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Why stones break better at slow shock wave rate than at fast rate: In vitro study with a research electrohydraulic lithotripter

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Abstract

Purpose—Stones break better when the rate of shock wave (SW) delivery is slowed. It has been hypothesized that increased cavitation at fast rate shields pulse propagation, interfering with the delivery of SW energy to the stone. We tested this idea by correlating waveforms measured at the SW focus with cavitation viewed using high-speed imaging.

Methods—U30-gypsum stones held in a 2 mm-mesh basket were exposed to 200SWs at 30 or 120SW/min from a research electrohydraulic lithotripter (HM3-clone). Waveforms were collected using a fiberoptic probe hydrophone. High-speed imaging was used to observe cavitation bubbles in the water and at the stone surface.

Results—Stone breakage was significantly better at 30SW/min than at 120SW/min. Rate had little effect on SW parameters in the water free field. In the presence of particulates released from stones, the positive pressure of the SW remained unaffected, but the trailing tensile phase of the pulse was significantly reduced at 120SW/min.

Conclusions—Cavitation bubbles do not persist between SWs. Thus, mature bubbles from one pulse do not interfere with the next pulse, even at 120SW/min. However, cavitation nuclei carried by fine particles released from stones can persist between pulses. These nuclei have little effect on the compressive wave, but seed cavitation under influence of the tensile wave. Bubble growth draws energy from the negative-pressure phase of the SW, reducing its amplitude. This likely affects the dynamics of cavitation bubble clusters at the stone surface, reducing the effectiveness of bubble action in stone comminution.

Keywords

shock wave lithotripsy; rate effect; cavitation bubbles; stone breakage; high-speed photography; fiber optic hydrophone

Introduction

The rate of shock wave delivery in lithotripsy can have a significant effect on the efficiency of stone fragmentation. Stone breakage is improved by slowing the shock wave rate. This has been demonstrated in a variety of in vitro test systems using model stones [1–4], in an *in vivo* pig model in which artificial stones were implanted in the renal calyceal system via

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percutaneous access [5], and recently, several clinical studies have reported improved outcomes when shock waves are delivered at 60 SW/min compared to 120 SW/min [6–8].

The mechanism responsible for this effect of shock wave rate likely involves the growth and collapse of cavitation bubbles. Shock waves generate cavitation in fluid media such as the urine surrounding stones, and it has been suggested that the bubbles created by shock waves delivered at fast rate may act to shield subsequent shock waves, blocking the transmission of shock wave energy to the stone [1–9]. However, experimental studies of cavitation in lithotripsy using high-speed photography [10–13] and a laser scattering bubble detection method [14] have shown that the lifetime of cavitation bubbles in lithotripsy is less than one millisecond. That is, the cavitation bubble growth-collapse cycle is about a thousand times shorter than the interval between successive shock waves delivered at the typical rate of 120 SW/min used in clinical lithotripsy. Thus, if cavitation bubbles disappear during the interval between shock waves, what physical mechanism explains why stone breakage is better at slower rates? The current report examines this problem.

Materials and Methods

This study was conducted using a laboratory electrohydraulic lithotripter patterned after the Dornier HM3 lithotripter [15]. The power supply to the shock source of this research lithotripter fully charges the capacitor for operation at up to 5 Hz pulse repetition frequency (300 shock waves per minute). Filtered (5μm), deionized water in the lithotripter test tank was degassed to about 20% saturation, and conductivity was adjusted to ~600μs [15]. Gypsum model stones [16] held in a 2 mm mesh basket (Fig. 1) were used to test the effect of shock wave rate on the efficiency of stone breakage. Stones were treated with 200 shock pulses administered at 0.5 or 2 Hz (30 and 120 shock waves/minute) pulse repetition frequency.

Shock waves were recorded using an FOPH-500 fiber-optic probe hydrophone (RP Acoustics, Leutenbach, Germany) using a data acquisition protocol for capture of shock waves in nonstop regime [17]. For these measurements, the optical fiber tip was positioned at the geometric F2 focal point of the lithotripter, perpendicular to the axis of shock wave propagation. Pressure waveforms were recorded either in the water free field, or about 2 mm in front of the mesh basket (Fig. 1), and were post-processed using programs written in LabVIEW (National Instruments, Austin, TX).

An Imacon 468 (DRS Hadland, Inc., Cupertino, CA) ultra high-speed digital imaging system was used to capture cavitation activity in the water free field and at the stone surface [17,18]. This camera was capable of capturing 7 frames at rates up to 100 million frames/sec, and inter-frame timing could be set to capture very rapid events (as short as 10 ns between frames) or events over a longer time frame (microseconds to milliseconds).

Results

Stones broke better at slow rate than at fast rate. An example of stone fragments retained in the mesh basket after 200 shock waves is shown in Fig. 2. The stone treated at 30 SW/min (left) was broken into numerous pieces, while the stone at 120 SW/min (right) remained largely intact.

We and others [1–9] have hypothesized that the effect of the shock wave rate on stone breakage is a consequence of shock wave–bubble interactions. To test this idea, the high-speed camera was used to image the cavitation field, and in separate experiments the FOPH was used to capture waveforms at different shock wave rates. Figure 3 shows bubbles generated in the water free field at rates of 30, 120 and 300 shock waves per minute. It is clear that as rate is increased, more bubbles are produced. If bubbles generated along the shock wave axis pose a barrier to the transmission of SW energy, it should be possible to detect an effect of SW-rate on the amplitude of the pressure pulse, and possibly other characteristics of the waveform. Therefore, sets of 100 SW's were recorded at F2 in the water free field for pulses fired at 30 and 120 SW/min. Even with this large sample size (100 SW per condition) there was no difference in peak positive pressure (27.4±5.1 MPa at 30 SW/min; 27.3±4.4 MPa at 120 SW/min, $p>0.7$) or peak negative pressure (−5.9±1 MPa at 30 SW/min; −6.0±1.3 MPa at 120 SW/min, $p>0.2$) at these two rates.

Hydrophone measurements with the mesh basket and stone in place (Fig. 1) showed a different result. Mean values for peak positive pressure were about the same at both rates (26.8±4.3 MPa at 30 SW/min; 26.1±4 MPa at 120 SW/min, $p>0.13$), but there was a significant effect on the amplitude of the negative pressure at two rates (−5.7±1.6 MPa at 30 SW/min; −3.9±1.6 MPa at 120 SW/min, $p<0.0001$). Figure 4 shows representative waveforms at the two rates, and illustrates a reduction in the negative tail at 120 SW/min even though the positive pressure was virtually identical to the pulse at 30 SW/min.

The reason why the leading positive-pressure phase of the shock wave remained the same at both rates can be understood from high-speed photography. Figure 5 presents a sequence of high-speed camera images that captures cavitation bubbles at the proximal surface of a stone treated at 120 SW/min. This series shows the entire cavitation cycle, from inception of bubble growth, to bubble collapse. The bubble cycle is longer at the stone surface than in the surrounding water, such that at 600 μs the cloud at the stone is collapsing, but there are no bubbles visible in the surrounding water. All visible bubbles –including those on the stone – disappear long before the arrival of the next lithotripter pulse (at 500,000 μs). Cavitation clouds (Fig. 3, 5) are not present when the next shock wave arrives, and thus do not interfere with the propagation of the leading positive-pressure phase of the pulse. Still, there was a measurable effect of shock wave rate on the amplitude of the negative pressure of the shock wave (Fig. 4). Previous studies have shown that, whereas visible bubbles do not last between pulses, there are microscopic bubbles – bubbles visible by B-mode ultrasound – that can persist [17,19]. These are too small to affect propagation of the positive-pressure phase of the shock wave, but the negative-pressure phase stimulates these microscopic bubbles to grow, and thus energy from the negative-pressure phase remains with the growing bubbles and does not propagate with the shock wave.

Discussion

Our observations suggest that cavitation along the path from the shock source to the focal zone of the lithotripter can interfere with the delivery of acoustic energy to the target. However, this does not appear to be a matter of crude shielding or blocking of the shock wave, as shock wave rate had no effect on the leading positive pressure phase of the pulses. This is understandable, since even at a rate of 120 SW/min, the delay between shock waves (pulse interval) is vastly longer than the lifetime of cavitation bubbles in the water. That is, the cavitation bubbles generated by one shock wave do not last long enough to interfere with the next shock wave. Instead, the rate of shock wave delivery appeared to affect the amplitude of the trailing negative pressure phase of the shock wave, but only in the immediate vicinity of the target stone. That is, the negative pressure was reduced for shock waves delivered at 120 SW/min, but only when a stone was present. It may be that particulates dislodged from the stone by shock wave impact or the action of cavitation bubbles at the stone surface, served as nuclei that seeded cavitation in the vicinity of the stone. Thus, the rate effect may be dependent on the quality of the medium —the ability of the medium to support cavitation.

In previous studies we have observed that increasing the gas content of the water in the lithotripter tank can reduce the amplitude and duration of the negative pressure phase of the shock wave, regardless of the rate of shock wave delivery [17]. Those experiments showed that as bubbles grew under the influence of negative pressure, the energy for bubble growth came from the negative tail of the lithotripter pulse. That is, some of the energy of the negative phase of the shock wave was recruited into the growth of cavitation bubbles. Under conditions that favor cavitation, some of the energy of the shock wave does not continue to propagate with the pulse, but is instead left behind in the water, in the form of the kinetic and potential energy of water surrounding the growing cavitation bubbles. Thus, during propagation through cavitating liquid, the lithotripter pulse loses some of the energy that would otherwise have been delivered to the stone.

The current study suggests an acoustics mechanism responsible for the reduced negative pressure delivered to stones at fast rate, but it does not explain how lowering the amplitude of the negative pressure phase of the shock wave reduces the efficiency of stone comminution. One possible explanation involves the role of shear waves in stone breakage. It has been shown that during propagation through a stone, the negative tail of the shock wave contributes to local stress gradients that lead to fracture. For example, when the leading positive-pressure component of the pulse reflects off the back-side of a stone, and its pressure is reversed in phase to negative, the maximum tensile force generated within the stone occurs at the point where this reflected wave (now negative pressure) is amplified by the negative pressure contributed by the original trailing negative phase of the shock wave [20]. The magnitude of this constructive interference would be reduced by reduction in the amplitude of the negative tail of the pulse. Cavitation at the stone surface may also be affected by a reduction in negative pressure due to bubble growth along the path of the shock wave; cavitation cluster collapse can generate substantial forces that can cause fractures, widen fissures and erode the stone surface. In addition, cluster collapse produces strong secondary shock waves. Thus, the collapse of cavitation bubbles at the stone surface can contribute to comminution at more than one level—directly in the sense that cluster collapse causes pitting, and indirectly in that the force of impact sends a shock wave into the stone that contributes to the internal stresses involved in fracture failure. A reduction in the negative pressure of shock waves would reduce the driving force for cavitation, and possibly affect stone breakage.

Our findings show that treatment at fast rate reduces the amplitude of the negative pressure of the shock wave. This does not mean that shock waves delivered at fast rate are safer. It appears that the rate mechanism could be a local effect around the stone, as hydrophone measures in the free field of well-degassed water showed no reduction in negative pressure. Fluids in the body are well degassed, and thus the system studied here imitates their state. Fast rate shock waves that are on target to hit the stone, may show reduced negative pressure, but those that miss the stone due to incorrect targeting, patient movement or respiratory motion [21] will be full-energy, full-impact pulses. Since it takes significantly more shots to break stones at fast rate than at slow rate, shock waves delivered at fast rate have the potential to create more vascular damage, not less [22].

Several patient studies [6–8] have demonstrated that stone comminution is more efficient when shock waves are delivered at slower rates, but the potential effect of rate on renal injury has not been thoroughly addressed. In a prospective study, Pace and colleagues assessed the efficacy and safety of treatment at 60 versus 120 shock waves per minute [6]. They observed a significant improvement in success rate (i.e. stone-free status or asymptomatic fragments at 3 months) at the slower shock rate, but the occurrence of complications (ER visit, hospital admission, stent or nephrostomy, steinstrasse, UTI) within three months of treatment was not different between the two rates. Early in the history of lithotripsy, investigators exploited the ability of piezoelectric lithotripters to fire at exceptionally fast rates (e.g. 120 SW/s). From this era, there is a report of the anecdotal observation of fewer subcapsular hematomas in patients treated at a rate of 75 versus 7,200 shock waves per minute [23]. A laboratory study of renal injury in rabbits treated with a piezoelectric lithotripter describes increased vascular trauma in animals treated at 1200 SW/min compared to 150 SW/min [24], and a study performed using a research electrohydraulic lithotripter showed a substantial increase in renal injury in dogs treated at 600 SW/min compared to the more conventional rate of 60 SW/min [25]. These reports may suggest that rate is a factor in renal injury, but by current standards the conditions of treatment were extreme. It is quite possible that the mechanisms of injury at the exceptionally fast rates used in these studies are different from the much slower rates used in current clinical practice. This is an area where additional investigation could be beneficial.

These in vitro experiments, our past work using stones implanted in pig kidneys [5], and laboratory and clinical studies by others [1–4,6–8], clearly demonstrate that stone breakage by shock waves becomes less efficient as the firing rate is increased. Our findings point to the value of slowing the rate of delivery, but do not suggest whether rates slower than 30 SW/min would be beneficial, nor do they show how rapidly shock waves can be administered without compromising breakage efficiency. Three recent clinical studies that address the effect of rate on the clearance of renal stones show that a rate of 60 SW/min is more effective than treatment at 120 SW/min [6–8]. It is possible that rates slower than 60 SW/min could be even better. We know of only one study in which patients were treated at a rate slower than this (20 SW/min), but the effect of rate was not investigated in this work [26]. Since treatment time is an important consideration at many centers [8], there may be value in finding ways to achieve the best comminution at faster rates. Our observations suggest that fine particles dislodged from stones act to enhance cavitation that, in turn, reduces the negative pressure of the shock waves. Further study will be needed to firmly establish the role of stone particles as cavitation nuclei, and their role in the mechanism of rate. It is interesting, however, to speculate that if a means could be devised to clear cavitation nuclei from the vicinity of a stone during shock wave delivery, this might permit more efficient treatment at faster rates.

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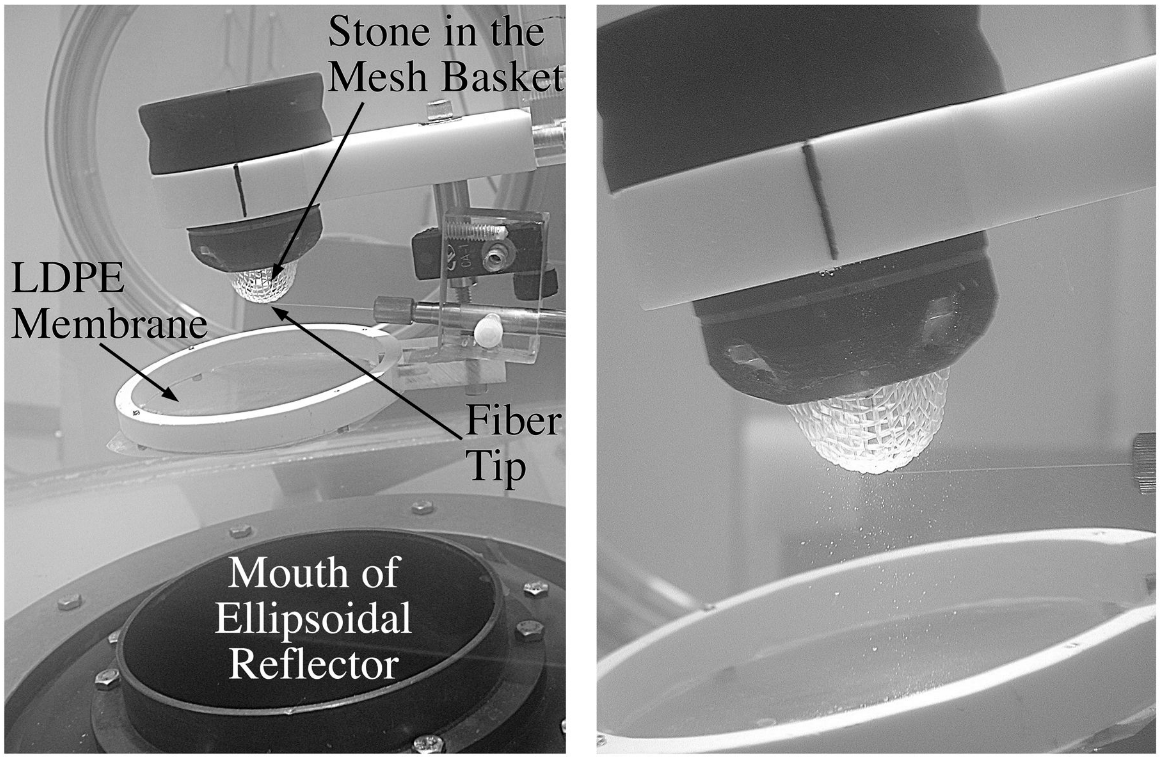

Figure 1.
Experimental setup. The tip of the fiber optic probe hydrophone was positioned at the focus of the lithotripter in front of a 2 mm mesh basket holding a model stone. Low density polyethylene (LDPE) membrane was used to prevent stone debris (visible in enlargement) from falling into the ellipsoidal reflector.

Figure 2.
Stone breakage at 0.5 Hz (30 SW/min) was better than at 2 Hz (120 SW/min).

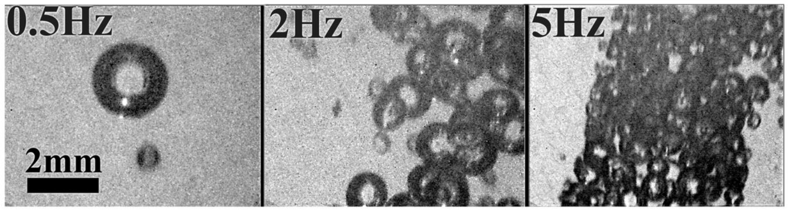

Figure 3.

Cavitation bubbles in the water free field at different firing rates. By inspection, it is clear that the number of bubbles increases as the firing rate of the lithotripter is increased.

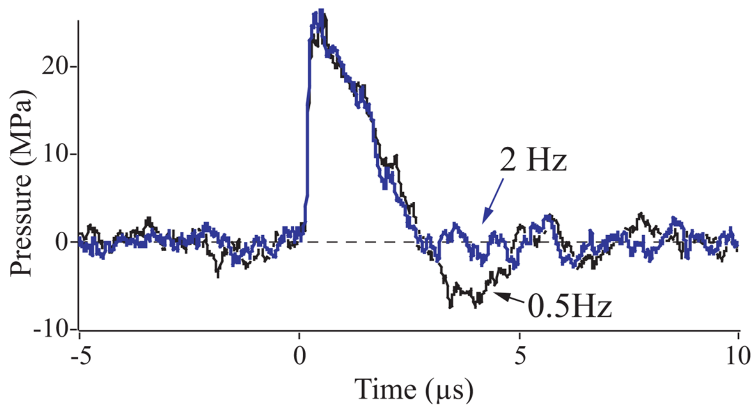

Figure 4.
Representative waveforms (shot #32 of 200) recorded at 0.5 Hz (30 SW/min) and 2 Hz (120 SW/min) in front of the basket with stone. The leading positive-pressure phase was virtually identical at both rates, but the trailing negative pressure phase was reduced at 2 Hz compared to 0.5Hz.

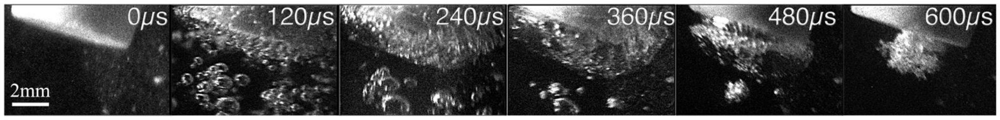

Figure 5.
Cavitation bubbles generated at the surface of a model stone treated at 120 SW/min. These sequential images captured at 120-microsecond steps show that the cavitation cycle lasts only about 600 μs. The first frame (0μs) was recorded when the shock wave had just arrived at the stone, and shows fine particles that were dislodged from the stone by the previous shot. The frame at 600 μs shows implosion of the cavitation cloud at the stone surface, and bubbles are no longer visible in the surrounding water.