Modelling of Laser-Induced Cavitation Bubbles for Ureteroscopy

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The kidneys are two hollow fist-size organs that filter the blood, removing waste and excess water and producing urine. The urine then passes through the tube-like ureters to the bladder. Kidney stones are mineral deposits, most commonly *calcium oxalate*, that grow in the ureters or the hollow cavity of the kidneys. Stones occur when there is an excess of stone-forming chemicals in the urine, and/or a lack of stone-inhibiting chemicals. Kidney stones affect 13% of the UK population with a recurrence rate of approximately 50% within ten years.

One of the most common treatments for kidney stones is *ureteroscopy and laser lithotripsy*, commonly referred to as just ureteroscopy. In this process, a *ureteroscope*, a tube with a small camera and light at the tip, is passed through the urethra and bladder and into the ureter or kidney to the position of the stone. The ureteroscope contains a hollow cylindrical *working channel* in which tools, including an optical fibre, are inserted. The stone is broken by laser lithography, in which a packet of laser pulses is directed at the kidney stone to either fragment it into smaller chunks that can be retrieved individually or to "dust" it into pieces that are so small they can be flushed out. Saline is pumped to the area of the stone through a channel in the scope and flows out between the scope and ureter to clear dust and debris. Ureteroscopy is performed under anaesthetic and takes between 60 and 90 minutes.

Energy from the laser is transferred to the kidney stone as thermal energy, which is the primary mechanism for fragmentation. However, some laser energy is also transferred to the surrounding fluid in the kidney, causing heating and phase changes. An initial laser pulse produces a vapour bubble between the laser fibre and the stone, as can be seen in Figure 1, and therefore subsequent laser pulses partially pass through this bubble. As vapour absorbs significantly less energy than liquid, the bubble allows more of the energy from the subsequent pulses to reach the stone; for this reason, a bubble is considered beneficial. Once the bubble collapses, the next pulse will again create a bubble and the process continues. However, bubbles can also have detrimental effects, for example if a bubble collapses too energetically, the stone can be pushed away.

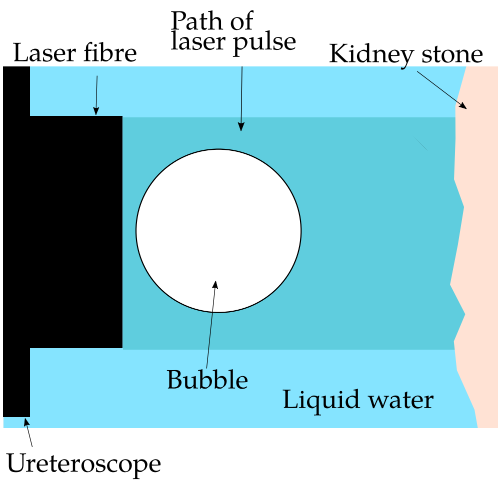

Figure 1 – Schematic of bubble, laser fibre and stone. Diagram not to scale.

Newer laser systems give increased choices of power, frequency and duration of pulses, and allow surgeons to control the way in which the stone breaks. For dusting in particular, it is preferable to have a high-frequency low power transfer of energy to the stone. Our objective is to develop a mathematical framework suitable for studying laser and bubble interactions and quantifying optimal laser settings.

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Model

We focus on finding the pattern of laser pulses within a packet that maximises the lifetime of the bubble. We define t_c to be the first instance at which the bubble reaches its maximum radius before beginning to collapse. We model the bubble as a spherical region of water vapour and non-condensible gas, such as air, within liquid water. The bubble's expansion and contraction is described by balancing the energies in the system, namely the kinetic energy of the liquid surrounding the bubble, and the potential energy due to a pressure difference inside and outside the bubble.

We assume that we begin with a micro-bubble at rest, i.e. not expanding or contracting, and therefore with zero kinetic energy. Firing a single laser pulse gives the bubble an amount of energy which is transferred into kinetic energy, causing expansion. The expansion continues until the pressure within the bubble drops low enough to cause the bubble to collapse. The collapse in turn creates high pressure within the bubble and so the bubble expands again. This is a simplification of the real mechanisms at play and, in particular, neglects any temperature or phase changes that occur once the bubble has been created. We also neglect all forms of energy loss and therefore the cycle of expansion and collapse continues infinitely as depicted by the blue line in Figure 2.

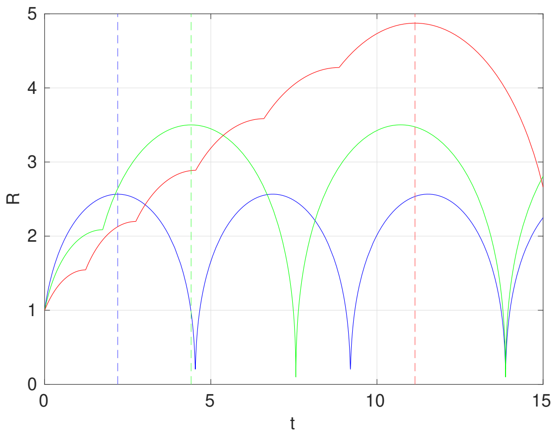

Figure 2 – Graphs showing how the radius of the bubble varies over time. The blue, green and red lines are the cases of one, two and six pulses respectively. The dashed line in each colour marks t_c for that bubble. In each case, the energy has been distributed optimally for that number of pulses to maximise t_c.

We study the effect of splitting the quantity of laser energy into a packet of two smaller pulses; after the first pulse is fired, while the bubble is still in the expansion phase, we fire a second pulse to "boost" the kinetic energy. We look at both the timing and distribution of energy between the two pulses, using various mathematical and computational techniques, to find the conditions that maximise t_c. We find that, after giving the first pulse, it is optimal to wait for the bubble to expand to its maximum radius before giving another pulse to cause further expansion, as shown in the green line in Figure 2. We also find that is it optimal to split the energy unevenly between the two pulses, with more energy in the second pulse. The exact optimal split is dependent on a number of parameters, such as the initial bubble size and the intensity of the laser. We then consider a packet of up to six pulses. Following the result for two pulses, we assume that it is always optimal to give each pulse when the bubble is at the peak of expansion from the previous pulse, as depicted for the case of six pulses by the red line in Figure 2. We then find (computationally) the distribution of energy between the pulses that maximises t_c. In all cases, we see that less energy should be dedicated to the earlier pulses.

Conclusions

We have constructed a mathematical model to describe the dynamics of a vapour bubble in liquid as it absorbs pulses of laser energy. We found that, to maximise the lifetime of the bubble, it is optimal to split the laser energy into many smaller pulses, at least up to the case of 6 pulses; this result can be seen in Figure 2. Following the initial pulse, each subsequent pulse should be given when the bubble reaches its maximum radius. We have also developed the tools to find the optimal percentage of energy to dedicate to each pulse, for a given set of parameters.

We have taken the first steps in predicting the behaviour of laser-induced bubbles for ureteroscopy. We intend to improve this model in future work to give further control over the shape and size of the bubble. When an optimal pule pattern is found, it can be quickly tested and implemented by utilising the existing settings of the laser. Predicting the behaviour of the bubble will remove uncertainly during ureteroscopy allowing the procedure to be quicker and easier for the surgeon and safer for the patient.

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