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We present experimental observations of microjets formed by cavitation microbubbles. An underwater electric discharge, applied beneath a flat free surface, produces a primary compression wave, which undergoes several phase inversions upon reflections from the free surface and spark-bubble interface. The first reflection yields a tension wave, which produces a cloud of secondary cavitation bubbles in the liquid, some of which form microjets upon collapse. The tuning of these reflections enables an effective control of the microjet direction in the bubble cloud. All of the jets of the microbubbles between the spark bubble and free surface are directed radially away from the spark bubble. The mechanical response of an alumina plate placed between the electrodes and free surface generates a quasi-planar compression wave, which, following its multiple reflections from the free surface and plate, orients the microjets in the same direction toward the plate. These observations imply that the jet direction is determined mainly by the secondary compression wave, which is the first and thus most energetic compression wave acting on a sufficiently grown cavitation bubble. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

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In recent years, cavitating bubbles have attracted significant attention for medical applications owing to the powerful phenomena occurring during their violent collapse and ensuing mechanical and chemical effects. The erosive power of these bubbles is mostly attributed to the shock wave emission and formation of high-speed microjets as the bubbles collapse in a nonspherical manner. Shock waves from extracorporeal lithotripters (ESWL) transfer proteins into cells,1 which is likely attributed to the formation of small cavities produced by the tensile phase of the ESWL or by their reflections from bodily tissues.2 Ultrasonic irradiation of cells in the presence of microbubbles enhances the membrane permeabilization; this phenomenon is referred to as sonoporation, which assists targeted cellular drug or gene delivery.3–5 Many mechanisms for cell penetration by these bubbles have been suggested, one of which is the formation of directed microjets.6 Therefore, the control of the microjet direction could promote such localized targeting.

Extensive theoretical, experimental, and numerical studies have been carried out to investigate the formation of microjets due to shock waves acting on bubbles, with pioneering work having started a few decades ago.7,8 The directions of microjets have been controlled using a planar shock wave9 or focused ultrasound10 on existing bubbles. The microjet is generally oriented in the direction of the shock wave propagation. However, in confined environments, such as in-between different tissues in the body, the subsequent reflections of the pressure waves from surfaces make the control of the microjetting more complex. In particular, it is important to understand the behavior of a cloud of gas or vapor bubbles when complex interactions between pressure waves and surfaces are involved, which typically occurs in most medical applications.

In this study, we experimentally investigate the jetting in secondary microcavities produced in water by the first shock wave reflection from the free surface. In order to tune the jetting direction, the interactions between a near free surface and two types of shock waves are analyzed: one with a spherical and one with a quasi-planar propagation.

A schematic of the experimental setup is shown in Fig. 1. It consists of generation of a cavitation bubble using an electric-discharge-induced plasma in a small cuvette (25 × 30 × 60 mm³) filled with distilled and air-saturated water. The pulsed high-voltage circuit consists of a DC power source, spark gap switch, resistances, and capacitors; it can produce a voltage of up to 30 kV.11 The spherically propagating shock wave, denoted as primary compression wave, is generated by the vapor bubble expansion from the spark plasma, denoted as the primary bubble (potential energy at the maximum radius: ~1.4 mJ). The quasi-planar wave is produced by placing a 0.2-mm-thick alumina plate above and in contact with the electrodes. The mechanism for the primary compression wave generation is different: as an electric discharge is applied, the mechanical response of the excited plate generates a quasi-planar compression wave upward into the liquid. Shadowgraphs of the pressure wave
propagations and bubble dynamics are recorded with an ultra-high-speed intensified charge-coupled device (ICCD) camera (ULTRA Neo, NAC Image Technology Co. Ltd.), which could capture 12 subsequent images with a speed of up to $200 \times 10^6$ frames/s and an exposure time of 5 ns, and with a CMOS camera (HPV-X, Shimadzu) capturing 256 frames with a speed of up to $10 \times 10^6$ frames/s and an exposure time of 60 ns. A continuous laser is used for backlight illumination. The image is magnified up to a magnification of 300 by a large-distance microscopic objective (VHZ-50L, Keyence). The pressures of the various compression and tension waves are measured using a calibrated fiber optic probe hydrophone (FOPH 2000, RP Acoustics) with a bandwidth of up to 100 MHz and rise-time of 3 ns. The hydrophone tip is placed under the free surface of the water, above the electrodes. The optical hydrophone is connected to an oscilloscope (WaveSurfer MXs-B, Lecroy) sampling at 1 GHz.

Figure 2(a) illustrates a typical interaction of the spherical primary compression wave emitted at the electric discharge with a free surface. Secondary cavitation bubbles (maximum radius range: 20–120 μm) appear in a stochastic manner between the primary bubble and free surface after the passage of the reflected tension wave [Fig. 2(b)]. The microjets emerge during the rebound of these microbubbles; they have the same direction as that of the spherically propagating primary compression wave. Figure 2(c) visualizes such microjets and shows their directions for bubbles in different positions with respect to the center of the electrodes. An example of the life of a jetting bubble is presented in Fig. 2(d). Further reflection of the tension wave from the primary bubble interface causes another phase inversion, turning the tension wave back into a compression wave, denoted as the secondary compression wave. Such a wave is visible at approximately 1.5 μs after the electric discharge in the fiber optic probe hydrophone signal in Fig. 2(e). The severe noise in the beginning of the signal is caused by the electric discharge. The directions of all of the observed microjets projected onto the 2D image plane are presented in Fig. 2(f) as angles between the jet and vertical axis as a function of the bubble position with respect to the center of the electrodes. The bubble position and microjet angles are denoted in (c).
primary compression wave or later reflections. As the formation of the cavities occurs stochastically in distinct locations and with bubbles with different maximum radii, the pressure wave passages occur at different stages during the life of each individual bubble. The bubbles in the current setup are subject to the passages of multiple pressure waves, whose reflections occur at time intervals of 0.9 \( \mu \text{s} \), while the bubble oscillation times are in the range of 4 to 20 \( \mu \text{s} \). However, as these bubbles rebound, the majority form downward jets.

Figure 4(a) shows an example of secondary cavitation bubble-jetting occurring exceptionally in the opposite direction to the secondary compression wave. The neighboring bubbles \( R_1 \) and \( R_2 \) form microjets oriented upward and downward, respectively. It should be noted that the images that only show the directions on the 2D image plane are considered, excluding the possible directions away from the plane. The bubbles are located at approximately equal distances of \( \sim 530 \mu \text{m} \) from the free surface and plate. For each bubble, the collapse time \( T_C \), i.e., the measured time between the instants when the bubble reaches its maximum and minimum sizes, is significantly different from the natural collapse time in the absence of pressure waves predicted by the Rayleigh model, 

\[
T_R = \frac{1}{C_0} \left( \frac{\rho}{p_\infty - p_v} \right)^{1/2},
\]

where \( \rho \) is the water density, \( p_\infty \) is the pressure in the liquid, and \( p_v \) is the vapor pressure.\(^\text{14}\) For \( R_1 \) and \( R_2 \), \( T_C/T_R \) are 0.65 and 1.17, respectively. This can be attributed to multiple pressure waves interacting with these bubbles during their growth and collapse, as shown in Fig. 4(b), which presents the passage of each pressure wave in time. Although \( R_1 \) and \( R_2 \) have very similar maximum bubble radii, \( R_{\text{max}} = 65.3 \mu \text{m} \) and 63.4 \( \mu \text{m} \), respectively, the measured collapse time of \( R_2 \) is almost 55% longer than that of \( R_1 \). The bubble’s radial

FIG. 3. (a) Selected images of the interaction between the primary compression wave emitted by the motion of the alumina plate and free surface. The numbers denote (1) primary compression wave, (2) tension wave, (3) reflected tension wave, and (4) secondary compression wave. The interframe time is 400 ns. The black scale-bar corresponds to 200 \( \mu \text{m} \). (b) Visualization of secondary microcavities, at 9 \( \mu \text{s} \) after the discharge. The white scale-bar corresponds to 200 \( \mu \text{m} \). (c) Visualization of microjets and angle convention. (d) Selected images visualizing the life of a jetting microcavity. The interframe time is 1.4 \( \mu \text{s} \); the black scale-bar corresponds to 100 \( \mu \text{m} \). (e) Fiber optic hydrophone pressure signal as a function of the time after the electric discharge. (f) Secondary cavitation microjet direction as a function of the bubble position with respect to the center of the electrodes. The bubble position and microjet angles are denoted in (c).

FIG. 4. (a) Selected images of two bubbles collapsing under the effect of the reflected pressure waves. The interframe time is 2 \( \mu \text{s} \). The black scale-bar corresponds to 100 \( \mu \text{m} \). The microjets are highlighted with red circles. (b) Radial evolution of the two bubbles in (a). The bubble radius is obtained by the equivalent radius of the area. \( t = 0 \mu \text{s} \) is defined to correspond to the upward passage of the primary compression wave at the location of the bubbles. The dashed and dotted lines indicate the passages of compression and tension waves, respectively, while the arrows in the top part indicate each wave’s direction (up and down alternately).
evolution appears to be highly sensitive to the stage in the bubble’s lifetime during which the compression and tension waves act. The pair of tension waves acts on $R_2$ at the end of its growth phase, thus prolonging its growth, while $R_1$ has already reached its maximum size by this time and thus does not expand further.

Furthermore, we should identify the wave among the multiple compression waves that has the largest influence on the microjet direction. Considering that a pressure wave loses a considerable amount of energy at every passage, most likely the secondary compression wave determines the direction, particularly when it propagates spherically. However, there may be other factors affecting the jet direction, such as neighboring bubbles [in Fig. 4(a), there could be a hidden neighboring bubble away from the image plane], pressure waves reflected at their surfaces, flow of the surrounding liquid, or later pressure wave acting on the bubble at an appropriate time in its last collapse phase. It has been previously shown that a later interaction of the pressure waves with the bubble within their collapse phase leads to a stronger jetting of the bubble. Furthermore, the acoustic emissions from the collapse of the neighboring bubbles, despite not being observable in the images, could also be sufficient to result in jetting. In the case of $R_1$, the jet might be attributed to these factors. However, the observation that 95% of the jets are directed downward implies that the secondary compression wave is likely the dominating factor.

In conclusion, these observations provided valuable insights into the behavior of microcavity clouds under the effect of multiple pressure wave passages. A single pressure wave could both generate cavities and make them collapse with a microjet. For pressure waves reflecting between two liquid–gas interfaces (e.g., bubble and free surface), the microjets formed by the microbubbles in-between them were always oriented in the direction of the compression wave owing to the phase inversion from each surface. For pressure waves reflecting between one liquid–gas interface and rigid surface with a high acoustic impedance compared to that of the liquid, there were compression waves in both directions as only one surface led to phase inversion. The microjets generally followed the direction of the secondary compression wave, which was the first compression wave experienced by a cavitation bubble.

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1. M. Delius and G. Adams, Cancer Res. 59, 5227 (1999).
2. C. D. Ohl, M. Arora, R. Ikink, N. De Jong, M. Versluis, and M. Delius, Biophys. J. 91, 4285 (2006).
3. P. Prentice, A. Cuschiere, K. Dholakia, M. Prausnitz, and P. Campbell, Nat. Phys. 1, 107 (2005).
4. T. Kodama, Y. Tomita, K. Koshiyama, and M. Blomley, Ultrasound Med. Biol. 32, 905 (2006).
5. N. Kudo, K. Okada, and K. Yamamoto, Biophys. J. 96, 4866 (2009).
6. A. Delalande, S. Kotopoulis, M. Postema, P. Midoux, and C. Pichon, Gene 525, 191 (2013).
7. F. P. Bowden, Philos. Trans. R. Soc. London, A 260, 94–95 (1966).
8. A. Philipp, M. Delius, C. Scheffczyk, A. Vogel, and W. Lauterborn, J. Acoust. Soc. Am. 93, 2496 (1993).
9. C. D. Ohl and R. Ikink, Phys. Rev. Lett. 90, 214502 (2003).
10. B. Gerold, P. Glynne-Jones, C. McDougall, D. McGloin, S. Cochran, A. Melzer, and P. Prentice, Appl. Phys. Lett. 100, 024104 (2012).
11. S. Kanazawa, M. Hirao, S. Akamine, T. Ichiki, T. Ohkubo, M. Kocik, and J. Mizeraczyk, J. Inst. Electrost. Jpn. 34, 1 (2010).
12. K. Ando and A.-Q. Liu, Phys. Rev. Lett. 109, 044501 (2012).
13. O. Supponen, D. Obreschkow, M. Tinguely, P. Kobel, N. Dorsaz, and M. Farhat, J. Fluid Mech. 802, 263 (2016).
14. L. Rayleigh, Philos. Mag. 34, 94 (1917).
15. G. N. Sankin, W. N. Simmons, S. L. Zhu, and P. Zhong, Phys. Rev. Lett. 95, 034501 (2005).
16. E. A. Brujan, T. Ikeda, K. Yoshinaka, and Y. Matsumoto, Ultrason. Sonochem. 18, 59 (2011).