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Stone Comminution Correlates with the Average Peak Pressure Incident on a Stone during Shock Wave Lithotripsy

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Abstract

To investigate the roles of lithotripter shock wave (LSW) parameters and cavitation in stone comminution, a series of *in vitro* fragmentation experiments have been conducted in water and 1,3-butanediol (a cavitation-suppressive fluid) at a variety of acoustic field positions of an electromagnetic shock wave lithotripter. Using field mapping data and integrated parameters averaged over a circular stone holder area ($R_h = 7$ mm), close logarithmic correlations between the average peak pressure ($P_{+(avg)}$) incident on the stone ($D = 10$ mm BegoStone) and comminution efficiency after 500 and 1,000 shocks have been identified. Moreover, the correlations have demonstrated distinctive thresholds in $P_{+(avg)}$ (5.3 MPa and 7.6 MPa for soft and hard stones, respectively), that are required to initiate stone fragmentation independent of surrounding fluid medium and LSW dose. These observations, should they be confirmed using other shock wave lithotripters, may provide an important field parameter (i.e., $P_{+(avg)}$) to guide appropriate application of SWL in clinics, and facilitate device comparison and design improvements in future lithotripters.

Keywords

Shock wave lithotripsy; average peak pressure; stone comminution; cavitation; acoustic energy

1. Introduction

Shock Wave Lithotripsy (SWL) is a medical technology for non-invasive disintegration of kidney stones in a patient without surgery. Since the early 1980s, SWL has been widely used in clinics as the first line therapy for a majority of renal and upper urinary stones (Chaussy and Fuchs 1989; Rassweiler et al. 2011). Moreover, the success of the 1st-generation shock wave lithotripter (i.e., the Dornier HM3) has stimulated the development of a large number of 2nd- and 3rd-generation lithotripters using different technologies for shock wave generation, focusing, and patient coupling, which have unavoidably affected the performance of modern lithotripters (Coleman and Saunders 1989; Lingeman 1997; Rassweiler et al. 2005). Unfortunately, after extensive use in clinics, 2nd- and 3rd-generation

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Conflict of interest statement

None declared.

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lithotripters have been shown to be less effective in stone comminution, with a higher propensity for tissue injury and stone recurrence compared to the original HM3 (Graber et al. 2003; Gerber et al. 2005), largely due to an incomplete understanding of the fundamental principles of SWL (Lingeman 2003; Cleveland and McAteer 2005; Rassweiler et al. 2011). Therefore, it is critical to determine the relationship between lithotripter field parameters and treatment outcome.

Numerous studies have been carried out to investigate the mechanisms of stone comminution in SWL (Coleman et al. 1987; Sass et al. 1991; Gracewski et al. 1993; Zhong and Chuong 1993; Zhong et al. 1993; Lokhandwalla and Sturtevant 2000; Eisenmenger 2001; Xi and Zhong 2001; Zhu et al. 2002; Cleveland and Sapozhnikov 2005; Sapozhnikov et al. 2007). Most of these previous studies, although valuable in elucidating the mechanism of action in stone fracture especially during the early stage of SWL, did not identify the critical parameters in a lithotripter field that correlate closely with stone comminution. Among various lithotripter field parameters investigated, only effective acoustic energy of the incident lithotripter shock wave has been shown to correlate with stone fragmentation in different stone models (Koch and Grunewald 1989; Granz and Kohler 1992; Delius et al. 1994; Eisenmenger 2001). The acoustic energy, however, is an integrated parameter that cannot be readily related to the characteristics of the lithotripter field such as pressure, beam width, and pulse profile that are more relevant for design improvement of modern shock wave lithotripters. Furthermore, acoustic energy does not differentiate the contributions of stress waves acting within the stone from cavitation mechanisms acting in the fluid surrounding the stone.

In this study, we have performed a series of stone comminution tests *in vitro* under a wide range of lithotripter field parameters using artificial stones of different physical properties. Our results demonstrate that stone comminution in SWL correlates closely with the average peak pressure surrounding the stone in a logarithmic function above a minimal pressure threshold required to initiate stone fragmentation. Implications of this new observation to the mechanisms of stone comminution and improvement of lithotripter design will be discussed.

2. MATERIALS AND METHODS

2.1 Shock wave source and experimental setup

An axisymmetric electromagnetic (EM) shock wave generator mounted at the bottom of a Lucite tank ($L \times W \times H = 40 \times 40 \times 30$ cm) filled with 0.2 μm -filtered and degassed water (<3 mg/L O_2 concentration, 23°C) was used throughout this study (Figure 1a). A 3-D positioning system (VXM-2 step motors with BiSlide-M02 lead screws, Velmex, Bloomfield, NY) placed above the water tank was used for precise placement of a fiber optic probe hydrophone (FOPH 500, RP Acoustics, Leutenbach, Germany) for shock wave field characterization or a flat-base cylindrical tube holder (height $\times$ inner radius = 53×7 mm) during stone comminution experiments. The tube holder is made of Delrin® plastic (E. I. DuPont de Nemours & Co., Wilmington, DE) with a ~ 0.5 mm thick silicone rubber base membrane for minimal interference with LSW transmission to the stone. A cylindrical coordinate system (z, r) was chosen with its origin aligned with the geometric focus of the shock wave source (Figure 1b).

The pressure waveforms and distributions in the geometric focal plane ($z = 0$ mm) and two pre-focal planes ($z = -20$ mm and -40 mm) of the shock wave source were measured using the FOPH 500 with radial step sizes of 1 mm ($0 < r < 6$ mm), 2 mm ($6 < r < 14$ mm), and 5 mm ($r > 14$ mm), respectively. Representative pressure waveforms at discrete positions along the z -axis and in the focal plane are plotted in the inset of Figure 1c, which shows the local peak positive pressures (P_+) vs. radial distance (r) from the central axis in the three

aforementioned planes, together with the average peak pressures ($P_{+(avg)}$) calculated within the area encompassed by the stone holder at the respective positions (see section 2.2).

2.2 Determination of lithotripter field parameters

Based on the pressure waveforms measured, lithotripter field parameters such as P_+ and derived pulse intensity integral (PII) were determined following the standard IEC 61846 lithotripter field characterization protocol (Commission 1998). To calculate $P_{+(avg)}$ at off-axis positions, trinomial fits that closely capture the radial distribution of $P_+(r)$ were used to find $P_{+(avg)}$ through the middle Riemann summation normalized by the total summation area, as shown in equation (1):

$$P_{+(avg)} = \frac{1}{\pi R_h^2} \int_0^{2\pi} \int_0^{R_h} P_+(r) \cdot r dr d\theta \approx \frac{\sum_{i=1, j=1}^{n=12} P_+(\frac{x_i+x_{i-1}}{2}, \frac{y_j+y_{j-1}}{2}) \cdot (x_i-x_{i-1}) \cdot (y_j-y_{j-1})}{\sum_{i=1, j=1}^{n=12} (x_i-x_{i-1}) \cdot (y_j-y_{j-1})}, \quad (1)$$

where r was transformed to Cartesian coordinates (x, y), and a step size $\Delta x = \Delta y = 1$ mm was used in the Riemann sum. Each Riemann square falling on or outside of the stone holder perimeter was removed from summation, resulting in 120 total elements. The accuracy of the Riemann sum approximation was checked against spatial integration values obtained independently along the z -axis, where an exact solution of $P_{+(avg)}$ can be derived because of axisymmetry in pressure distribution at these locations. As shown in Table 1, the Riemann sum values fall within the integration results for circular cross-sectional areas corresponding to $R_h = 6$ mm and $R_h = 7$ mm. Uncertainty in these calculations is 5% from FOPH noise and possible pressure calibration errors. Since stone fragments did not necessarily disperse to the absolute edge of the holder during comminution tests, the Riemann sum values were deemed to be appropriate representations of $P_{+(avg)}$ incident on the stones (or fragments) in the holder. Furthermore, no averaging of P_+ was done along the z -axis, as fragmentation caused radial re-distribution of the stone/fragments, and the pressure distribution along the lithotripter axis was relatively uniform.

For effective acoustic energy calculations (i.e., compressive and tensile energy), the derived pulse intensity integral,

$$PII(r) = \frac{1}{Z_0} \int_{t_1}^{t_2} P^2(\tau, r) d\tau, \quad (2)$$

was fitted similarly to $P_+(r)$ using a trinomial function, where the temporal integration bounds of the acoustic pressure ($P(t, r)$) are first (t_1) and final (t_2) crossing points of 10% of the local P_+ and Z_0 is the acoustic impedance of water. PII was corrected over its integration bounds by subtraction of the averaged FOPH noise contributions. E_{eff} inside the stone holder,

$$E_{eff} = 2\pi \int_0^{R_h} PII(r) r dr, \quad (3)$$

was approximated (as in equation (1)) over a circular cross-sectional area of integration between $R_h = 6$ and 7 mm using a middle Riemann summation. Uncertainty from FOPH pressure calibration for the pulse intensity integral and energy calculation is <10%.

2.3 Stone phantoms and fluid medium surrounding the stone

Artificial kidney stones made of BegoStone Plus (BEGO USA, Lincoln, RI) with powder-to-water mixing ratios of 5:1 (for mimicking “hard” stones such as calcium oxalate monohydrate and brushite) and 5:2 (for mimicking “soft” stones such as uric acid or magnesium ammonium phosphate hydrogen) were prepared in spherical molds of 10 mm in diameter. The mechanical and acoustic properties of these artificial stones have been characterized previously (Liu and Zhong 2002; Esch et al. 2010). In general, the Young modulus (E) and shear modulus (G) of the hard BegoStone ($E = 27.4$ GPa and $G = 10.7$ GPa) are approximately 2 times of the corresponding values of soft BegoStone, whereas the quasi-static tensile failure strengths of the hard and soft BegoStones are 7.1 MPa and 3.1 MPa, respectively. All artificial stones were soaked in water for at least 2 hours prior to shock wave treatment.

To evaluate the effect of cavitation in stone comminution during SWL, the stone holder was filled either with water or 1,3-butanediol, which has similar acoustic properties to water (and thus similar characteristics in lithotripter shock wave propagation and interaction with the target stone), but much higher viscosity (98 cP vs. 1 cP for water). Therefore, cavitation activities in butanediol were significantly suppressed compared to water during stone comminution tests.

2.4 Stone comminution tests

Fragmentation tests were carried out at discrete positions both along the z -axis ($r = 0$ mm; $z = 0, -20, -40$ mm) and in the focal plane ($z = 0$ mm; $r = 0, 4, 8, 12$ mm) to cover a broad range of pressure and cavitation activities in the lithotripter field. At each field position, either 500 or 1,000 shocks were administered to the stone by the shock wave source at 13.8 kV with a pulse repetition frequency (PRF) of 1 Hz. To ensure consistency, at least 4 stone samples were tested at each field position. For off-axis positions, stones were treated at the same radial distance in all four quadrants to reduce potential bias from holder misalignments.

After SWL, stone fragments were collected and thoroughly rinsed in water, dried overnight, and sequentially sieved to isolate fragments into the size range of >4.0 mm, $4.0 \sim 2.8$ mm, $2.8 \sim 2.0$ mm, and <2.0 mm, respectively. Unless otherwise specified, stone comminution efficiency was determined by the weight percentage of stone fragments <2.0 mm normalized by the original stone weight. Original stone weight has been adjusted to account for losses during the pre-treatment water soaking procedure. The results are shown as mean $\pm$ standard deviation, and statistical analysis was performed using the student's t -test.

3. RESULTS

3.1 Stone comminution produced at different field positions, shock doses and medium conditions

Figure 2 shows the results of stone comminution produced at various field positions after 500 shocks (Figure 2a) and 1,000 shocks (Figure 2b), respectively. Both soft and hard BegoStone phantoms were used. Each sample was treated either in water or butanediol to assess the contribution of cavitation to stone comminution (Zhu et al. 2002; Sapozhnikov et al. 2007). Overall, several important features can be observed. First, the efficiency of stone comminution varied significantly with field position independent of stone type and fluid medium condition. The highest stone comminution was generally produced at the lithotripter focus and fragmentation efficiency decreased more rapidly off the lithotripter-axis (i.e., $z = 0$ mm, $0 < r < 12$ mm) than along the lithotripter-axis (i.e., $-40 < z < 0$ mm, $r = 0$ mm) moving pre-focally towards the shock wave source. This trend in stone comminution

correlates more closely with peak pressure at the stone holder centroid (P_+) and average peak pressure across the holder ($P_{+(avg)}$) than with the absolute peak pressure within the stone holder, as evidenced by results in the focal plane. Second, for the majority of field positions and medium conditions, stone comminution increased with the number of shocks delivered, indicating a progression of the accumulated stone damage during SWL. Third, the comminution efficiency of soft stones was statistically higher than hard stones ($p = 0.02$) at any given combination of field position, shock dose and medium condition, with the exception of those stones treated in water at the lithotripter focus for a 500 shock dose ($p = 0.08$). This finding is consistent with the observation that physical properties of renal calculi can impact the treatment outcome in SWL (Zhong et al. 1993; Williams et al. 2003). Fourth, for both soft and hard stones the comminution efficiency decreased drastically when the fluid medium surrounding the stone was changed from water to butanediol, despite their similarities in acoustic impedance. At the lithotripter focus, stone comminution efficiencies in water compared to butanediol were 23.9 and 16.5 percentage points (pp) higher after 500 shocks, and 34.7 and 31.2 pp higher after 1,000 shocks for soft and hard stones, respectively. This finding confirms the general consensus that cavitation is critical for producing effective and successful stone comminution in SWL (Zhu et al. 2002; Cleveland and McAteer 2005; Rassweiler et al. 2011).

3.2. Correlation between stone comminution and $P_{+(avg)}$

When stone comminution (SC) is plotted against the average peak pressure inside the holder, $P_{+(avg)}$, a strong correlation can be observed for each type of stones treated either in water or butanediol (Figure 3). This general correlation can be expressed by a logarithmic function of the form $SC = a \cdot \ln(P_{+(avg)}) + b$ where a and $\exp(-b/a)$ are the slope and pressure intercept of the fitted curve, respectively. The specific values of $\exp(-b/a)$ (i.e. the average peak pressure value at which $SC=0\%$) for individual curves, corresponding to different stone type and medium condition, are summarized in Table 2 together with pertinent physical properties of the stones. For each stone type (soft or hard), it can be observed that the slope increases from butanediol to water and from 500 shocks (Figure 3a) to 1,000 shocks (Figure 3b). This finding is consistent with the aforementioned observations that stone comminution is significantly greater in water than in butanediol, and increases progressively with shock number. More interestingly, the curves for each stone type are found to converge to the same intercept, independent of the fluid medium and total number of shocks used in the treatment. This intercept defines the minimal pressure threshold to initiate fragmentation for each type of stones. The fragmentation thresholds in $P_{+(avg)}$ were found to be 7.6 MPa for hard stones and 5.3 MPa for soft stones, both of which exceed the quasi-static tensile failure strength (σ_f) of the respective stone types (see Table 2). All hard BegoStone samples tested at $P_{+(avg)} < 7.6$ MPa resulted in no fragmentation, and were removed from fitting results.

3.3. Correlation between stone comminution and E_{tot}

Figure 4 shows the stone comminution results of the previous sections plotted against total acoustic energy (E_{tot}), which equals to the product of single pulse effective energy (E_{eff}) and the total number of shocks delivered during the treatment. Linear correlations of the form $SC = a \cdot E_{tot} + b$, where a and b are slope and y -intercept, respectively, yield coefficients of determination (R^2 values) similar to those given in Figure 3 for logarithmic fits of SC vs. $P_{+(avg)}$ data. The fitting results shown in Table 2 do not appear to produce a consensus on a dose- and holder fluid-independent threshold for initiating fragmentation, as is the case with $P_{+(avg)}$, suggesting the manner in which energy is delivered to the stone is critically important to fragmentation in SWL. From 500 shocks (Figure 4a) to 1,000 shocks (Figure 4b), the slopes of each fit uniformly decrease, possibly indicating effects of attenuation from small fragments at the base of each holder (Zhu et al. 2002). Previous research has observed

linear correlation between cumulative total acoustic energy and stone comminution efficiency in the absence of attenuation from residual fragments (Granz and Kohler 1992; Delius et al. 1994; Eisenmenger 2001). Linear correlation analysis of total compressive energy and stone comminution (not shown) produced nearly equivalent coefficients of determination to those of total acoustic energy (compression + tension).

4. DISCUSSION

Currently, the established mechanisms of stone failure in SWL are dynamic fatigue (Lokhandwalla and Sturtevant 2000), spallation (Chuong et al. 1989; Lubock 1989; Vakil et al. 1991; Dahake and Gracewski 1997; Xi and Zhong 2001), geometric superfocusing (Gracewski et al. 1993; Xi and Zhong 2001), squeezing (Eisenmenger 2001), shear-induced failure (Xi and Zhong 2001; Cleveland and Sapozhnikov 2005; Sapozhnikov et al. 2007), and cavitation (Coleman et al. 1987; Crum 1988; Sass et al. 1991; Philipp and Lauterborn 1998; Zhu et al. 2002). The challenge of SWL research in recent years has been to correlate LSW parameters to fracture mechanisms in order to better guide lithotripter design and usage. In this study, we have identified a close correlation between stone comminution and $P_{+(avg)}$ both in water and butanediol (i.e. in the presence and relative absence of cavitation, respectively), suggesting an important role of the local peak pressure of the incident LSW in stone comminution during SWL. This assertion is further supported by the convergence of logarithmic curve fits to distinctive thresholds for the initiation of fragmentation for a given stone type, independent of LSW dose or holder fluid used. A minimal pressure exceeding the tensile failure strength of the stone material is required to initiate the fracture, which is consistent with Griffith's theory for brittle fracture (Griffith 1921).

The distribution of P_+ is generally considered an important feature in SWL. Most of the 2nd- and 3rd-generation lithotripters have higher absolute P_+ , narrower focal width, and are less efficient in disintegrating urinary stones than the original HM3 lithotripter (Lingeman 2003). For a given effective acoustic energy, it has been shown that a lithotripter field with low peak pressure and broad focal width produces better stone comminution than its counterpart of high peak pressure with narrow focal width under clinically relevant *in vitro* test conditions (Qin et al. 2010). This previous observation is supported by the primary finding of the present study, i.e., it is the averaged pressure incident on a stone (not the absolute peak pressure in a lithotripter field) that determines stone comminution in SWL. Moreover, based on the pressure threshold for fragmentation of a given stone type, it may be possible to develop better criteria for defining the effective fragmentation area of individual lithotripters to facilitate device comparison and improve the design of clinical strategy for SWL treatment in general. However, lithotripter comparability based on effective fragmentation area is contingent upon verification of stone fragmentation thresholds in multiple devices.

The significant differences in stone comminution between stones treated in water compared to butanediol support the notion that cavitation is essential for producing effective stone fragmentation in SWL (Zhu et al. 2002). Cavitation acts synergistically with the LSW-induced stress waves and accelerates the fracture processes by initiating crack sites along the stone surface. However, cavitation alone will not produce a comparable rate of fragmentation in SWL (Lautz et al. 2011). It has been observed that stone comminution efficiency correlates to cavitation-related parameters such as PRF (>1.0 Hz) (Greenstein and Matzkin 1999; Weir et al. 2000; Madbouly et al. 2005; Pace et al. 2005), which is beyond the scope of this study, but may represent a stage of intermediate synergy between cavitation and stress waves, where the pre-focal absorption of tensile energy (Pishchalnikov et al. 2005) produces a cavitation effect in between those of butanediol and water (at PRF = 1.0 Hz).

5. Conclusions

A close correlation between $P_{+(avg)}$ and stone comminution efficiency in SWL has been observed for different types of stones and fluid medium conditions. This correlation establishes a critical link between a measurable field parameter of lithotripter shock waves and the resultant stone comminution, which may provide valuable guidance for design improvement of modern shock wave lithotripters.

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References

12. Chaussy CG, Fuchs GJ. Current state and future developments of noninvasive treatment of human urinary stones with extracorporeal shock wave lithotripsy. *The Journal of urology*. 1989; 141:782–9. [PubMed: 2645437]
13. Chuong, CJ.; Zhong, P.; Arnott, HJ.; Preminger, GM. Stone damage modes during piezoelectric shock wave lithotripsy. In: Lingeman, JE.; Newman, DM., editors. *Shock Wave Lithotripsy II: Urinary and Biliary*. New York: Plenum; 1989. p. 103–6.
14. Cleveland, R.; McAteer, JA. The Physics of Shock Wave Lithotripsy. 2005. p. 317–32.
15. Cleveland RO, Sapozhnikov OA. Modeling elastic wave propagation in kidney stones with application to shock wave lithotripsy. *The Journal of the Acoustical Society of America*. 2005; 118:2667–76. [PubMed: 16266186]
16. Coleman AJ, Saunders JE. A survey of the acoustic output of commercial extracorporeal shock wave lithotripters. *Ultrasound in medicine & biology*. 1989; 15:213–27. [PubMed: 2741250]
17. Coleman AJ, Saunders JE, Crum LA, Dyson M. Acoustic cavitation generated by an extracorporeal shockwave lithotripter. *Ultrasound in medicine & biology*. 1987; 13:69–76. [PubMed: 3590362]
18. Crum LA. Cavitation microjets as a contributory mechanism for renal calculi disintegration in ESWL. *The Journal of urology*. 1988; 140:1587–90. [PubMed: 3057239]
19. Dahake G, Gracewski SM. Finite difference predictions of P-SV wave propagation inside submerged solids. II. Effect of geometry. *The Journal of the Acoustical Society of America*. 1997; 102:2138–45. [PubMed: 9348675]
110. Delius M, Ueberle F, Gambihler S. Destruction of gallstones and model stones by extracorporeal shock waves. *Ultrasound in medicine & biology*. 1994; 20:251–8. [PubMed: 8059486]
111. Eisenmenger W. The mechanisms of stone fragmentation in ESWL. *Ultrasound in medicine & biology*. 2001; 27:683–93. [PubMed: 11397533]
112. Esch E, Simmons WN, Sankin G, Cocks HF, Preminger GM, Zhong P. A simple method for fabricating artificial kidney stones of different physical properties. *Urol Res*. 2010; 38:315–9. [PubMed: 20652562]
113. Gerber R, Studer UE, Danuser H. Is newer always better? A comparative study of 3 lithotripter generations. *The Journal of urology*. 2005; 173:2013–6. [PubMed: 15879807]
114. Graber SF, Danuser H, Hochreiter WW, Studer UE. A prospective randomized trial comparing 2 lithotripters for stone disintegration and induced renal trauma. *The Journal of urology*. 2003; 169:54–7. [PubMed: 12478101]
115. Gracewski SM, Dahake G, Ding Z, Burns SJ, Everbach EC. Internal stress wave measurements in solids subjected to lithotripter pulses. *The Journal of the Acoustical Society of America*. 1993; 94:652–61. [PubMed: 8370871]
116. Granz B, Kohler G. What makes a shock wave efficient in lithotripsy? *The Journal of stone disease*. 1992; 4:123–8. [PubMed: 10149177]
117. Greenstein A, Matzkin H. Does the rate of extracorporeal shock wave delivery affect stone fragmentation? *Urology*. 1999; 54:430–2. [PubMed: 10475348]

118. Griffith AA. The phenomena of rupture and flow in solids. Philosophical Transactions of the Royal Society of London Series A-Mathematical and Physical Sciences. 1921; 221:163–98.
119. Lingeman JE. Extracorporeal shock wave lithotripsy. Development, instrumentation, and current status The Urologic clinics of North America. 1997; 24:185–211.
120. Lingeman JE. Extracorporeal shock wave lithotripsy--what happened? The Journal of urology. 2003; 169:63. [PubMed: 12478103]
121. Liu Y, Zhong P. BegoStone--a new stone phantom for shock wave lithotripsy research. The Journal of the Acoustical Society of America. 2002; 112:1265–8. [PubMed: 12398432]
122. Lokhandwalla M, Sturtevant B. Fracture mechanics model of stone comminution in ESWL and implications for tissue damage. Physics in medicine and biology. 2000; 45:1923–40. [PubMed: 10943929]
123. Lubock P. The physics and mechanics of lithotripters. Dig Dis Sci. 1989; 34:999–1005. [PubMed: 2663390]
124. Madbouly K, El-Tiraifi AM, Seida M, El-Faqih SR, Atassi R, Talic RF. Slow versus fast shock wave lithotripsy rate for urolithiasis: a prospective randomized study. The Journal of urology. 2005; 173:127–30. [PubMed: 15592053]
125. Pace KT, Ghiculete D, Harju M, Honey RJ. Shock wave lithotripsy at 60 or 120 shocks per minute: a randomized, double-blind trial. The Journal of urology. 2005; 174:595–9. [PubMed: 16006908]
126. Philipp A, Lauterborn W. Cavitation erosion by single laser-produced bubbles. J Fluid Mech. 1998; 361:75–116.
127. Pishchalnikov YA, Sapozhnikov OA, Bailey MR, Pishchalnikova IV, Williams JC, McAteer JA. Cavitation selectively reduces the negative-pressure phase of lithotripter shock pulses. Acoust Res Lett Onl. 2005; 6:280–6.
128. Qin J, Zhong P, Simmons WN, Sankin G. Effect of lithotripter focal width on stone comminution in shock wave lithotripsy. Journal of the Acoustical Society of America. 2010; 127:2635–46. [PubMed: 20370044]
129. Rassweiler JJ, Knoll T, Kohrmann KU, McAteer JA, Lingeman JE, Cleveland RO, Bailey MR, Chaussy C. Shock wave technology and application: an update. European urology. 2011; 59:784–96. [PubMed: 21354696]
130. Rassweiler JJ, Tailly GG, Chaussy C. Progress in lithotripter technology. EAU Update Series. 2005; 3:17–36.
131. Sapozhnikov OA, Maxwell AD, MacConaghy B, Bailey MR. A mechanistic analysis of stone fracture in lithotripsy. The Journal of the Acoustical Society of America. 2007; 121:1190–202. [PubMed: 17348540]
132. Sass W, Braunlich M, Dreyer HP, Matura E, Folberth W, Preismeyer HG, Seifert J. The mechanisms of stone disintegration by shock waves. Ultrasound in medicine & biology. 1991; 17:239–43. [PubMed: 1887509]
133. Vakil N, Gracewski SM, Everbach EC. Relationship of model stone properties to fragmentation mechanisms during lithotripsy. J Lith Stone Dis. 1991; 3:304–10.
134. Weir MJ, Tariq N, Honey RJD. Shockwave frequency affects fragmentation in a kidney stone model. Journal of Endourology. 2000; 14:547–50. [PubMed: 11030533]
135. Williams JC Jr, Saw KC, Paterson RF, Hatt EK, McAteer JA, Lingeman JE. Variability of renal stone fragility in shock wave lithotripsy. Urology. 2003; 61:1092–6. discussion 7. [PubMed: 12809867]
136. Xi X, Zhong P. Dynamic photoelastic study of the transient stress field in solids during shock wave lithotripsy. The Journal of the Acoustical Society of America. 2001; 109:1226–39. [PubMed: 11303936]
137. Zhong P, Chuong CJ. Propagation of shock waves in elastic solids caused by cavitation microjet impact. I: Theoretical formulation. The Journal of the Acoustical Society of America. 1993; 94:19–28. [PubMed: 8354758]
138. Zhong P, Chuong CJ, Preminger GM. Propagation of shock waves in elastic solids caused by cavitation microjet impact. II: Application in extracorporeal shock wave lithotripsy. The Journal of the Acoustical Society of America. 1993; 94:29–36. [PubMed: 8354759]

139. Zhu S, Cocks FH, Preminger GM, Zhong P. The role of stress waves and cavitation in stone comminution in shock wave lithotripsy. *Ultrasound in medicine & biology*. 2002; 28:661–71. [PubMed: 12079703]

Figure 1.

(a) Diagram of the experimental setup and (b) close view of the lithotripter focus with comminution positions marked in focal plane and along acoustic propagation axis. (c) Peak pressure and average peak pressure ($R=7$ mm) data based on FOPH measurements. Inset are examples of averaged pressure waveforms ($n=4$) measured by the FOPH at relevant comminution positions.

Figure 2.

Hard (dark) and soft (light) stone comminution results (<2.0 mm) at various field positions using both water (no pattern) and 1,3-butanediol (pattern) as holder fluids and doses of (a) 500 and (b) 1000 shocks. P_+ and $P_{+(avg)}$ values are given above each field position group. Note: But. is used in figure legend to indicate 1,3-butanediol.

Figure 3. Hard (dark) and soft (light) stone comminution results in both water (solid) and 1,3-butanediol (dashed) plotted against corresponding $P_{+(avg)}$ values for doses of **(a)** 500 and **(b)** 1000 shocks. Logarithmic fits are presented with R^2 values shown in legend. Note: But. is used in figure legend to indicate 1,3-butanediol.

Figure 4.

Hard (dark) and soft (light) stone comminution results in both water (solid) and 1,3-butanediol (dashed) plotted against corresponding cumulative acoustic energy (E_{tot}) values for doses of (a) 500 and (b) 1000 shocks. Linear fits are presented with R^2 values shown in legend. Note: But. is used in figure legend to indicate 1,3-butanediol.

Verification of Reimann sum approximation for determining $P_{+(avg)}$ based on comparison with spatial integration values obtained along the z-axis.

Table 1

Position [mm]		$P_{+(avg)}$ [MPa]		
r	z	Numerical (1)	Integral ($R_0=6$ mm)	Integral ($R_0=7$ mm)
0	0	45.0	21.2	22.1
	-20	31.2	17.9	18.2
	-40	19.5	15.3	15.5

Table 2

Predicted pressure and total acoustic energy thresholds for initiating stone comminution.

BegoStone type	Dose	Holder fluid	Sample no.	Log fit $R^2 (P_{+(arg)})$	Min. $P_{+(arg)}$ (MPa)	Linear fit $R^2 (E_{tot})$	Min. E_{tot} (J)
Hard ($\sigma_f=7.1$ MPa)	500	H ₂ O	23–27	0.93	7.8	0.85	7.2
		Butt.	20–24	0.80	7.4	0.90	7.5
	1000	H ₂ O	32–36	0.91	7.6	0.85	13.8
		Butt.	20–24	0.88	7.4	0.88	14.4
AVE:				0.88	7.6	0.87	10.7
Soft ($\sigma_f=3.1$ MPa)	500	H ₂ O	28	0.92	5.5	0.93	3.8
		Butt.	24	0.91	5.3	0.99	3.5
	1000	H ₂ O	31	0.98	5.1	0.91	2.9
		Butt.	34	0.98	5.4	0.93	5.3
AVE:				0.95	5.3	0.94	3.9