Bubble Dynamics in Laser Lithotripsy

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Abstract. Laser lithotripsy is a medical procedure for fragmentation of urinary stones with a fiber guided laser pulse of several hundred microseconds long. Using high-speed photography, we present an in-vitro study of bubble dynamics and stone motion induced by Ho:YAG laser lithotripsy. The experiments reveal that detectable stone motion starts only after the bubble collapse, which we relate with the collapse-induced liquid flow. Additionally, we model the bubble formation and dynamics using a set of 2D Rayleigh-Plesset equations with the measured laser pulse profile as an input. The aim is to reduce stone motion through modification of the temporal laser pulse profile, which affects the collapse scenario and consequently the remnant liquid motion.

1. Introduction
As a minimally invasive method of fragmenting urinary stones, intracorporeal laser lithotripsy has been in use for over two decades [3]. In this procedure, an endoscope is inserted into the urethra to locate calculi and a fiber optic is inserted through the working channel of the scope. A pulsed laser is coupled into the fiber to irradiate the stone, causing the stone to disintegrate into smaller fragments which are later on washed out of the urinary tract. The most commonly used laser type is Holmium:YAG (λ = 2.01 μm) with a long pulse duration (e.g. τ = 300 μs). In Ho:YAG laser lithotripsy, the fundamental mechanism of transfer of laser energy to the stone is through formation of a vapor bubble that bridges the fiber optic with the urinary stone. Then the calculus absorbs the laser energy and is fragmented due to a photothermal mechanism [6].

The reported clinical challenge involved with laser lithotripsy is the retropulsive movement of the stone during laser ablation. Stone motion can prolong the operation time and cause clinical complications [5]. In order to reduce stone retropulsion, the effect of several parameters has been experimentally investigated, including optical pulse energy, fiber diameter, and the pulse length. Recent studies have shown that longer pulses reduce stone retropulsion [4].

Using high-speed photography, we have conducted in-vitro experiments for different settings of a clinical Ho:YAG laser while recording the bubble dynamics, stone motion, and the temporal pulse profile. Also we present a simple model to relate the laser pulse with the observed bubble dynamics.

2. Experimental setup
The experimental set-up is shown from the side and top view in figure 1. A transparent acrylic container (6 mm) is filled with water. An acrylic cube (100 x 50 x 57 mm) serves as stone phantom. The 270 μm fiber from the clinical Ho:YAG (Dornier, Ho:YAG λ =2.01 μm) is inserted from the right into the container. The dynamics of the bubble and stone movement is observed with a high-speed camera (Photron FASTCAM SA-X2). Illumination (200 W metal halide lamp) is provided from the back through a glass diffuser. The temporal profile of the laser pulse...
3. Experimental results: bubble dynamics and stone movement

Figure 2 depicts three series of images of bubble dynamics and stone movement. The first set, figure 2a, displays the growth and collapse of the elongated bubble during the Ho:YAG laser pulse. There the bubble grows from a pear shape to an elongated shape and collapses within 700 µs. The photodiode recordings of the laser pulse profile (see figure 3) reveal that the bubble grows as long as the laser is on, thus reaching its maximum size just before the laser pulse is switched off. After the laser energy is no longer deposited in the medium, the bubble starts shrinking and collapses within a few hundreds of microseconds.

The physical process that leads to formation of such elongated bubbles during mid-infrared laser irradiation is the metastable vaporization of superheated liquid [7]. During laser lithotripsy, the pulse width, \( \tau \), is significantly larger than the acoustic relaxation, but smaller than thermal relaxation time:

\[
t_{st} = \frac{\delta}{c} < \tau < t_{th} = \frac{\delta^2}{4k}.
\]

Here \( c \) is the speed of sound, \( k \) is the thermal diffusivity of the liquid medium, and \( \delta \) is the length scale of the irradiation volume, in this case the fiber diameter. For a Ho:YAG laser pulse of \( \tau=300\mu s \) delivered into water with a fiber diameter \( d=300\mu m \), since \( t_{st}=100\text{ ns} < \tau \), stress confinement does not occur and therefore no significant shock waves are produced during bubble formation. However, since \( \tau < t_{th} =1\text{ ms} \), the liquid is heated under thermal confinement, and maximum possible temperature is obtained inside the irradiated volume. In this condition, the liquid could be heated up to the spinodal limit before phase explosion leads to the formation of a vapor bubble. Optical temperature probing techniques show that water can be heated up to 250°C before phase transition occurs and the bubble is formed [2].

In the experiments with a phantom stone in front of the fiber optic, we observe that the formation of a vapor bubble is necessary for transmission of laser energy to the stone. Once the
bubble touches the stone, ablation of acrylic material occurs. Figure 2b reveals that the water separating the phantom from the fiber tip is vaporized and the ablation process begins once the vapor bubble reaches the phantom. Having a transparent phantom, transmission of the laser light into the phantom and resulting ablation of the material becomes visible as a bright region within the phantom, see circle in figure 2b. During this process the stone does not move.

As it is shown in figure 2c, the stone motion happens after the bubble collapse, and for a much longer time scale (80 ms) compared to the life time of the bubble (0.7 ms). We speculate that a ring vortex is created during the bubble collapse, the origin of which could be the liquid jet moving towards the stone. The heat induced Schlieren in the water allows us to reveal the long lasting circulatory liquid motion.

Figure 3. Photodiode recordings of the Ho:YAG laser pulse. Energy of the laser increases from setting 1 to setting 4. Although the peak power does not differ much between different settings, the pulse duration varies considerably.

Figure 4. Simulation results for two different laser settings compared with experiments. Bubble length ($z$) is along the axis of the fiber optic, while bubble width ($R(z,t)$) is normal to the fiber axis.

4. Mathematical modeling of the bubble shape

Similar to the modeling of elongated cavities for the classical water entry problem [1], we model the shape of the elongated bubble in laser lithotripsy by discrete layers, where each layer is governed by a two dimensional Rayleigh-Plesset equation. This model is based on the assumption of pure radial and potential flow. The full form of 2D Rayleigh-Plesset equation for a non-confined bubble is

$$
\left( R \ddot{R} + \dot{R}^2 \right) \log\left( \frac{R_{\infty}}{R} \right) - \frac{1}{2} \dot{R}^2 = \frac{-p_{\infty}(t) + p_B(t)}{p_l} - \frac{2\nu \dot{R}}{R} - \frac{\sigma}{p_l R},
$$

where all the variables are defined similar to [1]. We model the radius of the elongated cavity at any distance $z$ away from the fiber tip ($z = 0$) and time $t$, i.e. $R(z,t)$.

Based on the above model, two initial conditions are necessary to find the bubble shape at any time: initial radial velocity of each layer, and the time each layer starts expanding. These conditions are found through an energy balance argument based on hemispherical vaporization of the liquid at the fiber tip. At each layer, the bubble starts expanding with an initial radial velocity that is linearly correlated with the laser power $\dot{R}(z,t) = K_{exp} p_l(t = t_z)$. Here $K_{exp}$ is the correlation constant which could be found experimentally or estimated based on thermodynamics of superheated vaporization, and $p_l(t)$ is the laser power as a function of time. The time $t_z$ is the time when the laser has down to depth $z$, which is found from $t_z = E^{-1}(\frac{z}{K_{exp}})$,
where \( E(t) = \int_0^t p(t) \, dt \) is the laser energy deposited in the liquid up to time \( t \), and \( E^{-1} \) denotes the inverse of this function.

The photodiode measurements, see figure 3, are used as input for the bubble dynamics simulations for two different settings of a Ho:YAG laser. The results are compiled in figure 4. Although the peak power between both settings differs by less than 10% (see figure 3) their total pulse duration varies by 80%. In order to find how these different pulse profiles affect the bubble dynamics, we have plotted the bubble length as a function of time for the duration of laser irradiation, and maximum bubble radius for each setting in figure 4. The bubble length shows fair agreement with an average error of 20% with the simulation, while the bubble width \( (R_{\text{max}}) \) and collapse time \( (t_c) \) have a discrepancy of 10%. We understand that the model has shortcomings, in particular in the beginning of the pulse where a spherical bubble is generated. We are currently accounting for this. Nevertheless, the shape, temporal and spatial dynamics provide overall agreement.

5. Conclusion
While laser lithotripsy has been used as a standard method for fragmentation of urinary stones for over two decades, there are still unresolved problems regarding the physical process that takes place during this procedure. Regarding one of the main challenges in laser lithotripsy, stone movement, it should be noted that the motion happens after the bubble collapse and lasts for a long time, for about 100 ms, while the bubble life time is about 500 µs. Therefore, by controlling the bubble dynamics, we aim to reduce the liquid motion and stone movement after the collapse. Using a mathematical model for an elongated bubble, we show that it is possible to correlate the bubble dynamics with the laser pulse. We are currently developing a suitable laser system which may allows us to mitigate stone motion.

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