Cloud cavitation induced by shock-bubble interaction in a viscoelastic solid

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Abstract.
We experimentally study a shock-bubble interaction problem in a viscoelastic solid, which is relevant to shock wave lithotripsy. A gas bubble is produced by focusing an infrared laser pulse into gelatin. A spherical shock is then created, through rapid expansion of plasma that results from the laser focusing, in the vicinity of the gas bubble. The shock-bubble interaction is recorded by a CCD camera with flash illumination of a nanosecond green laser pulse. The observation captures cavitation inception in the gelatin under tension that results from acoustic impedance mismatching at the bubble wall. Namely, the shock reflects at the bubble interface as a rarefaction wave, which induces the nucleation of cavitation bubbles as a result of rupturing the gelatin.

1. Introduction

Cavitation is utilized in non-invasive medical treatment such as shock wave lithotripsy (SWL) and high-intensity focused ultrasound (HIFU) [1, 2]. When these acoustic waves are focused into the diseased part of patients (e.g., kidney stones or cancer cells), cloud cavitation will occur in the targeted region. The therapy is expected through mechanical and/or thermal actions of the cavitation bubble dynamics [3, 4]. However, controlling the extent of the acoustic cavitation is difficult and may give rise to side effects including unwanted tissue damage.

To minimize the side effects while maintaining the efficacy of cavitation treatment, controlling the nucleation of cavitation bubbles is desirable. One of difficulties in controlling the cavitating region is due to secondary cavitation resulting from interaction between incoming acoustic waves and the pre-existing cavitation bubbles. Such secondary cavitation is reported in the HIFU experiment where cavitation bubbles are nucleated by the backscattering of focused ultrasound from a pre-existing bubble in a gelatin-based tissue-mimicking phantom [5]; the compression part of the ultrasound is reflected as tension through acoustic impedance mismatching at the bubble wall [6], rupturing the material (i.e., the nucleation of cavitation bubbles). Similarly, secondary cavitation in water is obtained by interaction between laser-induced shocks and bubbles [7]. However, experimental observation of cavitation resulting from shock-bubble interaction in tissue-like materials is still lacking.

In this paper, we observe cloud cavitation induced by shock-bubble interaction in a tissue-mimicking material. The shock-bubble interaction and the subsequent cavitation in gelatin are captured by stroboscopic photography based on a nanosecond pulse laser. In what follows, we introduce the experimental procedure to visualize laser-induced phenomena and present analyses of the shock and cavitation dynamics.

2. Experiments

Sample preparation

A gelatin phantom was used as a tissue-mimicking medium. The phantoms were made by mixing 10 wt% gelatin (Type-A, Sigma Aldrich, St. Louis, MO, USA) with water. The solution was poured into a cylindrical dish (polystyrene) of 56 mm diameter and 16 mm height. The solution was stored in refrigeration at 4°C overnight and placed in room temperature before experiments.

Optical set-up

The experimental set-up (similar to that of Ando *et al.* [8]) was shown in Fig. 1. A Q-switched Nd:YAG laser (ULTRA 50 GRM, Quantel) emits single laser pulses simultaneously at wavelengths of 532 nm (green) and 1064 nm (infrared or IR) with a duration of 6 ns. An infrared pulse delivered into the gel was 1.58 ± 0.08 mJ (the ± sign denotes a standard deviation from 10 measurements). Optical breakdown was induced by focusing an IR laser pulse through a microscope objective (10×, NA = 0.25). After the optical breakdown, a spherical shock wave is radiated and a bubble arises from vaporization in the gelatin behind the shock [9]. Shadowgraphs (from top view) of the laser-induced phenomena (including shock-bubble interaction and the subsequent secondary cavitation) in the gelatin were captured using a CCD camera (Pixcelfly, PCO; one pixel = 0.6 μm) with stroboscopic illumination of a green laser pulse. The illumination timing was tuned by changing the length of the single-mode optical fiber through which the green laser pulse propagates.

Shock evolution measurement

The evolution of the laser-induced shock was first visualized in the gelatin (without bubbles inside) so as to estimate the shock pressure. To avoid wave reflections within the gelatin case, the IR laser pulse was focused sufficiently away from any boundaries.

Visualizing the shock-bubble interaction

A pre-existing, spherical gas bubble was created by focusing the IR laser pulse into the gelatin; even after the laser bubble collapses, non-condensible gas contents (air) are left. The size of the gas bubble slowly changes due to mass transfer driven by Laplace pressure effects [10]. When the bubble radius reaches 150 μm, the IR laser pulse was shot in the vicinity of the gas bubble in order to observe the interaction with the laser-induced shock. The distance from the laser focus to the proximal bubble wall is set at d = 121 μm (Fig. 2).

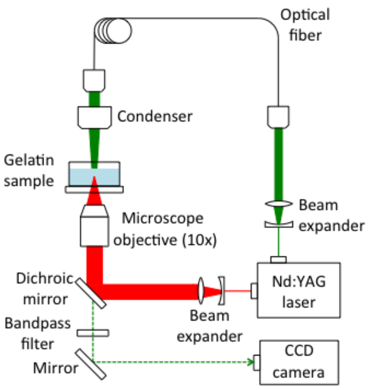


Figure 1. The optical system for visialization of laser-induced phenomena in gelatin.

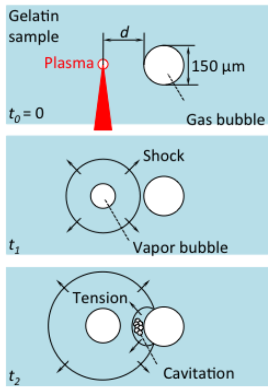


Figure 2. Sequence of the interaction of the laser-induced shock with a pre-existing gas bubble.

3. Results and discussion

Shock pressure estimation

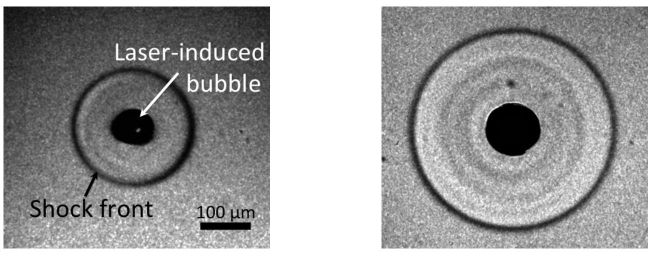
Figure 3 shows sequential images of the laser-induced shock and bubble. The shock is identified as a dark annulus and its front is defined as the midpoint of the annulus. Figure 4(A) shows the the temporal evolution of the shock front whose position, r_s, is measured from the laser focus; each point (denoted by the circle) is the average out of 10 measurements and the error bar represents the standard deviations. Noting that the shock speed is eventually reduced to the speed of sound, the shock front positions in Figure 4(A) are found to be well fitted to

$$r_s(t) = a_1 + C_0 t - a_2 \exp\left(-\frac{t - a_3}{a_4}\right) \tag{1}$$

where C_0 is the speed of sound in the gelatin phantom at room temperature (1520 m/s [11]), and a_1, a_2, a_3 and a_4 are parameters to be fitted by the least-squares method. Substituting the shock speed calculated from the fitting function (1) into the Rankine–Hugoniot relation for stiffened-gas-type materials [12], the shock pressure that depends on the distance from the laser focus is estimated (see Fig. 4(B)).

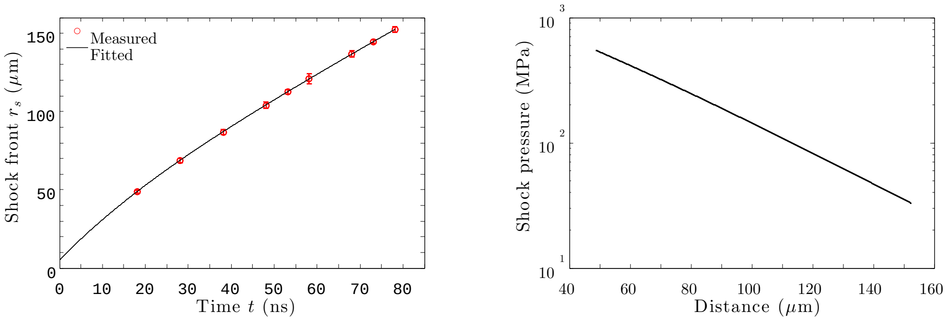
Shock-bubble interaction and cavitation

Figure 5 shows the sequential images of the laser-induced shock interacting with the pre-existing gas bubble in the gelatin. The shock wave reaches at the bubble wall in Fig. 5(A); the shock pressure is predicted at 81 MPa from Fig. 4(B). After the shock collision, it is reflected as a tension wave due to acoustic impedance mismatch between the gelatin and the bubble. This tension ruptures the gelatin, thus nucleating a cloud of cavitation bubbles as seen in Fig. 5(B). The secondary cloud cavitation is extending at a later time in Fig. 5(C). The pressure in the gelatin after the tension wave passage is determined by superimposing the incoming (shock) and reflected (tension) waves. Assuming that the incident shock decays significantly after its collision with the bubble, the gelatin under tension can in principle be subjected to very large negative



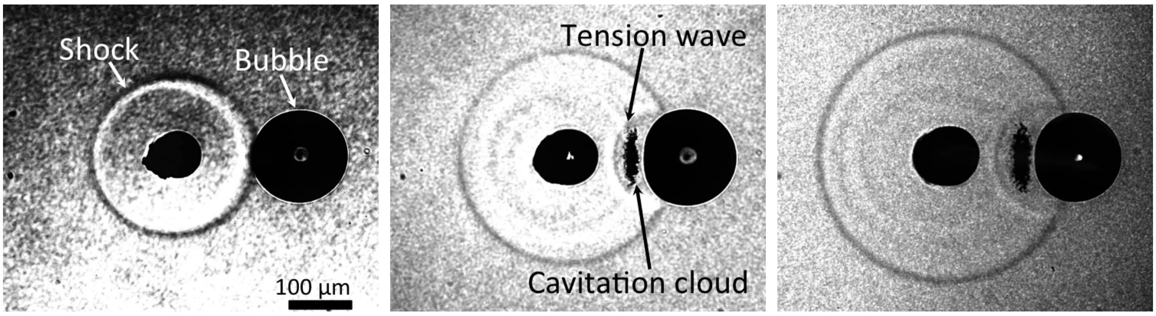
(A) 48.1 ns (B) 98.1 ns

Figure 3. Evolution of the laser-induced shock and bubble in the gelatin different times after the laser focusing. The time is measured from the laser focusing.



(A) (B)

Figure 4. (A) Temporal evolution of the shock front. (B) Shock pressure as a function of distance from the laser focus.



(A) 58.1 ns (B) 78.1 ns (C) 98.1 ns

Figure 5. Evolution of shock-bubble interaction and its accompanying cavitation in the gelatin. The time is measured from the laser focusing.

pressures (say, down to −81 MPa). However, before reaching such negative pressures, the gelatin would be ruptured with bubble nucleation at cavitation thresholds as seen in Figs. 5(B) and (C). This observation indicates that cavitating regions may possibly be extended due to the interaction between shocks and pre-existing cavitation bubbles in the application of SWL.

4. Conclusion

In this paper, we have demonstrate the possibility of having secondary cavitation in the viscoelastic solid induced by the interaction of a laser-induced shock wave and a pre-exsiting gas bubble, indicating a need to account for shock-bubble interaction in order to control cavitating regions in the application of SWL.

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