Beamwidth measurement of individual lithotripter shock waves

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(Received 10 January 2008; revised 13 August 2008; accepted 17 November 2008)

New lithotripters with narrower foci and higher peak pressures than the original Dornier HM3 electrohydraulic lithotripter have proven to be less effective and less safe. Hence, accurate measurements of the focal characteristics of lithotripter shock waves are important. The current technique for measuring beamwidth requires a collection of single-point measurements over multiple shock waves, thereby introducing error as a result of any shock-to-shock variability. This work reports on the construction of a hydrophone array sensor and on array measurements of individual lithotripter shock waves. Beamwidths for an electrohydraulic lithotripter with a broad-focus HM3-style reflector and a narrow-focus modified reflector were measured using both new and worn electrodes as well as two different electrical charging potentials. The array measured the waveform, beamwidth, and focal location of individual shock waves. The HM3-style reflector produced repeatable focal waveforms and beam profiles at an 18 kV charging potential with new and worn electrodes. Corresponding measurements suggest a narrower beamwidth than reported previously from averaged point measurements acquired under the same conditions. In addition, a lack of consistency in the measured beam profiles at 23 kV underscores the value of measuring individual shock waves. © 2009 Acoustical Society of America. [DOI: 10.1121/1.3050272]

PACS number(s): 43.80.Vj [CCC]

Pages: 1240–1245

I. INTRODUCTION

Shock-wave lithotripsy (SWL) is the most common treatment for uncomplicated renal stones.¹ Several recent studies have reported that when compared to outcomes with the original Dornier HM3 electrohydraulic lithotripter, new lithotripters have lower stone-free rates, increased retreatment rates, and increased severity and frequency of trauma to surrounding tissue.^{2–5} The differences in clinical outcomes may relate to the method of acoustic coupling to the patient (newer machines utilize a water filled pillow, while the HM3 utilizes a water bath).⁶ However, it is generally accepted that the tighter focal geometries and higher peak pressures of the newer machines have had great impact on clinical outcomes. More specifically, tissue injury is known to correlate with peak pressure, while the efficacy of targeting stones is likely reduced for shock waves with narrower focal regions.⁷ Moreover, experiments have also found that lithotripters with focal regions that are wide relative to the stone (e.g., the HM3) produce more effective stone fragmentation. The utility of a broad focal beamwidth lies in the ability of a shock wave traveling along the stone perimeter to generate shear waves within the stone.^{8–10} In response to clinical outcomes and experimental results, many manufacturers have released new lithotripters specifically marketed as “broad-focus.”

The inherent shock-to-shock variability of the acoustic field in spark-source electrohydraulic lithotripters makes it

very difficult to characterize instantaneous beamwidths. Typically, beamwidths are estimated from the sequential acquisition of point measurements within the focal plane using a single-element hydrophone. However, shock waves change significantly due to variations in spark energy and in the location of the spark between the electrodes.¹¹ These variabilities can alter the waveform shape in terms of rise time and pulse width. Moreover, the location of the focal region may shift. Accordingly, the combination of single-element hydrophone measurements from a series of different shock waves may yield broader estimates of beamwidth than are actually present. Given the clinical motivation described above for knowing the shock-wave beamwidth in lithotripsy, improved measurement tools are needed.

In this work, a linear array hydrophone was constructed and used to make instantaneous beamwidth measurements of individual lithotripter shock waves. Measurements were made with broad- and narrow-focus electrohydraulic lithotripters as well as with new and worn electrodes at different charging potentials. The different conditions tested were designed to ensure variability in both focal beamwidths and peak pressures.

II. METHODS

A. Hydrophone array

The hydrophone used in this effort was designed to be a linear array that roughly spans the –6 dB beamwidth of HM3-style lithotripters. From averaged single-point measurements in the same APL-UW lithotripter used in this ef-

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FIG. 1. The hydrophone array as sketched in (a) plan view and (b) elevation view. Part (c) comprises a photograph of the array as viewed from beneath the epoxy plug shown in (b). Note that some residual adhesive used in fixturing the array remains visible in the photograph. The array consisted of 20 PVDF elements that were $0.5 \times 4 \text{ mm}^2$, with a center-to-center element spacing of 0.7 mm. Note that the array elements and the overlay of the focal region for the HM3-style reflector are drawn to scale in (a). For the HM3-style reflector, the overlay represents a previously reported beamwidth that corresponds to the array orientation used in the present measurements.

fort, Cleveland *et al.*¹² reported peak pressures in the focal plane. Linear interpolation of these data implies a -6 dB beamwidth of about 14 mm for the HM3 configuration. As depicted in Fig. 1(a), the array comprised 20 elements, each 4 mm long by 0.5 mm wide. The center-to-center element spacing was 0.7 mm, leading to a total array width of 13.8 mm. The 0.5 mm element widths were chosen to allow high spatial resolution along the length of the array; the larger 4 mm lengths were chosen to maintain higher element surface areas for impedance matching considerations.

This basic array geometry was fabricated using a technique described by Ketterling *et al.*¹³ A functional schematic and a photograph of the fabricated device are provided in parts (b) and (c) of Fig. 1. The transduction was performed by a 9 μm polyvinylidene fluoride (PVDF) membrane with one side electroded in gold (Ktech Corp., Albuquerque, NM). The gold electroding provided a common ground for all array elements. Using a thin layer of nonconductive epoxy that typically remained about 1 μm thick after curing, the other side of the PVDF membrane was bonded to a

copper-clad polyimide (CCP) film (RFlex 1000L810, Rogers Corp., Chandler, AZ). The actual pattern of array elements and electrical trace lines linking each element to a connection pad was etched onto the CCP using standard printed circuit board techniques. Lastly, the trace pads were spaced to fit into a standard zero-insertion-force (ZIF) flex connector. During the bonding process, the PVDF and CCP layers were clamped between two aluminum plates. After the bonding epoxy cured, a Teflon mold of 15 mm depth was attached to the CCP and filled with additional epoxy. Although not explicitly depicted in the figure, a custom printed circuit board linked the ZIF connector to 20 BNC connectors. Operating characteristics including center frequency and bandwidth have been reported in the literature for a similar device.¹³

Given the design details described above, it is instructive to consider expected performance characteristics of the hydrophone array. Since the bandwidth of PVDF is greater than 70 MHz, shock fronts with rise times of at least 14 ns can theoretically be resolved. However, angular misalignment of the array with the shock front will effectively average the shock over the element surface and increase its apparent rise time. For example, a 5° inclination of the 4-mm-long elements would lead to an apparent 200 ns rise time for a planar shock wave. In addition, spatial variations of the incident acoustic field will be averaged over the area of each element. Although little spatial averaging is expected along the 0.5 mm dimension of each element, the 4 mm dimension represents a nontrivial fraction of the nominal 14 mm beamwidth. Assuming an axisymmetric acoustic field in the plane of the array, averaging along the 4 mm dimension will effectively reduce the spatial resolution relative to that implied by the 0.5 mm element widths.

B. SWL measurements

Measurements were made in degassed water, with the hydrophone array placed at the focus of the APL-UW research lithotripter modeled after the Dornier HM3.¹² The array was oriented at the focus such that the $4 \times 0.5 \text{ mm}^2$ area of each element was approximately perpendicular to the axis of propagation of the shock wave. Moreover, the array was centered such that the middle elements were aligned at the geometric focus of the lithotripter. A charging potential of 15, 18, or 23 kV triggered single shock waves at a rate slower than 1/min. Two ellipsoidal reflectors were used: an HM3-style reflector (semimajor and semiminor axes: $a = 13.80 \text{ cm}$, $b = 7.75 \text{ cm}$) and a reflector insert that fit inside the HM3-style reflector ($a = 9.30$, $b = 6.24$). Both reflectors were axisymmetric in that they did not possess the fluoroscopy probe cutouts that are typically found in clinical lithotripters. The reflector insert was designed to create a tighter focus, as illustrated in Fig. 2. New electrodes (<200 shock waves) and worn electrodes at the end of their prescribed clinical lifetime (>2000 shock waves) were used. Worn electrodes possessed larger spark gaps and exhibited damage caused by arcing along a broad portion of their surface. As mentioned above, testing with new and worn electrodes ensured variability in the focal pressures.

FIG. 2. Scaled drawing of the tested lithotripter geometries. The ellipsoidal reflectors possess two foci, where $F1$ denotes the focus corresponding to the spark source and $F2$ denotes the remote focus corresponding to the treatment site and the central location at which beamwidth measurements were acquired.

Voltage measurements from the array elements were captured on six digital oscilloscopes with sampling rates of at least 50 MHz. Measurements were collected using an input impedance of 1 M Ω on the oscilloscopes and no preamplification. A custom LabVIEW program (National Instruments, Austin, TX) was used to digitally store select waveforms. Oscilloscope measurements corresponding to peak positive pressures of the focal waves were manually recorded for all array elements.

C. Relative sensitivities of array elements

Although array elements were not calibrated for absolute pressure measurements, the relative sensitivity of each element was determined using two independent methods. The first approach utilized the fact that a direct wave diverges spherically from the spark at the $F1$ focus. For the HM3-style reflector, the second focus ($F2$) is 228 mm away from $F1$. Considering the 13.8 mm width of the array and assuming that the direct wave is lossless and axisymmetric, the amplitude of the direct wave should vary by less than 0.1% across the array. Based on such geometric considerations, the amplitude of the direct wave was taken to be constant for all array elements for each incident shock wave. As such, measurements of the direct wave were used to determine the relative sensitivities of each element.

In the second approach, each element of the array was exposed to a controlled low-amplitude sound field. The sound field was produced by a focused transducer with a 0.375 in. diameter and a 2 in. focal length (Panametrics V326, Olympus NDT Inc., Waltham, MA) excited with a 5 MHz, 10 cycle tone burst. The transducer was mounted to motorized translation stages and could be moved precisely from element to element. For each measurement, the transducer was scanned across an element in 200 μ m increments, and an average of 100 tone bursts were acquired at a sampling rate of 100 MHz. The maximum peak amplitude was then extracted from the scan data to represent the relative sensitivity of the element. Given that the -6 dB lateral beamwidth of the transducer was 1.6 mm, the 200 μ m scan spacing was more than sufficient to capture the relative maximum of each element with negligible positioning error. Accord-

FIG. 3. Measured direct and focal shock waves from a single array element.

ingly, the maximum voltages from each element were compared to evaluate relative sensitivities. This second approach was pursued after acquisition of beamwidth measurements in order to provide an independent check of element sensitivities.

Ultimately, measurements of focal shock waves were normalized relative to the direct-wave sensitivities. First, varying sensitivity among array elements was addressed by scaling the responses of all elements to match that of the most sensitive element. Then, for each element, the peak voltage from the focal wave was divided by the peak voltage of an “average” direct wave generated with new electrodes at 18 kV. In lieu of an absolute pressure calibration, this normalization approach enables a consistent comparison of results. Moreover, the focal-to-direct-wave ratio can be compared to previous calibrated measurements. From the same APL-UW lithotripter with the HM3-style reflector and a charging potential of 18 kV, Cleveland *et al.*¹² reported peak positive focal pressures of 29.9 MPa with a standard deviation of 4.7 MPa. With an HM3 spark source at a charging potential of 20 kV, Coleman *et al.* measured peak-positive, direct-wave amplitudes between 1 and 3 MPa at $F2$.¹¹ With a comparable source at the same charging potential, Müller measured the direct wave closer to the source; assuming a $1/r$ scaling, the measured amplitude was equivalent to 0.8 MPa at $F2$ of the HM3-style geometry.¹⁴ From previous measurements, in addition to the somewhat lower 18 kV charging potential in the present work, direct-wave amplitudes near 1 MPa can be expected. Accordingly, focal-to-direct ratios may be interpreted to roughly represent megapascal.

III. RESULTS

A. Array performance

Individual array elements were able to measure waveforms consistent with those previously reported for the HM3. A sample waveform acquired while using the HM3-style reflector and new electrodes is shown in Fig. 3. The sensitivity of the hydrophone array was sufficient to reveal the direct wave seen at $t=0$ as well as the focused wave at $t \approx 30 \mu$ s. Typical waveforms exhibited a peak positive spike of about 1 μ s duration followed by a negative trough of about 4 μ s, which is the commonly described classic lithotripter waveform.^{11,12} The shock front was slightly rounded and not strongly shocked. As discussed above, angular misalignment

FIG. 4. Normalized element sensitivities. The solid line indicates the element-by-element mean of measurements from six direct waves, while the vertical bars indicate ± 1 standard deviation at each element. The x and o markers represent sensitivities determined from exposure of the array to a low-amplitude, 5 MHz source.

of the array such that its elements were not parallel to the shock front is a likely explanation for the slow rise times observed.

As described in the previous section, data were collected to evaluate the relative sensitivities of array elements. Measurements of direct waves were recorded using new electrodes with charging potentials of 18 or 23 kV for the HM3-style reflector and 15 or 18 kV for the reflector insert. Note that direct-wave amplitudes were resolved with different oscilloscope settings from those used for the data in Fig. 3. While all of the direct-wave data exhibited consistent sensitivities for each element, data from the reflector insert were collected while one of the elements was not producing a signal. Hence, the remaining data from six shocks were normalized and averaged to determine relative sensitivities. Each direct-wave measurement was normalized across all elements so that the most sensitive element possessed a value of unity. An average of normalized measurements is plotted as the solid line in Fig. 4, where the vertical bars represent ± 1 standard deviation for each element. As implied by the plot, the same element at $x = -3.15$ mm was effectively the most sensitive for all measurements. In addition, even though sensitivity varied significantly among array elements, the relative sensitivity of each element was consistent from shock to shock.

To independently confirm the direct-wave data, relative sensitivity measurements were also acquired using a low-amplitude, 5 MHz source. Using the same normalization described above, these data are plotted in Fig. 4 with "x" and "o" markers. The o measurements show good quantitative agreement with the direct-wave data. In contrast, the elements corresponding to the x measurements exhibited a consistent, but low, sensitivity near 0.2. One of these elements (at $x = +4.55$ mm) had a similarly low sensitivity from the direct-wave measurements, while the others previously had higher sensitivities.

From the evaluation of sensitivity measurements, two qualitative element behaviors can be identified. These behaviors comprise high-sensitivity responses (above about 0.4) and low-sensitivity responses (≤ 0.2). As noted above, one array element exhibited no response during the acquisition of some direct-wave measurements and subsequent measurements of focal shock waves. Interestingly, this same element (at $x = +2.45$ mm) exhibited a low but consistent response

FIG. 5. Beam profiles measured for individual shock waves. Shock waves were generated using (a) the reflector insert, a charging potential of 18 kV, and new electrodes (three shock waves); (b) the HM3-style reflector, 18 kV, and new electrodes (four shock waves); (c) the HM3-style reflector, 18 kV, and worn electrodes (four shock waves); and (d) the HM3-style reflector, 23 kV, and new electrodes (five shock waves). Note that direct-wave measurements at 18 kV were used for all normalizations, thereby allowing a direct comparison of the amplitudes in all plots. The -6 dB beamwidth of the thickest-line profile is marked in (a).

23 months later when additional sensitivity data were acquired at 5 MHz. Based on a visual observation of the PVDF surface, the drops in sensitivity for the x elements appear to be related to cavitation- or stress-related damage to either the bond epoxy between the PVDF and CCP or the epoxy-plug backing. However, the PVDF itself still remained acoustically active for the x elements, as evidenced by their nonzero responses, thereby lending credence to the hypothesis that the PVDF had separated from its CCP backing layer.

B. Beam profiles

After correcting for individual element sensitivities as described above, the beam profiles of individual shock waves are presented in Fig. 5. Because all measurements were normalized relative to the direct wave from the HM3-style reflector at 18 kV, all plotted amplitudes can be directly compared. As shown, measured profiles were sorted based on test

TABLE I. Measurements from individual shock waves.

Conditions		Beamwidth (mm)		Peak location (mm)
		Mean	Range	Range ^a
(a)	Insert reflector 18 kV, new electrodes (three shock waves)	6.3	4.9	0.0
(b)	HM3-style reflector 18 kV, new electrodes (four shock waves)	10.2	2.0	3.5
(c)	HM3-style reflector 18 kV, worn electrodes (four shock waves)	11.1	4.3	3.5
(d)	HM3-style reflector 23 kV, new electrodes (five shock waves)	...	...	11.2

^aDenotes the maximum minus the minimum observed value for measurement of either beamwidth or location of peak pressure.

conditions. Focused beams were produced using four distinct combinations of either the HM3-style or the insert reflector, a charging potential of 18 or 23 kV, and new or worn electrodes. In Fig. 5(a), the -6 dB beamwidth of the profile corresponding to the thickest line is explicitly marked and labeled. Note that dashed circles in (a) and (c) denote array elements that consistently measured lower pressures than their neighbors and were ignored in the estimation of beamwidths for these test conditions.

Each of the profiles plotted in Fig. 5 was used to estimate the -6 dB beamwidth and the transverse location of the peak pressure. These data for independently measured shock waves are provided in Table I, in which “range” for either beamwidth or location of peak pressure denotes the maximum minus the minimum observed value. Comparing the four separate groups of shock-wave measurements, several key differences are apparent. First, from test conditions (a) and (b), the insert reflector produced narrower beamwidths, higher peak pressures, and a more consistent localization of the peak pressure than did the HM3-style reflector. In Table I, identical peak-pressure locations were measured for all shock waves from condition (a), thereby yielding a range of zero for peak location. Despite measuring a low number of shock waves, the beamwidths estimated for conditions (a) and (b) are statistically different at a 95% confidence level ($p \approx 0.04$ when beamwidths are assumed to come from normally distributed samples with equal variances). Considering conditions (b) and (c) for the HM3-style reflector, worn electrodes altered the shape of beam profiles and generated slightly higher peak pressures than new electrodes at a charging potential of 18 kV.

At a charging potential of 23 kV with new electrodes, the HM3-style reflector tended to produce higher peak pressures than at 18 kV, as expected. However, shock waves generated at 23 kV also exhibited much greater variability. Given the inconsistency of measured beam profiles shown in Fig. 5(d), corresponding beamwidths were not estimated. As for the observed locations of peak pressure, the greater variability is demonstrated by the 11.2 mm range, inasmuch as peak pressures occurred near both ends of the array. Assum-

ing that peak-pressure locations are normally distributed, the variances of conditions (b) and (d) are statistically different at a confidence level of 89%. Hence, the location of peak pressure was quantitatively less consistent in case (d). This result again demonstrates that the array can be used to discern system variability based on only a few measured shock waves.

In addition to the above comparisons among test conditions used in this effort, measurements with the HM3-style reflector can also be compared to data derived from single-point hydrophone measurements. The -6 dB beamwidth of the HM3-style reflector for the APL-UW lithotripter was previously reported to be about 14 mm.¹² For the relevant conditions tested in this effort, average beamwidths were found to be 10–11 mm. Although this difference may not be statistically significant, these results are consistent with the expectation that averaging of single-point measurements from multiple shock waves leads to an overestimation of beamwidth. Aside from beamwidth, a loose comparison of peak positive pressures can also be made. Single-point data indicated pressures of 29.9 ± 4.7 MPa at 18 kV for the HM3-style lithotripter used in this effort.¹² Such a pressure range is fully consistent with the array profiles shown in Fig. 5(b) if the aforementioned direct-wave amplitude of 1 MPa is assumed.

IV. DISCUSSION AND CONCLUSIONS

A linear hydrophone array constructed and tested in this effort was useful for quickly and precisely measuring the beamwidths of focused shock waves. Data described above represent the first simultaneous acoustic field measurements of individual lithotripter shock waves. Previous data from the literature consisted of point measurements at a single spatial location for each shock wave, thereby requiring averages over multiple shock waves in order to assess the beam characteristics of focal waves. Given the inherent shock-to-shock variabilities of electrohydraulic lithotripters, simultaneous field measurements provide the unique benefit of avoiding any inaccuracies introduced by averaging over multiple shocks. Indeed, even though relatively few shock waves were measured in this effort, the resulting data suggest that beamwidths for the APL-UW lithotripter may be about 25% narrower than previously reported from averaged measurements. This discrepancy may be due to averaging effects and/or the use of a much coarser spatial resolution for the single-point measurements (data were collected on a 5 mm spacing in the focal plane¹²). A more definitive assessment of beamwidths requires further investigation.

In spite of the inherent variabilities associated with spark jitter in electrohydraulic lithotripters, measured focal beams at 18 kV were fairly similar for given conditions [see Figs. 5(a)–5(c)]. Such repeatability is consistent with previous observations of shock-induced fountains.¹⁵ However, the data at 23 kV exhibit much less uniformity. Although spark jitter alone may explain the increased variability at higher charging potentials, Pishchalnikov *et al.*¹⁶ documented the potential for bubbles to distort the acoustic field. In addition, propagation through tissue inhomogeneities may affect the

characteristics of focal shock waves under clinical conditions. More specifically, scattering associated with random variations in the acoustic propagation path has been shown to reduce the amplitude of certain components of focal lithotripter waveforms.^{6,17,18} However, it is still not known whether the scattered energy can be refocused elsewhere in the tissue. As demonstrated by the data at 23 kV, a hydrophone array can identify disparate focal locations of individual shocks and is therefore uniquely suited to address such questions of refocusing.

The array used in this effort proved fairly consistent and robust. However, despite the measurement of consistent beam profiles at 18 kV, changes in sensitivity of some elements over time imply that some damage did occur. From the data presented in Fig. 4, it appears that element sensitivities were typically repeatable even though they tended to eventually drop to a low-sensitivity state. While further investigation of manufacturing variabilities and damage modes is warranted, the demonstrated utility of direct-wave characterization suggests a strategy for acquiring future measurements. If array signals are digitized with sufficient bit depth and temporal length to capture both direct and focal waves, element sensitivities could be explicitly monitored for all measurements. Such an approach is appealing from perspectives of simplicity and quality assurance.

Although the hydrophone design implemented in this effort was successful in proving the feasibility of array measurements in SWL, improvements could be made in future designs. With regard to durability, half of the elements suffered a drop in sensitivity after exposure to approximately 100 shock waves and subsequent aging over about two years. Based on experience with other hydrophones in similar acoustic fields, damage may have been caused by bubble collapses at the surface of the PVDF. Hence, modifications of the array to include a protective coating or immersion in oil might be useful to improve consistency and robustness. In addition, fabrication techniques to yield a more uniform epoxy thickness between the PVDF and the CCP can be pursued to potentially improve element-to-element consistency as well as durability. Ultimately, the life expectancy of such hydrophone arrays may be on the order of 1000 shocks; however, even a shorter lifetime on the order of 100 shocks would be reasonable given an approximate fabrication cost of less than \$400. As a final comment on array design, the fabrication technique allows adjustment of the number of elements, element size, and element spacing, thereby enabling performance to be tailored to specific lithotripters.

ACKNOWLEDGMENTS

The authors thank our collaborators at the Center for Industrial and Medical Ultrasound and the Consortium for Shock Waves in Medicine. Specifically, we thank Aaron Midkiff (Department of Electrical Engineering, University of Washington) for help in the initial testing of the array and Professor Robin Cleveland (Department of Aerospace and Mechanical Engineering, Boston University) for helpful dis-

cussions. This work was supported by the Riverside Research Institute Fund for Biomedical-Engineering Research, the National Institutes of Health (DK 43881), and the National Space Biomedical Research Institute (SMS00402).

- ¹M. S. Pearle, E. A. Calhoun, and G. C. Curhan, "Urologic diseases in America project: Urolithiasis," *J. Urol.* (Baltimore) **173**, 848–857 (2005).
- ²A. P. Evan, J. A. McAteer, J. C. Williams, L. R. Willis, M. R. Bailey, L. A. Crum, J. E. Lingeman, and R. O. Cleveland, "Shock wave physics of lithotripsy: Mechanisms of shock wave action and progress toward improved SWL," in *Textbook of Minimally Invasive Urology*, edited by R. Moore, J. Bishoff, S. Loening, and S. Docimo (Martin Dunitz Limited, London, 2004), pp. 425–438.
- ³K. Kerbl, J. Rehman, J. Landman, D. Lee, C. Sundaram, and R. V. Clayman, "Current management of urolithiasis: Progress or regress?," *J. Endourol* **16**, 281–288 (2002).
- ⁴J. E. Lingeman, "Extracorporeal shock wave lithotripsy devices: Are we making progress?," in *New Developments in the Management of Urolithiasis*, edited by J. E. Lingeman and G. M. Preminger (Igaku-Shoin, New York, 1996), pp. 79–96.
- ⁵J. A. McAteer, M. R. Bailey, J. C. Williams, Jr., R. O. Cleveland, and A. P. Evan, "Strategies for improved shock wave lithotripsy," *Minerva Urol. Nefrol* **57**, 271–287 (2005).
- ⁶Y. A. Pishchalnikov, J. S. Neucks, R. J. VonDerHaar, I. V. Pishchalnikova, J. C. Williams, Jr., and J. A. McAteer, "Air pockets trapped during routine coupling in dry head lithotripsy can significantly decrease the delivery of shock wave energy," *J. Urol.* (Baltimore) **176**, 2706–2710 (2006).
- ⁷R. O. Cleveland, R. Anglade, and R. K. Babayan, "Effect of stone motion on in vitro comminution efficiency of Storz Modulith SLX," *J. Endourol* **18**, 629–633 (2004).
- ⁸R. O. Cleveland and O. A. Sapozhnikov, "Modeling elastic wave propagation in kidney stones with application to shock wave lithotripsy," *J. Acoust. Soc. Am.* **118**, 2667–2676 (2005).
- ⁹W. Eisenmenger, "The mechanisms of stone fragmentation in ESWL," *Ultrasound Med. Biol.* **27**, 683–693 (2001).
- ¹⁰O. A. Sapozhnikov, A. D. Maxwell, B. MacConaghy, and M. R. Bailey, "A mechanistic analysis of stone fracture in lithotripsy," *J. Acoust. Soc. Am.* **121**, 1190–1202 (2007).
- ¹¹A. J. Coleman, J. E. Saunders, R. C. Preston, and D. R. Bacon, "Pressure waveforms generated by a Dornier extra-corporeal shock-wave lithotripter," *Ultrasound Med. Biol.* **13**, 651–657 (1987).
- ¹²R. O. Cleveland, M. R. Bailey, N. Fineberg, B. Hartenbaum, M. Lokhandwalla, J. A. McAteer, and B. Sturtevant, "Design and characterization of a research electrohydraulic lithotripter patterned after the Dornier HM3," *Rev. Sci. Instrum.* **71**, 2514–2525 (2000).
- ¹³J. A. Ketterling, O. Aristizábal, D. H. Turnbull, and F. L. Lizzi, "Design and fabrication of a 40-MHz annular array transducer," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **52**, 672–681 (2005).
- ¹⁴M. Müller, "Dornier Lithotripter im Vergleich Vermessung der Stoßwellenfelder und Fragmentationswirkung (Comparison of Dornier Lithotripters—Measurement of shock wave fields and fragmentation effectiveness)," *Biomed. Tech.* **35**, 250–262 (1990).
- ¹⁵O. A. Sapozhnikov, M. R. Bailey, and L. A. Crum, "Shot-to-shot variability of acoustic axis of a spark-source lithotripter," *J. Acoust. Soc. Am.* **105**, 1269 (1999).
- ¹⁶Y. A. Pishchalnikov, J. A. McAteer, W. Kreider, J. C. Williams, Jr., I. V. Pishchalnikova, and M. R. Bailey, "Influence of cavitation on lithotripter shock waves," in *Proceedings of the 19th International Congress on Acoustics*, Madrid, Spain, September 2–7, 2007; URL: http://www.sea-acustica.es/WEB_ICA_07/fchrs/papers/nla-02-005.pdf (Last viewed August 13, 2008).
- ¹⁷Y. A. Pishchalnikov, O. A. Sapozhnikov, M. R. Bailey, I. V. Pishchalnikova, J. C. Williams, Jr., and J. A. McAteer, "Cavitation selectively reduces the negative-pressure phase of lithotripter shock pulses," *ARLO* **6**, 280–286 (2005).
- ¹⁸R. O. Cleveland, D. A. Lifshitz, B. A. Connors, A. P. Evan, L. R. Willis, and L. A. Crum, "In vivo pressure measurements of lithotripsy shock waves in pigs," *Ultrasound Med. Biol.* **24**, 293–306 (1998).