Underwater holmium-laser-pulse-induced complete cavitation bubble movements and acoustic transients

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The complete evolution of holmium-laser-pulse-induced cavitation bubble movements and acoustic transients underwater are investigated experimentally. The laser was single fiber-guided and had a 300 mJ pulse energy and 300 μ s pulse duration (full width at half-maximum). In our experiments, more than four oscillations and four acoustic transients were demonstrated. 272 μ s after laser onset, the cavitation bubbles reached their maximum transverse and longitudinal lengths of 2046 and 1914 μ m, respectively. The maximum transverse and longitudinal bubble wall velocities were 28.9 and 39.2 m/s at 560 and 528 μ s after laser onset, respectively. This investigation will be helpful to make good use of cavitation effect in medical applications of holmium laser pulses.

cavitation bubble, acoustic transient, holmium laser pulse

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Pulsed holmium lasers at wavelengths of 2.12 μ m have attracted considerable interest, because of their applications in the precise removal of biological tissues [1]. When the optical fiber is not in direct contact with the target tissue, cavitation bubbles (CB) are formed by absorption of the laser radiation by the liquid separating the fiber tip and the tissue surface [2]. These bubbles can directly affect the laser ablation process [3]. After formation, the CB undergoes multiple cycles of expansion and collapse, accompanying shockwave emission [2,4]. However, many studies have reported that this evolution is not sequential but transient. All images must be reconstructed from different CBs induced by pulsed lasers with identical parameters [5] by performing shadow and Schlieren photography [2,4–10]. However, because of the poor pulse-to-pulse repeatability of these laser sources, the pulse width, pulse energy and response time always fluctuate even under the same ambient environments. Consequently, the presented images cannot

represent the true dynamics of the CBs [6]. Therefore, it is necessary to visualize the complete evolution of a CB induced by a single holmium laser pulse. This will aid in the explanation of the full effect of CBs on tissue ablation applications.

A schematic diagram of the experimental setup is shown in Figure 1. A DG645 digital delay/pulse generator (Stanford Research Systems, USA) was linked to a holmium laser system (Wuhan National Laboratory for Optoelectronics), a high-speed camera (FASTCAM SA1.1, Japan) and an oscillograph (Agilent Technologies InfiniVision, 350 MHz, 2 GSa/s). After the LED light source (Balogh, SLT-P007, LED luminance >12000 Mcd) was initiated independently, the pulse generator could be used in a single-shot-triggering mode. The bubble dynamics and acoustic transients were recorded and detected using the camera and needle hydrophone (Institute of Acoustics, Chinese Academy of Sciences, sensitivity > 10 nV/Pa), respectively. The distal fiber tip was placed in a 10 cm $\times$ 10 cm $\times$ 10 cm quartz container filled with pure water, and was kept 3 cm

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Figure 1 Schematic diagram of the experimental setup.

below the water surface to insure sufficient inertial confinement.

It can be seen from Figure 2 that more than four oscillations occurred. Brightness variations could be observed for more than three oscillations. However, the corresponding volume variations could not be confirmed. Less than 48 μs after laser onset, the CB began to form, which agrees well with previously reported results [8]. The CB was pear-shaped during the first oscillation period, but the CB separated from the fiber tip at the beginning of the second oscillation period and took on a mushroom-shape. At the beginning of the third period, the bubble shape was more irregular. At 616 μs , the CB collapsed and then divided into two parts. During the fourth oscillation period at 632 μs , the two parts then recombined into one that had an increased diameter 495 μm . After 632 μs , the diameter of the bubble stayed approximately constant at 495 μm .

In Figure 3 the maximal transverse lengths can reach 2046, 1036, 693, 495 μm at 272, 484, 600, 632 μs after laser onset, respectively. The maximal longitudinal lengths can reach 1914, 1386, 660, 495 μm at 272, 512, 592, 632 μs after laser onset, respectively. From 64 to 224 μs , the corre-

lation of the transverse and longitudinal diameters of CBs with respect to time are approximately linear. Their transverse and longitudinal diameters vary from 660 and 495 μm to 1980 and 1815 μm , respectively. Then they maintain the same diameters of 1980 and 1815 μm from 224 to 240 μs . At 256 μs they increase to 2046 and 1914 μm , respectively, and maintain the same diameters for about 32 μs (from 256 to 288 μs). Another important phenomenon during every oscillation period, especially for the first, is that the slopes of the diameter change with respect to time for transverse diameters are slower than those of longitudinal diameters. The last important phenomenon is that the transverse diameters are always bigger than the longitudinal diameters, except when close to the maximum expansion phase during the second expansion phase because of a small part of bubble attached to the fiber tip (this phenomenon vanishes after 484 μs). In Figure 4 during the entire oscillation process the longitudinal bubble wall velocities are always faster than the transverse bubble wall velocities, and their maximal velocities reach 39.2 and 28.9 m/s at 528 and 560 μs after laser onset, respectively.

To avoid the acoustic transients induced by bubble collapse, which can damage the hydrophone, and effects from the hydrophone on the bubble dynamics, the distance between the tips of the hydrophone and the fiber was set to 4 mm. The absolute pressure measurement results, without the preamplifier, are shown in Figure 5. In addition to the strong pressure peaks (marked 1–4), which were induced by the collapse phases of the bubble oscillations (1–4), there is a slow increase in pressure (shown by the arrow) after the beginning of the laser pulse. This is an indication of CB formation [6]. The pressures were 23.375, 8, 6.7 and 2.96 bar for peaks 1, 2, 3 and 4, respectively. The minimum bubble radius is smaller than 300 μm (see image taken at 416 μs in Figure 2). Therefore, if we assume a $1/r$ damping of

Figure 2 Sequential images of CB formation recorded using a high-speed camera with a frame rate of 25000 frames per second. The time (μs) given for each image represents the time after the onset of a single holmium laser pulse ($E_p = 300$ mJ, duration = 300 μs). The pulses were delivered via a fiber of 600 μm core diameter and a 660 μm cladding diameter. The object on the left side of the first picture is the needle hydrophone.

Figure 3 Time evolution of the transverse and longitudinal lengths.

Figure 4 Time evolution of the transverse and longitudinal velocities of the bubble walls. $V>0$ and $V<0$ denote expansion and collapse velocities, respectively.

the pressure, where r is the distance from the collapse center, we calculate a pressure of more than 312 bar at a distance of 300 μm from the collapse center. From the high-speed photography results (Figure 2), it can be seen that 40 μs after holmium laser onset the CB begins to form. Because the time interval between the bubble formation and the first acoustic transient is 278 μs , we calculated that the first pressure pulse is generated 18 μs after the end of holmium laser pulse. This agrees with the findings in [6].

Assuming that the temporal profiles of the positive pressure waves (shown in Figure 5 I, II, III and IV) can be approximated by exponential pulses with full width at half maximum pulse durations equal to those given by the hydrophone measurements [11], we calculated the relevant parameters of the corresponding four shock waves. These are listed in Table 1. The efficiency of energy conversion from the holmium laser pulse to acoustic transients was up to 0.0927%.

In our experimental results, the four shock waves had bipolar shapes with a positive compression wave followed by a negative wave. However, other researchers [2,5–10]

Figure 5 Oscilloscope traces of the acoustic transients induced by the CB evolution ($E_p = 300$ mJ, duration = 300 μs) at the submerged fiber tip (600 μm). The four shock waves, 1, 2, 3 and 4 are shown on shorter time scales in I, II, III and IV, respectively.

Table 1 Parameters of the acoustic transients

Acoustic transient	Δt_s (ns)	p_s (MPa) ^{a)}	E_s (μJ) ^{b)}	E_s/E_p (%)
No. 1	520	2.3375	278	0.0927
No. 2	880	0.8023	55.5023	0.0183
No. 3	800	0.6744	36.6517	0.0122
No. 4	520	0.2965	4.437	0.0015

a) p_s , Shock wave peak pressure; b) E_s , shock wave energy.

reported there was only a positive compression wave, which are induced by free-running holmium lasers (pulse widths of several hundreds μs). However, our observation can be explained in terms of momentum conservation. If the cavitation threshold is exceeded, the total momentum, which is proportional to the time integral over the stress wave, must remain zero. On the other hand, the initial asymmetry of the bipolar wave must be compensated by this additional negative stress [12]. Furthermore, the response time (several decades nanoseconds) of the needle hydrophone is too slow to satisfy the experimental requirements. Therefore, this phenomenon must be further investigated theoretically and experimentally in future work.

In conclusion, the complete evolution of holmium-laser-pulse-induced cavitation bubble movements and acoustic transients was investigated. An acoustic transient with peak compress wave of 312 bar was generated by the first collapse of the induced CB. This suggests that CB formation is a potential cause of acoustical tissue damage during medical

application of holmium laser pulses in a liquid environment such as arthroscopic or angioplasty surgery.

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