Single-shot measurements of the acoustic field of an electrohydraulic lithotripter using a hydrophone array

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Piezopolymer-based hydrophone arrays consisting of 20 elements were fabricated and tested for use in measuring the acoustic field from a shock-wave lithotripter. The arrays were fabricated from piezopolymer films and were mounted in a housing to allow submersion into water. The motivation was to use the array to determine how the shot-to-shot variability of the spark discharge in an electrohydraulic lithotripter affects the resulting focused acoustic field. It was found that the dominant effect of shot-to-shot variability was to laterally shift the location of the focus by up to 5 mm from the nominal acoustic axis of the lithotripter. The effect was more pronounced when the spark discharge was initiated with higher voltages. The lateral beamwidth of individual, instantaneous shock waves were observed to range from 1.5 mm to 24 mm. Due to the spatial variation of the acoustic field, the average of instantaneous beamwidths were observed to be 1 to 2 mm narrower than beamwidths determined from traditional single-point measurements that average the pressure measured at each location before computing beamwidth. © 2013 Acoustical Society of America. [http://dx.doi.org/10.1121/1.4795801]

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I. INTRODUCTION

Shock-wave lithotripsy (SWL) is a procedure used for treating kidney stones. SWL generates shock waves (SWs) external to the body and then focuses the acoustic energy onto kidney stones within the body. The SWs are delivered continuously, at a rate of about 2 Hz, in order to fragment the stone into pieces small enough (<2 mm) to pass naturally through the urinary tract. SWL was first introduced in 1980¹ and quickly revolutionized the treatment of kidney stones such that by the 1990s, 90% of kidney stone treatments in the United States and Europe were performed using SWL.^{2,3} SWL continues to be widely used to treat kidney stones, although recent trends suggest that endoscopic treatments, such as ureteroscopy, are becoming nearly as common.⁴

The original Dornier HM3 (Dornier MedTech GmbH, Wessling, Germany), still considered the gold standard by some,⁵ was an electrohydraulic lithotripter (EHL) which used an electrode (spark plug) placed at the first focus of a hemi-ellipsoidal reflector to generate a high-pressure acoustic field. The spark discharge resulted in a spherical SW which, upon reflection by the ellipsoidal reflector, was focused to the kidney stone positioned at the second focus of the reflector.

Because the breakdown of the water associated with the spark is a stochastic process, the location of the spark varies from shot-to-shot and this leads to a shot-to-shot variation of the focused SW at the second focus of the ellipsoid. It has been hypothesized that this variability in the acoustic field may contribute to the effectiveness of EHLs because the variable acoustic field, combined with patient motion (e.g., respiratory), helps increase the probability that a SW impacts the stone each time the EHL fires.⁶

Since the introduction of the HM3, manufacturers have been building lithotripters with predominantly higher peak pressure amplitudes and narrower focal zones. These “improvements” were based on the assumption that higher pressures would more effectively fragment a stone, and smaller focal sizes would result in a greater fraction of the acoustic energy being incident on the stone and, thus, reduce the amount of tissue trauma. However, clinical studies have shown that the newer generation of machines that have narrower, higher-pressure acoustic fields require an increased rate of re-treatment and increase the rate of negative bioeffects.^{7–9} The increased side-effects are likely due to the higher amplitude and the higher number of SWs employed by the narrower focal zone lithotripters. In response to clinical results and additional research on beamwidth,^{10–12} some manufacturers have begun marketing machines with broader focal zones. Recent experimental work with stone phantoms has provided evidence that broad focal zones produce better stone comminution.¹³

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Even though EHL acoustic fields are known to have variability, they are exclusively probed with single-element hydrophones that measure accurate temporal waveforms but endure only a finite number of shock exposures before they fail (typically 100–500).^{14–16} Lateral beamwidth is determined after averaging pressure measurements at a series of spatial locations rather than averaging measurements of the instantaneous acoustic field. Because the true instantaneous spatial pressure distribution in an EHL varies from shot to shot, the averaged spatial parameters will be affected by the shot-to-shot jitter. This is relevant because the acoustic dose (e.g., energy delivered to patient) is determined based on measurements within the cross-sectional area defined by the lateral beamwidth in the focal plane.¹⁷ A hydrophone array would overcome these limitations of single-point measurements by permitting measurements of the instantaneous acoustic field, although it would still be susceptible to damage.

Here, we present improvements to a hydrophone array described initially by Kreider *et al.*¹⁸ with further refinements discussed by Ketterling *et al.*¹⁹ The arrays were composed of a piezopolymer film bonded to a copper-clad polyimide substrate. The substrate had the array elements and electrical trace lines etched onto its surface. The acoustic signals received from the 20 array elements could be simultaneously digitized in order to provide an instantaneous measurement of acoustic pressure along the lateral axis. The initial device and data-acquisition system established feasibility, but they were not optimal for repeated testing and rapid data collection. The current design improves upon the fabrication process of the earlier devices and provides hydrophone elements with better sensitivities and longer lifetimes.

We present instantaneous measurements of an EHL acoustic field using 20-element hydrophone arrays, although we note that the hydrophones could be used just as readily in non-sparked-based lithotripters. The center of the array was placed at the focal position of the EHL and data were collected from all 20 array channels. Shock exposures were applied until beyond element failure, which normally occurred first at the center of the array. The resulting data, acquired simultaneously from all 20 elements, were processed to determine beamwidth, peak pressure location, and peak positive pressure. The instantaneous beamwidth measurements were compared to beamwidth values obtained by averaging at each spatial location in order to determine how instantaneous values compared to traditional single-element hydrophone measurements.

II. MATERIALS AND METHODS

A. Array fabrication

The basic method of fabricating the hydrophones, described previously in Refs. 18 and 19, was based on a technique originally used to fabricate high-frequency imaging transducers.^{20,21} The array pattern for the hydrophones was etched onto copper-clad polyimide (CCP) film (Circuits Unlimited, Inc., Carson, CA) with trace lines running from each element to connection pads that mated to standard, flat

flexible cable (FFC) connectors [Fig. 1(b)]. To make a hydrophone, a thin layer of low viscosity epoxy (Hysol RE2039, HD3561, Loctite Corp., Olean, NY) was first placed over the array elements on the CCP. A piezopolymer film, one side with a conductive gold layer and one side without, was laid on top of the epoxy with the conductive gold side placed away (i.e., up) from the CCP and epoxy. The stacked layers were then pressed together between acrylic plates [Fig. 1(a)] and the assembly was left to cure overnight. A rubber gasket was inserted between the piezopolymer film and the upper acrylic plate to allow for a high pressure to be exerted on the assembly without damaging the film, such that the bonding was optimized and the remaining layer of epoxy was as thin as possible ($\approx 1 \mu\text{m}$). Once the epoxy cured, the hydrophone component was separated from the press-fit assembly, and some epoxy was removed with sand paper to uncover the ground plane. Silver paint was used to provide an electrical path between the ground plane of the hydrophone (i.e., gold electrode) and the copper ground path on the CCP [Fig. 1(c)]. Finally, the trace lines on the CCP were covered with a thick layer of adhesive tape to ensure insulation from water and reduce electrical noise. Unlike earlier versions of the hydrophone array,¹⁹ an epoxy backing-plug was not bonded to the CCP behind the array elements. This was done to avoid hard edges that could cause acoustic scattering near hydrophone elements and also simplified the fabrication process.

The arrays used in these experiments were fabricated with $9 \mu\text{m}$ poly(vinylidene fluoride-tetrafluoroethylene) [P(VDF-TrFE)] film (Piezotech, Hérouville, France). The array hydrophones consisted of 20 elements, each with dimension $0.5 \text{ mm} \times 0.5 \text{ mm}$, spaced at either 1.25 or 1 mm center-to-center. When ready to test, the arrays were mated to a 30 cm FFC with a zero-insertion-force (ZIF) connector soldered on one end and then mounted in an acrylic frame (Fig. 2). The frame contained a compartment that permitted a water-tight seal of the ZIF connector as well as strain relief for the ribbon cable. The array was sandwiched between two thin strips of rubber (above and below the elements) in order to properly align the elements in plane and secure the hydrophone against movement. Rubber was used instead of a harder material to reduce acoustic scattering near hydrophone elements. The end of the FFC opposite the array connection was linked to a printed circuit board that contained connectors which then fanned out to standard coaxial cabling.

B. Data acquisition and processing

The instantaneous voltage waveforms generated by the 20 array elements were digitized using two 8-channel, 12-bit cards (CompuScope 8289, Gage Applied, Lockport, IL) and one 4-channel, 8-bit oscilloscope (Waverunner 6030, LeCroy, Chestnut Ridge, NY). The cabling from the array was linked to the digitizers and terminated with $1 \text{ M}\Omega$. Data were acquired by triggering the digitizers at an appropriate delay after SWs were initiated. A sampling rate of 125 MSamp/s was used for all trials and data were acquired for a

FIG. 1. (Color online) (a) Press-fit assembly used to bond the piezopolymer film to the CCP. A rubber gasket was employed to avoid damaging the thin piezopolymer film and to press out as much epoxy as possible. (b) Example of a CCP film with array pattern etched onto it. The array elements are at the top of the image and the connection pads are at the bottom. Also, 100 μm trace lines linked the elements to the pads. The copper along the outer edge of the CCP served as a ground plane. (c) After assembly, the piezopolymer was firmly bonded to the CCP. The conductive gold layer of the piezopolymer film was linked to the CCP ground plane using silver paint. The trace lines were covered with adhesive tape to ensure insulation.

duration of 131 μs . The data were stored for later processing using a MATLAB (The Mathworks, Inc., Natick, MA) interface.

In the post-processing, a 15 MHz low-pass, four-pole Butterworth filter was first used to remove high-frequency cable resonance that arose from a suboptimal transmission line. The filter was selected to remove the ringing while having a minimal impact on the temporal peak pressure and rise time. The resulting waveforms were processed element by element to determine peak positive pressure (p_+), duration of the positive phase, rise time and peak negative pressure. For individual SWs, -6 dB lateral beamwidths were quantified by means of the full-width half maximum (FWHM) profile of p_+ as suggested in the IEC 61846 standard.¹⁷ The

locations on either side of the array where p_+ first dropped below half of the largest p_+ measured were determined with linear interpolation. In order to simulate single-element hydrophone measurements, the p_+ values for each element were averaged over the total number of shocks and then beamwidth was calculated.

C. EHL testing and calibration

SWs were generated by a research EHL that was designed to mimic the acoustic output of the Dornier HM3.²² An 80 nF capacitor was charged to 14, 17, or 20 kV and then discharged through a newly acquired, refurbished electrode (Model SG-80, Healthtronics, Austin, TX). For each hydrophone experiment, a “fresh” electrode was placed within an ellipsoidal reflector which itself was mounted to the bottom of the test tank. The test tank was then filled with water that had been degassed, within the previous hour, to below 5 ppm.²² The water had a conductivity of 660 $\mu\text{S}/\text{cm}$. Because the water regassed at a rate of about 1 ppm/d, a pinhole degasser was used during the experiments to maintain the degassed state of the water.²³ The hydrophone array and bracket were mounted to a motorized positioning system so that the hydrophone elements lay in a plane normal to the acoustic axis. The tenth element was aligned to the focus of the EHL using a pointer temporarily placed over the reflector. Typically, 10–20 SWs were required to complete the alignment process which meant that the electrode was in a used state when the first beamwidth measurements were acquired. We estimated an alignment uncertainty of 1 mm which was on the order of the spacing between elements.

For each voltage setting, three separate hydrophone arrays were utilized, yielding a total of nine trials. Arrays H1 to H3 were tested at 14 kV, H4 to H6 at 17 kV and H7 to H9 at 20 kV. As noted above, a newly refurbished electrode was used for each hydrophone test. SWs were administered at 1 Hz until the voltages measured on multiple elements

FIG. 2. (Color online) The hydrophone arrays were mounted in an acrylic bracket. The array (a) was linked to a 30 cm FFC (b) and the connection was sealed in a water-tight compartment (c) that also served to provide strain relief to the cabling. The hydrophone elements were secured between thin strips of rubber in order to eliminate out-of-plane motion (d). The FFC linked to a printed circuit board that fanned out to standard coaxial cabling (not shown).

FIG. 3. (Color online) Direct-wave voltage vs shot number collected by elements 1, 10, and 20 for H9 tested at 20 kV.

reduced noticeably. The arrays tested at higher excitation voltages generally failed sooner due to the larger incident acoustic pressures and associated cavitation fields. Each array was exposed to at least 600 SWs while some recorded a few thousand. Every SW was recorded for later processing. After use, the damaged array was replaced with a new one and a new experiment with different excitation conditions was performed.

Arrays were calibrated using the direct wave from the EHL. We previously measured the amplitude of the direct wave, $\hat{p}_i$, at the geometric focus to be $\hat{p}_i = 1.2 + (V_C - 18)/20$ MPa where V_C is the charging voltage of the capacitor in kilovolts (unpublished data). Element sensitivity was given by $S_i = \hat{p}_i/\hat{V}_i$ where $\hat{p}_i$ is direct-wave pressure amplitude and $\hat{V}_i$ is the output voltage amplitude. The expected variation in amplitude of the direct wave due to geometrical spreading was negligible ($<1\%$) over the spatial extent of the array.

In practice, we were unable to calibrate using a single direct-wave event due to variability from shock to shock. Some variation was due to the direct wave itself with additional variation possible from small changes in orientation of the elements relative to the sound field because the hydrophone was not rigidly backed and the hydrophone film was not rigidly mounted in the bracket. A small amount of bending was possible from end to end because the hydrophone was flexible, but the surface would be near planar once the hydrophone was mounted in the bracket. On the element level, the film was flat because the assembly process ensured a planar structure. When mounted, the hydrophone was not constrained in the sense of tension mounting, so it could shift slightly when hit by the SWs. However, over multiple shots, the variation would be expected to converge to the original position of the hydrophone.

Figure 3 shows an example of direct-wave variation on three elements of H9 (two outer and one central) tested at

20 kV. A variation around a mean value was clearly observed from shock to shock for the three elements. In addition, until damage became apparent on element 10, the pressure of the direct wave was fairly uniform across the three elements, as would be expected from the planar nature of the direct wave once it reached the hydrophone. The outer elements recorded a steady, rising pressure even after 1000 shocks, which would indicate the electrode was still in good condition and even generating slightly stronger shocks over time.

Because of the observed variation in direct-wave pressure and previous measurements that demonstrated the relative sensitivity of all the elements from a single hydrophone array typically were within 10% of the mean sensitivity,²⁴ we made the decision to calculate a single, uniform sensitivity value for all of the elements rather than to obtain an element-by-element sensitivity or to determine a new sensitivity for every direct wave. However, for two of the arrays, the relative sensitivity displayed an unusually large variation on a select few central elements. Therefore, for these two arrays (H4 and H9) we chose to use an element-by-element calibration method because the average sensitivity approach led to beamwidths that were clearly not physical. Using the outlined calibration approach, five of the nine arrays yielded average sensitivities of approximately 43 MPa/V and the remaining four arrays displayed sensitivities in the range of 30 to 37 MPa/V (Table I).

III. RESULTS

A. Temporal response

Figure 4(a) shows representative waveforms measured by the 7 central elements of array H1 for a single SW fired at 14 kV. The direct wave, which was used to calculate sensitivity, was evident in each trace line at $185 \mu\text{s}$ while the focused wave arrived at $214 \mu\text{s}$. Figure 4(b) shows the pressure-time trace of the waveform of the 10th element. The value of p_+ was 24.8 MPa and the duration of the positive phase was $1.4 \mu\text{s}$, which was consistent with previous single-element hydrophone measurements for this source.²² The smooth foot at the front of the waveform, a feature which is also apparent in fiber-optic hydrophone measurements,^{25,26} was likely due to a slight distal positioning of the hydrophone that artificially increased the rise time.²⁷ The rise time based on 50%–90% of the peak pressure was 16 ns, which is in line with other measurements.^{22,27} We note that the theoretical rise time of the SW is substantially less than 1 ns, and we are unaware of any hydrophone that can accurately capture such a rapid rise time.

The measured peak negative pressure of -3.7 MPa was smaller in amplitude than the -6 to -10 MPa that has been reported.²² This may be due to scattering by structures

TABLE I. Mean sensitivity and standard deviation for each array.

Hydrophone	14 kV			17 kV			20 kV		
	H1	H2	H3	H4	H5	H6	H7	H8	H9
Sensitivity (MPa/V)	43.7 ± 3.4	42.4 ± 3.6	43.8 ± 5.1	36.9 ± 3.0	45.1 ± 4.4	29.4 ± 1.7	30.2 ± 2.2	46.5 ± 7.5	37.5 ± 3.2

FIG. 4. (a) Typical time-domain waveforms data collected by 7 elements (7 through 13) of array H1 at 14 kV. The direct wave was visible for each trace near $185 \mu\text{s}$. (b) Pressure-time trace of the focused SW measured by the central element showing the characteristic EHL features of a rapid rise time with a longer negative phase.

around the hydrophone that interfered with the negative phase or may have resulted from some very localized cavitation at the surface of the element that developed during the negative pressure phase. The limitation of piezopolymer membranes for measuring the negative phase in high-pressure acoustic fields due to the presence of cavitation at the hydrophone surface is a known issue and can be attributed to the hydrophobic properties of piezopolymer.²⁸ A vapor or a gas bubble will have a greater effect during the tensile phase as the cavity grows and slightly reduces the surface area available for acoustic detection. While the rise time and peak negative pressure are relevant parameters for characterizing time-domain shockwave characteristics, we were mainly interested in beamwidth features and, therefore, we will focus on the parameters derived from p_+ .

B. Lifetime assessment

Lithotripters are designed to generate pressure sufficient to fragment kidney stones and typically also damage hydrophones placed in the focal region. In Fig. 5(a), the evolution

of the peak positive pressure is shown for the three central elements of array H4 as a function of the number of SWs applied at 17 kV. Element 10 decrease in output over the first 100 shots, indicating a fairly steady decay of performance. In comparison, element 9 maintained uniform output up to 200 shots, at which point it failed suddenly. Element 11 showed a general decay up to 800 shots after which it failed. In general, the elements near the center of the array, where the pressures were the highest, were the first to fail and the elements that were exposed to lower pressures lasted much longer (Fig. 3).

Identifying the onset of element failure was critical for determining the interval over which measurements could be considered reliable. For this reason, we carefully examined the evolution of p_+ throughout the experiments. To separate single-shot variability from longer-term trends, a moving average was computed over 10 consecutive SWs for each element. We defined damage to occur when the moving average dropped below 50% of the measurements at the beginning of the experiment. We chose this definition for element failure because failure typically occurred soon after p_+

FIG. 5. (Color online) (a) Pressure evolution of elements 9, 10, and 11 of H4 tested at 17 kV. These central elements, where pressure was highest, tended to fail sooner. (b) Cumulative element failure data for all hydrophones tested at 17 (H4 to H6) and 20 kV (H7 to H9). No failures were observed for hydrophones tested at 14 kV. At higher voltages, at least two elements failed. More failures were seen for the higher pressures of the 20 kV excitation.

began to show clear signs of decreasing value. For example, for H4 tested at 17 kV [Fig. 5(a)], element 10 failed after 30 SWs, element 9 failed after 210 SWs and element 11 failed after 780 SWs.

Figure 5(b) displays the shock-wave number at which elements progressively failed for arrays tested at 17 and 20 kV. The 14 kV cases are not shown because no element failures were observed, even after 1000 shocks. The number of shocks acquired before the first element failed was between 30 and 520 at 17 kV, and between 40 and 120 at 20 kV. Arrays exposed to the higher-pressure, 20 kV shocks were more likely to fail than those exposed to 17 kV shocks. The 17 kV results varied widely, with initial element failures occurring at 30, 350, and 520 shocks, but with only 2 or 3 elements failing after 1000 shock exposures. The 20 kV failures had less variation with more than four elements failing before 200 shots. The variation in the number of SWs to failure can be related to the variability of the acoustic field of the EHL, and also to the stochastic nature of cavitation, which is likely the dominant mechanism producing failure.

C. Beam characterization

Figure 6 shows five instantaneous beam patterns of individual 14 kV SWs recorded by H1. In this subset of the data, the location of p_+ deviated by as much as 4 mm from the nominal focus and the p_+ values ranged from 27 to 33 MPa. It should be noted that the instantaneous beam patterns measured by the one-dimensional array corresponded to projections of the actual beams on the axis of measurement. Because the acoustic field could vary in three dimensions, the actual values of p_+ could be higher than measured if the peak did not fall on the axis of our measurement. Despite the variation between instantaneous measurements, averaging p_+ at each element over all SWs does, at least for this case, result in a smooth lateral profile with a single peak (dashed line). However, the beamwidth of the average tends to be wider than the instantaneous beamwidth (thick solid line). To calculate the instantaneous beamwidth, SWs were laterally shifted

FIG. 6. Beam profiles of H1, tested at 14 kV, for five individual SWs (solid) and the average (dashed) over all SWs. Thick solid line is the average of instantaneous beamwidths, shifted such that the peak pressures coincide at the same element.

such that their peak pressures were aligned and then an average beamwidth was calculated.

Figure 7(a) displays the beamwidth of the average pressures at each array element for hydrophones tested at 14 kV. The curves were derived from the shock-to-shock beamwidths up until damage to one of the hydrophone elements was detected. The three arrays displayed a smooth lateral profile, although with some asymmetry. This asymmetry was a result of presenting the beamwidth as the average pressure on each element even though we know that the SW had spatial and pressure variability. Computing the instantaneous beamwidth average would result in curves similar to what was shown in Fig. 6 (thick solid line).

Figures 7(d) and 7(g) show beamwidths for the arrays tested at 17 and 20 kV. In general, increasing the charging voltage resulted in an increase in the averaged peak pressure, with H7 being the only exception. Except for H4 and H9, which displayed notches in their central region, the beam patterns were smooth with some asymmetry again visible. The notches in H4 and H9 were also a result of the method of displaying the beamwidth and highlights the problem with finding beamwidth from single-point measurements. A better understanding of how shock-source variability affects beamwidth measurements can be found by plotting the variation in beamwidth and element location of p_+ from shock to shock.

A plot of instantaneous beamwidth as a probability distribution is shown in Fig. 7(b) for the three hydrophones tested at 14 kV. The overall trends of the 14 kV arrays were similar, with a sudden rise of probability and then a gradually decreasing tail. The shock-to-shock beamwidth probability for the 17 and 20 kV cases are shown in Figs. 7(e) and 7(h). Unlike the 14 kV cases, these probability curves did not show a strong similarity amongst themselves. At 17 kV, H5 had a beamwidth probability distribution centered near 12 mm with a fairly uniform drop-off to either side, but the distribution of H4 and H6 did not show distinct central peaks. At 20 kV, H8 and H9 revealed peaks in the probability distribution near the center peak, but H7 had more spread in the beamwidths without a distinct peak. The results provide further quantitative evidence that higher excitation voltages resulted in more shock-to-shock variation in the beamwidth and illustrates why averaging at single points leads to beamwidth measurements that are not representative of the instantaneous acoustic field.

Figure 7(c) plots the probability that p_+ was located on a given element for the arrays tested at 14 kV. The peak probability was at element 10 for H1, between elements 8 and 9 for H2 and on element 9 for H3. This was consistent with our estimate of 1 mm accuracy in positioning. For each of the 14 kV arrays, more than 70% of the shots resulted in a peak pressure over three central elements. This indicates that the alignment of the axis of the acoustic field was stable and suggests that the variation in p_+ had more to do with the overall acoustic field amplitude rather than overall spatial shifts of the acoustic field. The non-uniform distribution for the location of p_+ combined with the variable beamwidths displayed in Fig. 7(b) help explain the asymmetry observed for the beamwidths in Fig. 7(a). For the 17 and 20 kV excitation cases [Figs. 7(f) and 7(i)], there was much more jitter in

FIG. 7. (a), (d), and (g) Average instantaneous beam patterns, (b), (e), and (h) beamwidth probability, and (c), (f), and (i) p_+ location probability for all nine hydrophones.

the locations where the peak pressure occurred with only H5 showing signs of a distinct peak in probability. Interestingly, H4 and H9 showed signs of having a bimodal distribution for the location of p_+ and, in fact, this was the reason for the notches observed in the beamwidth plots.

Figure 8 shows a box plot of all beamwidths measured for the nine arrays as well as the beamwidth found after averaging the shock-to-shock p_+ values from each element. In all

FIG. 8. Box plot comparing instantaneous beamwidths with average beamwidths. Outer whiskers indicate full range of each data set while inner boxes indicated the 25%–75% range. The solid line in each box is the median. The mean of the instantaneous beamwidth is shown as a solid square and the beamwidth of the average is shown as a solid circle.

cases, the instantaneous beamwidth was smaller than the beamwidth attained by averaging. The overall collection of the instantaneous beamwidths tended to remain between 8 to 12 mm, with a slight increase as voltage increases. Table II summarizes the beamwidth measurements for all nine hydrophones. The difference between the two methods of beamwidth calculation was typically 1 to 2 mm. The results demonstrate that single-element hydrophone measurements of an EHL will overestimate the FWHM beamwidth.

The effect of the displacement of the beam on the beamwidth is shown in Fig. 9. It can be seen that for cases where the peak pressure was close to the nominal beam axis, the beamwidth was smaller. This was consistent with the presumption that the EHL spark occurred close to the first focus of the reflector which would result in near-ideal focusing. When moving away from the central array elements, the effective beamwidth increased, presumably because the true

TABLE II. Average beamwidth vs beamwidth of the average.

Hydrophone	14 kV			17 kV			20 kV		
	H1	H2	H3	H4	H5	H6	H7	H8	H9
Instantaneous Beamwidth (mm)	8.2	11.7	9.3	10.6	12.5	11.8	10.8	12.2	11.0
Beamwidth of Average (mm)	8.5	13.2	11.5	11.8	13.3	13.9	13.2	14.6	11.9

FIG. 9. Average beamwidth vs the element number for which the beamwidth was recorded. The narrowest beamwidth measured tended to be towards the center of the hydrophone array for each of the excitation voltages.

location of p_+ had moved off axis as a result of the inherent jitter in the location of the spark. An off-axis shift in p_+ would imply a blurring (i.e., broadening) of the focus, as was observed (Fig. 9). Thus, the jitter led to large beamwidths of up to ≈ 16 mm, but very few SWs were this far off axis [Figs. 7(b), 7(e), and 7(h)].

To further study the asymmetry of the beam profile, the distance from the location of the beam centroid to the location of the peak pressure was calculated. At 14 kV excitation,

the centroid of H1 was within 1 mm of the peak pressure $>70\%$ of the time [Fig. 10(a)], which suggests a symmetric beam pattern and was consistent with the beamwidth and p_+ element probability plots [Figs. 7(b) and 7(c)]. For H3, the centroid was within 1 mm of the peak pressure 40% of the time, about one half the value seen with H1, and within 2 mm about 70% of the time. For H2, the centroid was within 1 mm of the peak pressure only 12% of the time and the range needed to be extended to about 3 mm to reach 70%. This suggests that for the H2 electrode, there was more inconsistency in the acoustic field due to jitter in the spark location because of manufacturing variability.^{29,30} For the 14 kV cases, the general trend was for the probability to decrease as distance from the centroid increased.

This decreasing trend was not as apparent for the 17 kV cases [Fig. 10(b)]. While the centroid of H6 was within 2 mm of the peak pressure more than 70% of the time, the 70% probability distance did not occur until 3 mm for H4 and H5. The general trend at 17 kV was towards more variability of the centroid within 2 mm of the peak pressure location with only H6 showing a steady decline in probability as centroid distance increased. At 20 kV, only one hydrophone (H7) had its centroid within 2 mm of the peak pressure more than 70% of the time. The other two 20 kV hydrophones (H8 and H9) had their centroids within 3 mm of the peak pressure 70% of the time [Fig. 10(c)]. At 20 kV, none of hydrophones displayed a steady decrease of probability as distance from the centroid increased. In general, increasing the voltage

FIG. 10. Distance from p_+ to the beam centroid for arrays tested at (a) 14, (b) 17, and (c) 20 kV.

yielded beams whose centroid was displaced from the location of p_+ .

IV. DISCUSSION AND CONCLUSIONS

The instantaneous acoustic field of an EHL was measured using a 20-element hydrophone array based on a piezopolymer membrane. The hydrophone array was able to capture the acoustic field from the single shot of an EHL in an axis lateral to the propagation of the SW. This allowed for the effect of shot-to-shot variation in the beam pattern to be measured. It was found that the highest peak pressure was within 3 mm of the nominal acoustic axis of the lithotripter about 70% of the time, but in some cases could be up to 5 mm away from the axis. The movement of the beam was more pronounced when higher voltages were used to drive the spark discharge, indicating more spark-location variability with voltage.

The average of the instantaneous measurements showed that the beamwidth was no more than 12.5 mm, with the smallest recorded value of 8.2 mm. It was found that, at any discharge voltage, the instantaneous beamwidths were consistently 1–2 mm narrower than what would be measured by a single-element hydrophone scanning the field over multiple SWs. The beamwidth of this particular lithotripter was previously reported as 10 mm for a charging voltage of 18 kV.²² This value was less than all of the beamwidth-of-the-average values that we measured except for H1 at 14 kV. Considering that the two equivalent EHL systems tested in Ref. 22 had beamwidths of ≈ 15 mm, the originally reported 10 mm was likely an underestimate due to the particular combination of spark source, its variability, and the uncertainty of measuring beamwidth with a single-element hydrophone and a limited number of SWs.

Although our beamwidth measurements were based on the projection of the acoustic field on the axis of measurement (i.e., the linear hydrophone array), the measurements were reasonable estimates of the true beamwidth because variations along other axes that were within the focal plane would be very similar because of the radial symmetry of the sound field. In addition, the acoustic field in the direction of propagation evolved slowly, due to diffraction, over many millimeters, which meant that small shifts in axial position would have minimal impact on the measurements. As the beam became more displaced from the nominal acoustic axis, the beamwidth increased, which is consistent with the focus being smeared due to imperfect focusing.

As with other hydrophones, the array presented here suffered progressive damage as it was subjected to SWs. The lifetime was longest at 14 kV for which fatal damage was not observed, even after 1000 shocks. At 17 kV, elements failed after about 30 to 520 SWs and at 20 kV elements failed after about 40 to 120 SWs [Fig. 5(b)]. The damage to the array elements was typically caused by cavitation on the surface of the array and resulted in pitting of the piezopolymer or sometimes complete delamination.¹⁸ A possible solution to minimize cavitation would be to coat the film with a protective layer made of an impedance-matched, tear-resistant material such as Parylene which would extend element

lifetime and increase sensitivity. Although the hydrophone elements underwent progressive erosion from cavitation, the lifetime of the elements was consistent with single-element hydrophones that are commonly used for lithotripter measurements.^{14–16} However, the lifetime of the hydrophone array is effectively longer than with a single-element hydrophone because fewer SWs are needed to fully characterize a pressure field.

The refined hydrophone array presented here shows promise as a tool to characterize the acoustic fields of SWs and, at least for EHL systems with variable acoustic fields, could provide a motivation to reexamine acoustic dose levels. The relative simplicity of fabrication and ease of replacement in a test bracket could make the arrays a convenient disposable calibration device. The fabrication process provided a good overall uniformity of the sensitivities of the elements on one array and satisfactory reproducibility from one array to another. More uniform and reproducible sensitivities could be obtained by carefully monitoring the applied pressure when bonding the piezopolymer to the flex circuit. Finally, the array could be mounted onto a larger film which would then be tension mounted to a frame which is large enough that any scattering from the frame will arrive after the time window of interest has passed.

The data reported here were acquired with an EHL, but the array would work with non-sparked-based lithotripters as well. The array has the potential to allow for much faster field mapping and longer lifetime than is possible with a single-element hydrophone. The same design and fabrication process could be used to fabricate a two-dimensional array which would allow for complete characterization of the lateral motion of the SWs and further acceleration of the time it would take to carry out field mapping.

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