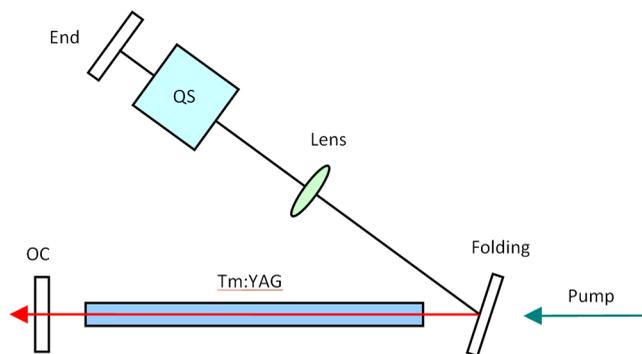


Fig. 2 Custom-made Q-switched (QS) Tm:YAG laser. Conventions: End—end mirror, QS—Q-switch, Lens—lens, Folding—folding mirror, Pump—pump beam, and OC—output coupling mirror.

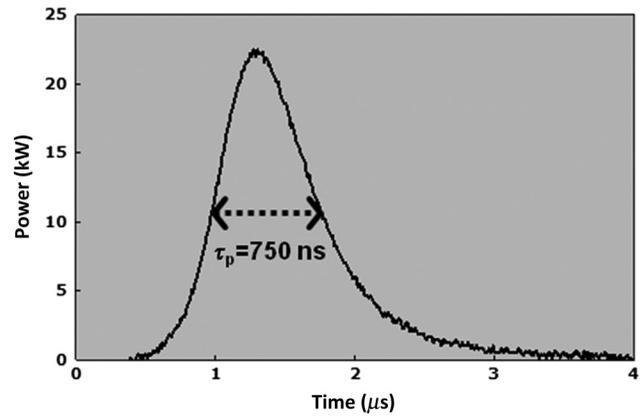


Fig. 3 QS Tm:YAG laser pulse.

maintain the stability of the laser cavity. A custom-made acoustic QS is placed inside the cavity to modulate the laser in QS mode. The laser was operating in 100-Hz rep rate with pulse energy of 20 mJ at the output end of fiber optic beam delivery system. A group of laser pulses at the output end of fiber was released or generated by an external shutter between the output coupling of laser cavity and laser beam delivery system. Figure 3 shows a temporal pulse structure diagram with pulse duration ( $\tau_p$ ) of 750 ns (FWHM). This range of pulse duration is known to generate shock wave pressure due to bubble collapse under water.<sup>8,13</sup> This laser can be a proper model to investigate dependency of water content in the phantom on ablation performance because of its peak water absorption coefficient of 70 cm<sup>-1</sup>.<sup>14</sup>

### 2.3 Experimental Method and Setup

In this study, we investigated the effects of water on calculus ablation efficiency using a QS Tm:YAG laser. The experimental setup is shown in Fig. 4. A 5 × 5 × 5 mm calculus phantom made in Sec. 2.1 was secured in a glass chamber using two-sided tape, and a 365-μm core fiber (S-LLF365 SureFlex Fiber, American Medical Systems) was positioned on top of the phantom (in contact mode). The 365-μm core fiber was connected to the QS Tm:YAG laser through a beam delivery optical system. There were three experimental conditions being investigated for this study including dry calculus in air, wet calculus in air, and wet calculus in water. For dry calculus in air, the phantom was cured overnight and dried by baking in an oven at 80°C for 1 h. For wet calculus in air, the phantom

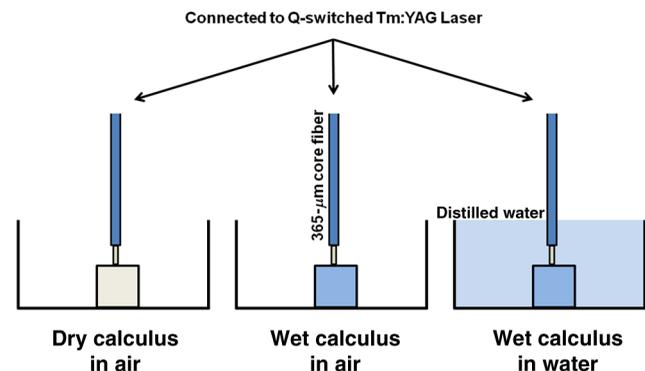
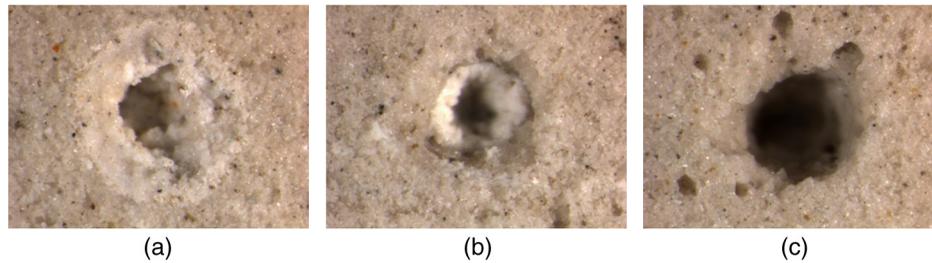


Fig. 4 Three experimental conditions: dry calculus in air, wet calculus in air, and wet calculus in water.



**Fig. 5** Typical screenshots of laser ablation areas under different sample conditions by Leica M205C series stereomicroscope: (a) dry sample; (b) wet sample; and (c) in-water sample.

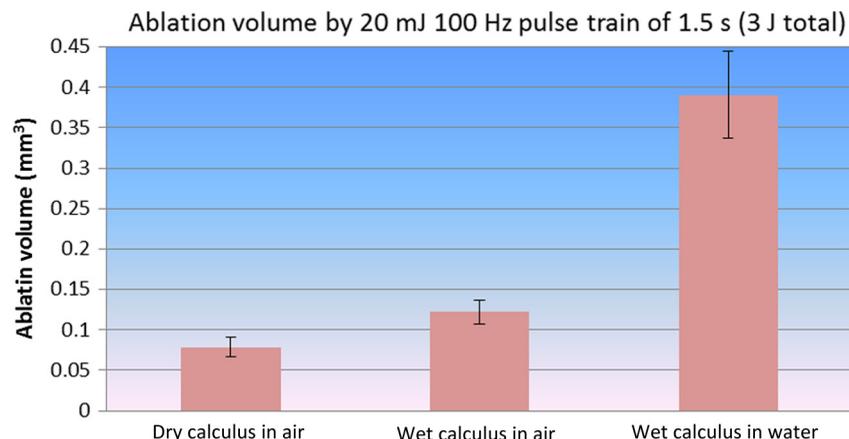
was submerged in distilled water for 5 min before drying with a lint-free wipe and installing in the glass chamber, and then the phantom was irradiated in air without water in the glass chamber. For wet calculus in water, the phantom was installed in the glass chamber and submerged in distilled water for 5 min before laser irradiation. In all conditions, the phantom was irradiated with a series of laser pulses at 20 mJ, 100 Hz, for 1.5s (with total energy of 3 J). Sample size for each condition was 15 ( $N = 15$ ). In the previous study,<sup>10</sup> we used Zygo NewView 7300 to measure the fragmentation volume. Zygo NewView 7300 is a “surface profiler,” which is good for very shallow surface structure analysis for the damage evaluation by single laser pulse in the previous study but not suitable for craters with depth of up to millimeter level in this new test. Therefore, a stereomicroscope was used to measure the volume of fragmentation. After laser irradiation (3 J), ablation volume at the irradiated area of each sample was measured using a Leica M205C series stereomicroscope for ablation performance comparison. The M205C has a smallest vertical adjustment wheel division of 1000th of an inch ( $25.4 \mu\text{m}$ ). Figures 5(a)–5(c) are the typical screenshots of laser ablation area under different sample conditions by Leica M205C series stereomicroscope. A typical dry sample laser ablation area (a) has a discolored or bleached circle, which indicates direct laser radiation impact and most likely reaching elevated temperature, and the center hole depth is the shallowest compared with the wet and in-water samples. A typical wet sample laser ablation area (b) has a bigger and deeper center hole, also with a laser impacted ring around the center hole but without color change. A typical in-water sample laser ablation area (c) has a much bigger and deeper hole. Although it is hard to get a sense of the depth from the two-dimensional pictures in Fig. 5, since they are taken through “one eye,” the shadow

darkness of the center hole is actually an indication of the depth qualitatively. The ablation volume is measured by taking layers of images (up to four layers of images are taken for each sample) of the laser impacted area at different depth which gives us the info on shape and depth, and then for each layer (section), the area of the hole is calculated by open software ImageJ.

### 3 Results and Discussion

Figure 6 shows the calculus ablation volume irradiated in contact mode at three different conditions: dry calculus in air, wet calculus in air, and wet calculus in water. With 3-J total laser radiation, calculus ablation volume was on average  $0.079 \text{ mm}^3$  for dry calculus in air,  $0.122 \text{ mm}^3$  for wet calculus in air, and  $0.391 \text{ mm}^3$  for wet calculus in water, and the standard deviations of all three measurement are all within 15% of the average. Calculus ablation volume for wet calculus in air increased 55% compared with dry calculus in air condition, and calculus ablation volume in water further increased 220% compared with wet calculus in air. The results indicated that there was significant dependency of water content on calculus ablation during laser lithotripsy. To the best of our knowledge, there can be three proposed ablation mechanisms that can explain why water can affect calculus ablation performance including shock wave generation due to laser pulse injection and bubble collapse, spallation, and microexplosion.<sup>15,16</sup>

The main chromophore of  $2.01\text{-}\mu\text{m}$  laser is water. Even though the laser pulse delivering fiber tip is in contact with the calculus surface, there is always a thin layer of water molecules in between the fiber tip and the calculus surface; therefore, a water bubble can be formed at the fiber tip if the laser radiates under water.<sup>9,12,15,16</sup> The shape of the water bubble will



**Fig. 6** Calculus ablation volume under three different conditions.

be a half sphere instead of a full sphere because of the solid calculus boundary limitation. There are two major shock waves for each laser pulse and calculus interaction, one is happening at the beginning of the laser pulse injection, and after some bubble life time, the bubble collapses, and then generate the second shock-wave pulse whose magnitude is associated with shape and size of the bubble, which is dependent on laser pulse duration, pulse energy, and other characteristics. The QS Tm:YAG laser with the pulse duration in nanosecond scale is well known to create a high shock-wave magnitude in water due to "stress confinement" condition,<sup>15,16</sup> and this shock wave can potentially affect calculus ablation performance. In case of dry and wet calculus in air, there was no shock wave due to water bubble collapse generated since the medium surrounding the calculus was air. For wet calculus in-water condition, there was water surrounding the calculus and shock wave due to laser pulse injection and water bubble collapse. From our previous study, in water without calculus phantom in contact with the fiber tip, the shock wave due to bubble collapse can be generated with a magnitude of 75 bars measured by the needle hydrophone at 2 mm away from the fiber tip. The test result in Fig. 6 also indicates a 220% increase in ablation volume for wet calculus in water than in air. Therefore, shock waves due to laser pulse injection and water bubble collapse were a significant factor that enhanced calculus ablation volume in water by QS Tm:YAG laser.

Another two ablation mechanisms were spallation and microexplosion.<sup>15,16</sup> In this study, the 365- $\mu\text{m}$  fiber was in contact with the calculus phantom, a significant portion of laser energy can be absorbed by the calculus phantom with minimal loss through water medium. As the phantom absorbed the laser, stress wave and temperature rise can be induced on the phantom surface due to localized rapid heating. The magnitude of stress wave and the temperature rise is proportional to absorption coefficient of the phantom.<sup>15</sup> In case of wet calculus in air and wet calculus in water, there was some interstitial water residing in the porous phantom. The total absorption coefficient of the wet phantom was expected to be higher compared with the dry phantom because the main chromophore of 2.01- $\mu\text{m}$  laser is water, as aforementioned. Therefore, the higher magnitude of the stress wave in wet calculus can cause more damage to the calculus due to stronger spallation process and this explained why there was 55% higher calculus ablation volume in wet calculus phantom. Not only spallation process but interstitial water in the porous phantom can also induce microexplosion process, because the interstitial water in the porous phantom can vaporize and locally increase the pressure inside the pores, which can also cause the phantom to rupture.

The results from this study gave us some evidence that water content in calculus phantom can affect ablation performance and similar tests can be conducted for Ho:YAG laser lithotripter in the future.

## 4 Conclusions

To our best knowledge, this is the first paper on investigation of lithotripsy ablation by Tm:YAG laser of 2.01  $\mu\text{m}$  with Q-switch operation. Based on the current setup, calculus ablation was dependent on water content in calculus phantom. Calculus ablation volume was 0.079, 0.122, and 0.391  $\text{mm}^3$  for dry calculus in air, wet calculus in air, and wet calculus in-water conditions, respectively, by a total 3-J laser pulse exposure (20 mJ, 100 Hz, 1.5s). Three ablation mechanisms that can explain why water can

affect calculus ablation performance were shock wave due to bubble collapse, spallation, and microexplosion. Increased absorption coefficient of wet calculus can cause stronger spallation process and can be a reason why higher calculus ablation volume was observed on wet calculus in air and in-water conditions. Interstitial water in the porous phantom can also help enhance calculus ablation through microexplosion process. The test result also indicates that the shock waves generated by short laser pulse under the in-water condition have great impact of the ablation volume by Tm:YAG QS laser lithotripter.

## Acknowledgments

The authors thank Joanne Banuelos of Boston Scientific Corporation for her assistance with preparing white gypsum cement used as tissue phantom, and Xirong Yang, Mike Scott, and Jason Gong of Boston Scientific Corporation for their assistance with preparing Tm:YAG QS laser system.

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