Microbubble dynamics and jetting near tissue-phantom biointerfaces

Jaka Mur,1,2 Vid Agrež,1 Jaka Petelin,1 and Rok Petkovšek1,3

1University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, SI-1000 Ljubljana, Slovenia
2jaka.mur@fs.uni-lj.si
3rok.petkovsek@fs.uni-lj.si

Abstract: Precise excitation of cavitation is a promising mechanism for microsurgery procedures and targeted drug delivery enhancement. The underlying phenomenon of interest, jetting behaviour of oscillating cavitation bubbles, occurs due to near-surface interactions between the boundary, liquid, and bubble. Within this study we measured boundary effects on the cavitation bubble dynamics and morphology, with an emphasis on observation and measurement of jetting behaviour near tissue-phantom biointerfaces. An important mechanism of boundary poration has been observed using time-resolved optical microscopy and explained for different tissue-phantom surface densities and Young’s modulus. Below a critical distance to the boundary, around γ = 1.0, the resulting jets penetrated the tissue-phantom, resulting in highly localized few micrometer diameter jets.

© 2022 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement

1. Introduction

Application of modern technology in a medical environment requires precision targeting, high localization and low collateral effects during both surgical procedures and drug application. A possible mechanism for microsurgery and localized drug delivery enhancement is through cavitation phenomena [1]. Cavitation occurs in liquids, with the most prominent resultant feature being the generation of oscillating vapour bubbles, in turn causing rapid liquid flows and jets [2]. Cavitation can be unwanted and even damaging under certain conditions [3], but through controlled occurrence important treatments in water-based environments can be achieved (destruction of bacteria [4], viruses [5], or liposome vesicles [6]).

Laser-induced breakdown (LIB) in liquids causes cavitation if certain conditions are met, generating a single bubble in addition to plasma and shockwaves [7]. The single bubble induced by laser-based generation serves as a precise tool, already proven as a medical photodisruptor tool or as a biofabrication methodology for efficient drug delivery [8,9]. The precision is also warranted by minimizing the bubble size, with contemporary (ultra)short pulsed laser sources enabling the generation of microbubbles [10].

Cavitation bubbles induced by strongly focused laser beams in an approximately infinite liquid are near spherical [11], retaining the shape through the following collapses and rebounds [12,13]. A presence of a boundary, even several maximum bubble radii away, causes distinctively altered behaviour, including asymmetry in bubble shape, liquid flows, and jets [14–18], the latest research showing presence of supersonic jets [19]. The exact behaviour depends on the dynamic properties of the boundary: near a rigid boundary, jetting behaviour towards the boundary is observed, while near a free boundary jetting occurs away from it.

Previous research on cavitation induced jetting phenomena focused on millimeter-sized bubble behaviour near elastic boundaries, studying mechanisms of tissue damage due to bubble collapse near the elastic boundary [20], penetration of the elastic boundary within a certain range of Young’s moduli [17], bone tissue ablation [21], either destructive poration of cells or viable sonoporation [22], and direct application of cavitation bubble jetting demonstrated for single-cell
membrane poration [23,24]. Similar poration was achieve by shockwaves on eukaryotic cells [25]. Other studies show double-bubble interactions leading to jetting and poration of tissue phantom materials [26].

We designed a study of near-surface effects on the cavitation bubble dynamics and morphology, focused on surface poration events. Tissues, and consequently tissue phantom materials such as agar gels, cannot act as a model rigid or free boundary. We aimed to investigate the behaviour of microbubbles and compare it to known boundary models to quantify the behaviour near a biointerface. The observed events were classified within the framework of Kelvin impulse measurements, seeking the influence of surface density and Young’s modulus parameters within the range of experimental variables and on micrometer scales, as opposed to previous studies using millimeter scale bubbles [27].

The experiments were designed to allow for virgin surface poration observation due to a single cavitation bubble collapse and accompanying jetting behaviour by employing high frame rate microscopy in combination with a tightly focused picosecond excitation laser source for LIB cavitation. Tight focusing and short laser pulse duration lead to bubble generation around 100 micrometers in diameter, in turn causing micro-jetting behaviour near various tissue phantoms of different density and Young’s modulus. To the best of our knowledge, the possibility of jetting behaviour on single micrometer scales was not demonstrated previously.

2. Materials and methods

The experiments were set up in way to allow for repeatable microbubble excitation and minimally obstructed visualization of near surface and sub-surface phenomena, including microporation. The emphasis for the latter was on the visualization of the first poration event at the given location.

2.1. LIB cavitation bubble excitation

LIB cavitation bubble excitation was generated using a custom fiber laser source at a 1030 nm wavelength with the pulse duration of around 60 ps, coupled to a laboratory made 3D printed experimental chamber with cover glass illumination- and viewports and a volume of $20 \times 20 \times 20 \text{ mm}^3$. Focusing of the excitation laser was done by water dipping microscope objective placed inside of the experimental chamber (Fig. 1(a)). The objective was a 40-times magnification Nikon CFI Apo NIR 40x W with a numerical aperture (NA) of 0.8 and working distance of 3.5 mm. The $1/e^2$ diameter of an ideally focused Gaussian intensity profile beam would be approximately 1.1 $\mu$m. We set the laser pulse energy to approximately 1.0 $\mu$J, corresponding to a stable cavitation bubble with the maximal diameter $2R_0 \approx 110 \mu m \pm 5 \mu m$. For a bubble with maximum radius $R_0$ and its centre located $h$ away from a boundary, we define a dimensionless distance parameter $\gamma = h/R_0$. In the experimental setup, the closest non-gel surface to the LIB location is the syringe edge at $\gamma \approx 38$ away, ensuring an undetectable level of influence from supporting structures on bubble dynamics and morphology.

2.2. Visualization

Detection of cavitation bubble and shock wave was based on a laser diode short pulsed illumination system (presented in [19]). We have already applied the concept to monitoring of shockwaves near a concave surface in previous work [28]. In this work, the illumination pulse was focused to the region of interest with NA of 0.25 and had a duration of 3 ns for high resolution imaging. The short duration of illumination pulse enables imaging of fast phenomena (e.g., microporation and shockwaves).

Due to the requirement for imaging of the initial poration event, we used a high frame rate camera, Photron Fastcam Nova 9s, set to a 476 kHz frame rate and consequently the resolution of $128 \times 48$ pixels. The full camera resolution of $1024 \times 1024$ pixels at low frame rates was used for alignment purposes. The pixel size was $20 \times 20 \mu m$ and the camera was used in combination
with an imaging microscope objective OptoSigma PAL-10-NIR with 10x magnification and NA of 0.3. The combination of imaging and illumination optics allowed an optical resolution of approximately 2 µm on the final images. Both the illumination and excitation laser sources as well as the camera were synchronized to each other, with the lasers being in sync to within 1 ns to ensure repeatable imaging of events in the time-domain. Experimental details are shown in Fig. 1.

The LIB excitation was first placed at around $\gamma = 1.5$ to ensure the LIB and sample surface lay in the imaging focal plane. The laser excitation was blocked, and the sample moved away to maximal $\gamma$. The sample was then gradually moved towards the LIB position, and a single LIB event and a corresponding synchronized single high-frame rate capture were triggered at each position. This approach was chosen to ensure observation of the initial poration event of the tissue-phantom surface.

2.3. Materials

Different boundary conditions were used for the experiments. For reference measurements of bubble behaviour near free and rigid boundaries we used the water-air interface near an air bubble [29] and a 3D printed plastic shape respectively. Tissue phantoms of different density and Young’s modulus were based on agar gels, using agar concentrations ranging from 1 wt% to 4 wt% in water, with additional samples made with added sucrose in concentrations between 25 wt% and 40 wt%. Agar was first dispersed in water at room temperature and then heated to above 90 °C for complete dissolution. Sucrose was added during the cooldown period if needed. Samples were stored at 5 °C afterwards to ensure complete gelation, with small quantities (0.1 ml) stored inside syringes to ensure the required gelation shape. Young’s modulus of agar gels has been
measured by multiple other groups [30–35], though exact values have a significant uncertainty. The measured values of other groups are gathered in Fig. 2 with an added exponential trendline.

![Fig. 2.](image)

**Fig. 2.** Joined agar gel Young’s modulus measurements of other groups [30–33,35], presented as a function of agar mass concentration in water with an added exponential trendline.

Using a range of agar concentrations and by adding sugar, we estimated that the Young’s modulus values of sample gels were varied between approximately 15 and 700 kPa (based on the trendline values in Fig. 2) and their density between 1.05 and 1.25 g/cm$^3$ [36]. Exact agar and sucrose concentrations for all different gels used in the experiments are listed in Table 1, with an added Young’s modulus estimation.

| Gel sample # | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|--------------|----|----|----|----|----|----|----|
| Agar wt%     | 1.0| 2.0| 3.0| 3.5| 4.0| 2.2| 1.7|
| Sucrose wt%  | 0  | 0  | 0  | 0  | 0  | 28 | 41 |
| Young’s modulus (kPa) | 15 | 80 | 250| 450| 700| 100| 60|

**2.4. Jetting behaviour calculation**

An oscillating bubble in an infinite liquid, for example generated by a LIB cavitation event, grows and collapses without inducing directed streams or jets of liquid, and its centre is not moving. Near a boundary, liquid jets form due to spatial asymmetry, resulting also in movement of the bubble centre. Depending on the boundary type, different jetting behaviour occurs, confirmed in previous research [37]. The dynamics can be described by an anisotropy parameter $\zeta$, a dimensionless measure of the liquid momentum at the collapse point (Kelvin impulse). The anisotropy parameter is as following:

$$\zeta = -0.195y^{-2} \quad \text{for rigid boundary,}$$

$$\zeta = +0.195y^{-2} \quad \text{for free boundary,}$$

$$\zeta = +0.195y^{-2}(4\alpha - 1 - 8\alpha^2 e^{2\alpha} E_1(2\alpha)) \quad \text{for inertial boundary,}$$

where we defined $\alpha$ with the liquid density $\rho$ and surface density $\Sigma$ as $\alpha = \rho h/\Sigma$ in accordance with [14,37], and used an exponential integral $E_1(x) = \int_1^\infty e^{-u}/udu$. Positive anisotropy parameter corresponds to jet formation away from the surface, and negative values towards it. While the behaviour near rigid and free boundaries is self-similar and intensifies close to the surface, an
inertial boundary either attracts or deflects the liquid jet, depending on the $h$ and surface density $\Sigma$.

### 3. Results and discussion

Classification of the observed events within the framework of Kelvin impulse calculations was done by measuring the bubble centroid position as a function of time delay after the initial bubble appearance (i.e., the LIB event). Data sets were obtained for various normalized distances $\gamma$ from the sample surface for all gel samples and both reference samples. The measurements were analysed and the calculated position data points of inertial boundary experiment were identified to closely resemble a logistic exponential function. The function was fitted on the obtained data points and the resulting fits are shown in Fig. 3 on select measurement sets for various $\gamma$ from the sample gel #3 (3 wt% agar gel concentration). A limited number of measurements is shown for clarity.

![Fig. 3. Bubble centroid position for various $\gamma$ values shown as a function of time delay after the LIB cavitation event. Measurement data sets are shown for gel sample #3. Images show bubble position at the indicated time delay (dashed black line at 20.9 $\mu$s time delay) for five different $\gamma$ values. The LIB position is marked with a dashed red line on all images.](image)

The logistic function fitted on each individual measurement set (separated by $\gamma$) was used as a parametrization tool, enabling to extract the time delay of bubble centroid response to the liquid flow after the initial cavitation and the response strength. The response strength, i.e., the bubble centroid position walk-off, is directly connected to the jetting direction, when present, and to the value of Kelvin impulse defined in section 2.1.

Using the parameters obtained by the logistic function, we extracted the bubble centroid movement behaviour observed throughout the measurements. A joint presentation of the resulting data is shown in Fig. 4 for a selection of different agar gels and reference measurements. The maximal bubble displacement was acquired from the fitting function analysis data as shown in Fig. 3. The value was chosen as a measure of the Kelvin impulse, in line with other works [17]. The measurements of bubble behaviour near reference rigid and free surfaces show that our experimental approach and the data analysis procedure work as expected, showing a typical jetting behaviour induced by the vicinity of a rigid or free boundary, respectively. The data points were cut off at certain minimal $\gamma$ values, depending on the bubble behaviour. At $\gamma$ values smaller than shown, the bubble centroid was stuck at the surface, resulting in equal maximal displacement values for those $\gamma$ values, losing the significance of the measurement.
Fig. 4. Maximal bubble displacement as a function of $\gamma$ for different samples. Near boundary behaviour shows typical response of an inertial boundary system for gels, and confirms the uniform jetting direction near a rigid/free boundary.

The equation for Kelvin impulse near an inertial boundary predicts a change in function value sign at a certain $\gamma_0$, indicating a transition in bubble behaviour from moving away from the surface at large $\gamma$ and towards it below $\gamma_0$ (according to the inertial boundary equation in section 2.4). The behaviour depends on surface density, but not explicitly on Young’s modulus, therefore assuming that the elastic effects are negligible. By fitting the equation with only two free parameters, the amplitude and surface density $\Sigma$, to the experimental data for all different sample gels, we found a good agreement between the model and the measured values.

Within the experimental range of Young’s moduli values, we found no significant deviations in the observed behaviour due to elastic effects, with the bubble behaviour well described by the inertial boundary equation. The good agreement between the experimental data and the fitted functions as well as the overall similarity across the measurements also implies that different pure agar gels (without sucrose, samples #1-5) have a near constant surface density. All corresponding measurements show weak positive impulse at large $\gamma$ with a steep transition into negative values below the transition point. Due to the weak impulse, no jetting behaviour away from the surface was visualized. However, the addition of sucrose contributed to a significant change in behaviour, indicating a decrease of surface density. According to the fitting parameters obtained, we observed an up to 3-fold decrease in surface density with the addition of sucrose. While the overall gel density increases with the addition of sugars, research shows that sucrose also decreases the length of characteristic chains [38,39]. The observed decrease in surface density, in contrast to the increased volumetric density, confirms the mentioned findings on a micrometer scale. An explanation in line with the findings is a shallower interaction depth induced with the addition of sucrose. The larger positive values of displacement between $\gamma$ values of 1 and 1.5 also correspond to the observed jetting behaviour away from the surface at these distances.

Bubble evolution sequences were imaged for all cavitation events and were also precisely visually assessed at low $\gamma$ values to detect any near-surface phenomena. Figure 5 shows bubble evolution in time from just after the initial LIB event up to 14.6 $\mu$s afterwards for gel samples #1, 2, 3, and 5 at the $\gamma$ values, where first surface poration events were observed. The initial LIB position is marked by the vertical dashed red line. We recorded poration event for all gel samples, regardless of the sample gel Young’s modulus or surface density, within the scope of experimental parameters. The poration events for 1-4 wt% agar gels also happen at the same normalized critical distance away from the boundary, $\gamma_c \approx 1.00 \pm 0.05$. Around the 4.2 $\mu$s and 10.4 $\mu$s time delays, a displacement of the surface is visible, indicating a mechanical interaction...
between the growing bubble pushing the surface away from the initial LIB position and the collapsing bubble towards it.

**Fig. 5.** Bubble evolution in time at a critical position for surface poration, visualized in subsequent camera frames for four different agar gels (1-4 wt%). The $\gamma$ values at the positions shown are 0.97, 1.02, 0.97, and 1.03 respectively. Each sequence shows the initial surface poration event for the respective sample. The surface position is marked by a light dashed curve, the vertical dashed red line marks the initial LIB event position, and the dashed red circles the bubble diameter at a given timestamp as measured far away from the surface.

Even though the poration behaviour is undistinguishable between the samples, a difference in the lifetime of the primary bubble growth and collapse can be observed and attributed to the changing Young’s modulus. With an increasing value of Young’s modulus, the maximum bubble radius decreases and correspondingly so does the time between the bubble generation and its collapse. The best visual representation of the decreased lifetime is by comparison of images at the 8.3 $\mu$s timestamp, showing a significantly decreased diameter of the bubble. The difference observed was on the order of 25 % for 4 wt% sample. For an optical comparison, the corresponding bubble diameters are added at chosen time stamps, illustrated by dashed red circles, as measured far away from the surface.

Post collapse dynamics of the primary bubble led to micro-jetting surface poration event for all sample gels at a certain $\gamma$ value, as shown in Fig. 5. The observed jets were approximately 5 $\mu$m in diameter and 20-50 $\mu$m in length (events shown in Fig. 6), exhibiting the precision necessary for poration of precisely selected target tissues and even single cells. The jet lengths are estimated due to high jet speeds (measured by other groups, e.g. [19]), exceeding the camera time-resolution. The elastic nature of the tissue phantom traps the gas temporarily, allowing the poration event to be imaged. Due to the measured behaviour following the description of an inertial boundary, poration was repeatedly achieved when the LIB cavitation occurred closer than
a critical $\gamma_c$ away from the surface. The mechanism of poration observed and analysed in this work is in line with the works of other groups, resulting e.g. in single cell membrane poration [23,24].

Fig. 6. Micro-jetting poration, estimated jet size was 2-4 $\mu$m in diameter and 25-30 $\mu$m in length. a) Original 128 × 48 pixel image. b) Upscaled image using cubic interpolation for better jet visualization. Scale bar: 20 $\mu$m

4. Conclusion

We measured the behaviour of LIB cavitation induced microbubbles near tissue phantom gels and found it corresponds to inertial boundary model calculations with different surface density values. The observed poration mechanic is independent of Young’s modulus and surface density values within the range of experimental parameters, covering relevant values of most soft biological tissues. A consistent micro-jetting poration for LIB cavitation events occurred below a similar threshold $\gamma_c$ value, thus indicating LIB cavitation being a repeatable and reliable poration initiation mechanic. While the poration mechanic was repeatable and similar across a large parameter space, we observed a trend towards shortening the initial bubble oscillation lifetime with an increased Young’s modulus of agar gel. Within the tissue phantom materials, we observed and measured repeatable and self-similar jets below 5 micrometers in diameter and up to 30 micrometers in length, i.e., the micro-jetting poration, suitable for drug delivery enhancement through cavitation as well as possibility of direct micro-surgery application.

Funding. Javna Agencija za Raziskovalno Dejavnost RS (J2-3057, L2-9240, P2-0270).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References
1. L. Meng, X. Liu, Y. Wang, W. Zhang, W. Zhou, F. Cai, F. Li, J. Wu, L. Xu, L. Niu, and H. Zheng, “Sonoporation of cells by a parallel stable cavitation microbubble array,” Adv. Sci. 6(17), 1900557 (2019).
2. U. Orthaber, J. Zevnik, R. Petkovšek, and M. Dular, “Cavitation bubble collapse in a vicinity of a liquid-liquid interface – Basic research into emulsification process,” Ultrason. Sonochem. 68, 105224 (2020).
3. B. K. Sreedhar, S. K. Albert, and A. B. Pandit, “Cavitation damage: theory and measurements – a review,” Wear 372-373, 177–196 (2017).
4. A. Šarc, J. Kosel, D. Stopar, M. Oder, and M. Dular, “Removal of bacteria Legionella pneumophila, Escherichia coli, and Bacillus subtilis by (super)cavitation,” Ultrason. Sonochem. 42, 228–236 (2018).
5. J. Kosel, I. Gutiérrez-Aguirre, N. Rački, T. Dreo, M. Ravnikar, and M. Dular, “Efficient inactivation of MS-2 virus in water by hydrodynamic cavitation,” Water Res. 124, 465–471 (2017).
6. Z. Pandur, I. Dogsa, M. Dular, and D. Stopar, “Liposome destruction by hydrodynamic cavitation in comparison to chemical, physical and mechanical treatments,” Ultrason. Sonochem. 61, 104826 (2020).
7. G. L. Chahine and A. Bovis, Cavitation and Inhomogeneities in Underwater Acoustics, W. Lauterborn, ed., (Springer-Verlag, 1980).
8. S. Uppal, Aashima, R. Kumar, S. Sareen, K. Kaur, and S. K. Mehta, “Biofabrication of cerium oxide nanoparticles using emulsification for an efficient delivery of Benzyl isothiocyanate,” Appl. Surf. Sci. 510, 145011 (2020).
9. L. Somaglino, L. Mousnier, A. Giron, W. Urbach, N. Tsapis, and N. Taulier, “In vitro evaluation of polymeric nanoparticles with a fluorine core for drug delivery triggered by focused ultrasound,” Colloids Surf., B 200, 111561 (2021).
10. A. Vogel, N. Linz, S. Freidank, and G. Paltauf, “Femtosecond-Laser-induced nanocavitation in water: implications for optical breakdown threshold and cell surgery,” *Phys. Rev. Lett.* **100**(3), 038102 (2008).
11. G. Simbaldi, A. Occhicone, F. Alves Pereira, D. Caprini, L. Marino, F. Michelotti, and C. M. Casciola, “Laser induced cavitation: plasma generation and breakdown shockwave,” *Phys. Fluids* **31**(10), 103302 (2019).
12. T. Wilson, T. L. Hall, E. Johnsen, L. Mancia, M. Rodriguez, J. E. Lundt, T. Colonius, D. L. Henain, C. Franck, Z. Xu, and J. R. Sukovich, “Comparative study of the dynamics of laser and acoustically generated bubbles in viscoelastic media,” *Phys. Rev. E* **99**(4), 043103 (2019).
13. B. G. Wilson, Z. Fan, R. Sreedasyam, E. L. Botvinick, E. L. Botvinick, V. Venugopalan, V. Venugopalan, and V. Venugopalan, “Single-shot interferometric measurement of cavitation bubble dynamics,” *Opt. Lett.* **46**(6), 1409–1412 (2021).
14. G. L. Chahine and A. Bovis, “Oscillation and collapse of a cavitation bubble in the vicinity of a two-liquid interface,” *Cavitation Inhomogeneties Underw. Acoust.* **4**, 23–29 (1980).
15. J. R. Blake and D. C. Gibson, “Cavitation bubbles near boundaries,” *Annu. Rev. Fluid Mech.* **19**(1), 99–123 (1987).
16. A. Vogel, W. Lauterborn, and R. Timm, “Optical and acoustic investigations of the dynamics of laser-produced cavitation bubbles near a solid boundary,” *J. Fluid Mech.* **206**(1), 299–338 (1989).
17. E.-A. Brujan, K. Nahen, P. Schmidt, and A. Vogel, “Dynamics of laser-induced cavitation bubbles near elastic boundaries: influence of the elastic modulus,” *J. Fluid Mech.* **433**, 283–314 (2001).
18. P. Gregorčič, R. Petkovšek, and J. Možina, “Investigation of a cavitation bubble between a rigid boundary and a free surface,” *J. Appl. Phys.* **102**(9), 094904 (2007).
19. F. Reuter and C.-D. Ohl, “Supersonic needle-jet generation with single cavitation bubbles,” *Appl. Phys. Lett.* **118**(13), 134103 (2021).
20. T. Kodama and Y. Tomita, “Cavitation bubble behavior and bubble-shock wave interaction near a gelatin surface as a study of in vivo bubble dynamics,” *Appl. Phys. B: Lasers Opt.* **70**(1), 139–149 (2000).
21. L. Zhang, L. J. H. Zhang, X. Li, J. Wang, and J. Zheng, “Dynamics characteristics of a laser-induced non-spherical bubble collapsing micro-jet and its enhancement on hard tissue ablation,” *Opt Lasers Eng.* **151**, 106893 (2022).
22. C.-D. Ohl, M. Arora, R. Ikin, N. de Jong, M. Versluis, M. Delius, and D. Lohse, “Sonoporation from jetting cavitation bubbles,” *Biophys. J.* **91**(11), 4285–4295 (2006).
23. G. N. Sankin, F. Yuan, and P. Zhong, “Pulsating tandem microbubble for localized and directional single-cell membrane poration,” *Phys. Rev. Lett.* **105**(7), 078101 (2010).
24. Z. G. Li, A. Q. Liu, E. Klaeboer, J. B. Zhang, and C. D. Ohl, “Single cell membrane poration by bubble-induced microjets in a microfluidic chip,” *Lab. Chip* **13**(6), 1144–1150 (2013).
25. L. M. López-Marín, B. E. Millán-Chiu, K. Castaño-González, C. Aceves, F. Fernández, A. Varea-Echavarria, and A. M. Loske, “Shock Wave-Induced Damage and Poration in Eukaryotic Cell Membranes,” *J. Memb. Biol.* **250**(1), 41–52 (2017).
26. V. Robles, E. Gutierrez-Herrera, L. F. Devia-Cruz, D. Banks, S. Camacho-Lopez, and G. Aguilar, “Soft material perforation via double-bubble laser-induced cavitation microjets,” *Phys. Fluids* **32**(4), 042005 (2020).
27. W. Xu, Y. Zhai, J. Luo, Q. Zhang, and J. Li, “Experimental study of the influence of flexible boundaries with different elastic moduli on cavitation bubbles,” *Exp. Therm. Fluid Sci.* **109**, 109897 (2019).
28. T. Pozar, V. Agrež, and R. Petkovšek, “Laser-induced cavitation bubbles and shock waves in water near a concave surface,” *Ultrason. Sonochem.* **73**, 105456 (2021).
29. Z. Lukač, R. Petkovšek, and M. Dular, “Cavitation bubble dynamics in a vicinity of a thin membrane wetted by different fluids,” *Sci. Rep.* **11**(1), 3506 (2021).
30. T. Terada and C. Tsboi, “Experimental studies on elastic waves(Part 1),” *東京帝国大学地震研究所* (1927).
31. T. Nitta, H. Haga, K. Kawabata, K. Abe, and T. Sambongi, “Comparing microscopic with macroscopic elastic properties of polymer gel,” *Ultramicroscopy* **82**(1-4), 223–226 (2000).
32. T. Z. Pavan, E. L. Madsen, G. R. Frank, A. A. O. Carneiro, and T. J. Hall, “Nonlinear elastic behavior of phantom materials for elastography,” *Phys. Med. Biol.* **55**(9), 2679–2692 (2010).
33. C. Li, Z. Huang, and R. K. Wang, “Elastic properties of soft tissue-mimicking phantoms assessed by combined use of laser ultrasonics and low coherence interferometry,” *Opt. Express* **19**(11), 10153 (2011).
34. V. T. Nayar, J. D. Weiland, C. S. Nelson, and A. M. Hodge, “Elastic and viscoelastic characterization of agar,” *J. Mech. Behav. Biomed. Mater.* **7**, 60–68 (2012).
35. A. Maccab, A. Shin, N. K. Namiri, N. Bajwa, M. S. John, Z. D. Taylor, W. Grundfest, and G. N. Saddik, “Quantitative characterization of viscoelastic behavior in tissue-mimicking phantoms and ex vivo animal tissues,” *PLOS ONE* **13**(1), e0191919 (2018).
36. N. G. Anderson, *The Development of Zonal Centrifuges and Ancillary Systems for Tissue Fractionation and Analysis* (U.S. Department of Health, Education, and Welfare, Public Health Service, National Cancer Institute, 1966).
37. O. Supponen, D. Obreschkow, M. Tinguely, P. Kobel, N. Dorsaz, and M. Farhat, “Scaling laws for jets of single cavitation bubbles,” *J. Fluid Mech.* **802**, 263–293 (2016).
38. A. Dorohovich, O. Goncharuk, D. Matias, and J. Kambulova, “Influence of sugars on the formation of structural and mechanical characteristics of of agar polysaccharides’ gels,” *Ukr. J. Food Sci.* **6**(1), 20–31 (2018).
39. A. L. Ellis, T. B. Mills, I. T. Norton, and A. B. Norton-Welch, “The effect of sugars on agar fluid gels and the stabilisation of their foams,” *Food Hydrocoll.* **87**, 371–381 (2019).