MEASUREMENTS OF ACOUSTIC PULSES IN SHOCK WAVE LITHOTRIPSY IN THE PRESENCE OF CAVITATION

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ABSTRACT
Acoustic pulses generated by shock wave lithotripters to disintegrate kidney stones consist of a leading positive-pressure phase of about 1-3µs duration with shock front amplitude ranging from 15-150 MPa and a trailing tensile component of several microseconds duration with peak negative pressure <20 MPa. Lithotripter shock waves generate cavitation bubbles, which continue their growth for hundreds of microseconds after passage of the pulse. Upon collapse, these transient cavities break up into numerous smaller bubbles, which, unless they dissolve, serve as cavitation nuclei for subsequent shock waves typically delivered at 1-2Hz pulse repetition rate. Such bubble fission can generate cavitation clouds as dense as several thousand bubbles per milliliter. However, measurements using a fiber-optic hydrophone show that the leading compressive component of the shock wave is not significantly affected by cavitation. Explosive bubble growth induced by the trailing tensile component of the lithotripter pulse causes each bubble to radiate a compressive wave which can destructively interfere with the negative tail of the pulse. The negative tail is further reduced by cavitation, as the energy for bubble growth comes at the expense of the tensile phase of the lithotripter shock wave. Cavitation-induced fluid motion along the acoustic axis is also observed.

INTRODUCTION
Although it has been long known that lithotripter shock waves can generate cavitation (see, for example, references in [1]), progress in understanding how generated bubbles affect the lithotripter pulse has been made only recently [2-5]. It has been shown that cavitation bubbles selectively reduce the tensile component of the pulse [2-5] and that this reduction of the negative-pressure phase of the shock wave correlates with reduced efficiency of stone comminution [6]. It is of interest to know if the observed attenuation of the tail of the lithotripter pulse is caused solely by cavitation in the immediate vicinity of the hydrophone, or by cavitation along the acoustic path, or both. In the present report, this is investigated by considering cases in which cavitation bubbles were localized at different positions along the acoustic axis of the lithotripter. Loss of the momentum of the acoustic wave to cavitation bubbles resulted in noticeable fluid motion introduced along the axis of the lithotripter in the presence of cavitation.

Preliminary numerical results to simulate a cluster of mutually interacting bubbles excited by a shock wave suggest that pressure waves radiated from these bubbles can contribute to attenuation of the trailing negative-pressure phase of the incident shock wave.

This report also introduces a post-processing data algorithm that allows reduction of the noise of the smooth part of the shock wave, while preserving the original structure of the shock front. It also describes the utility of inexpensive consumer-level conventional camcorders in capturing aspects of cavitation.
MATERIALS AND METHODS
This study was performed with a Dornier DoLi-50 electromagnetic lithotripter (Dornier MedTech Systems, Germany). Shock waves (SWs) were generated at power level 1, using 0.5 or 2 Hz pulse repetition rate (PRF). The water cushion of the DoLi-50 treatment head was coupled to the 0.13 mm Mylar acoustic window of a 15 liter test tank made of clear acrylic. LithoClear gel (Sonotech Inc., Bellingham, WA) was used as a coupling agent, as previously described [7]. Experiments were conducted in non-degassed tap water (dissolved gas 8.3ppm or 99% of saturation) at room temperature (22º-24°C).

Images of bubbles were captured using a Sony HDR-HC3 CMOS camcorder. As far as we know, this is the first report that describes the use of a conventional framerate consumer-level camcorder to study cavitation fields in shock wave lithotripsy. Therefore, the peculiarities of this tool are now described. Physical pixels in the camcorder’s sensor are capacitors that accumulate charge via a photoelectric effect, which means that images are integrated over time (typically during the interval between frames, i.e. an exposure time ~1/60s). This allows capture of transient cavitation bubbles even if they exist only for a few hundred microseconds. A light source should be positioned such that an amount of light from the bubbles exceeds the background illumination collected by CMOS pixels during the whole exposure time of the frames. Bubbles are displayed at their maximum size and, since bubbles emit micro-jets and spawn smaller bubbles, they are often seen as comet-tailed structures, unless the jets and spawned bubbles fall within the projected maximum size of the bubble (such as jets directed toward or away from the camcorder).

Acoustic pressure was measured using a fiber-optic probe hydrophone FOPH-500 (RP Acoustics, Leutenbach, Germany), which has become the de facto standard broadband hydrophone for measurements in shock wave lithotripsy. One advantage of this self-calibrated hydrophone is that it can be used for repetitive measurements in strong acoustic fields. When the glass fiber tip is broken by cavitation, a new tip can be prepared in a matter of minutes. However, even this state-of-the-art hydrophone is not immune to cavitation artefact. Apart from relatively rare distortion of the FOPH signal (when bubbles are formed right at the 100µm glass fiber tip), there could be more subtle distortion when cavitation bubbles form along the surface of the fiber [3]. Therefore, averaging by the oscilloscope was not used and shock waves were recorded and analyzed individually, so that spurious signals could be omitted during the post-processing of the data. Average waveforms were obtained by aligning individual signals at the half amplitude of the shock fronts, as previously described [8].

When cavitation fields significantly differ from pulse to pulse, averaging of the acoustic signals may not be an option and comparison of individual shock waves would be desirable. However, the relatively low signal-to-noise ratio of the FOPH-500 hydrophone makes this difficult to accomplish. Here we suggest a post-processing algorithm that reduced noise in the signals. The technique was written in LabVIEW (National Instruments, Austin, TX) and is demonstrated in Fig.1. The blue trace shows a shock wave recorded by the FOPH and the red curve illustrates the post-processed version. The method employs knowledge of two distinct parts of the frequency spectrum of shock pulses. In this sense it is similar to an approach used in numerical simulations to model nonlinear acoustic waves with discontinuities using spectral description [9]. A small portion of the recorded waveform in the immediate vicinity of the shock front (contains high frequency components) remains unchanged, but all the other data points (smooth part of the signal) are passed through a median filter to minimize the high-frequency noise introduced by the hydrophone. In addition, the number of data points necessary to faithfully represent a signal is dramatically reduced. A high digitizing rate remains only at the immediate vicinity of the shock front and is significantly reduced elsewhere. In plots throughout this report (except Fig.1) solid lines show either waveforms post-processed with this algorithm, or average signals, while dotted lines show unprocessed waveforms. In all plots vertical axes show acoustic pressure in MPa and horizontal axes represent time in microseconds.
The 100µm glass fiber of the FOPH hydrophone submerged in the water tank was typically difficult to see. Fig.2 shows a ruler positioned behind the tip of the hydrophone and the FOPH tip can be faintly seen in this image (within the circle 8). As can be seen in Fig.2, the dimensions of the field of view of the camcorder were about 34mm by 61mm. The depth of field was about 3-4 cm. All acoustic measurements were conducted at the focal point (F) of the lithotripter, and shock waves propagate from right to left in these images. The right edge of the field of the camera was about 1 cm from the Mylar membrane of the test tank, so that the majority of cavitation bubbles were captured by the camera.

RESULTS AND DISCUSSION
The leading positive-pressure phase of the lithotripter pulse was almost unaffected by cavitation, while its trailing negative-pressure component was noticeably reduced in the presence of cavitation. The left panel in Figure 3 illustrates abundant cavitation typically observed when shock waves were delivered at 2Hz PRF. The lithotripter pulse propagated from right to left in this image and the position of the hydrophone tip is marked by (F). The recorded shock wave is shown by the dotted red line (Fig.3, right panel). An average (20 SWs) temporal profile obtained at 2Hz PRF is shown by the solid red line. For comparison, the blue line shows averaged pulses when just a few or no cavitation bubbles were observed. Such sparse cavitation fields could be obtained when lithotripter pulses were delivered at slow PRF. As can be seen in Fig.3, in dense cavitation fields (red curve) peak positive pressure was only slightly reduced compared to shock waves recorded when cavitation was sparse (33.1 MPa versus 34.2 MPa). However, the signal behind the transition point from positive to negative acoustic pressure (≈2µs) was almost completely attenuated by cavitation, and the lithotripter shock wave appeared to transform into a purely positive-pressure pulse (red line). Without cavitation (blue line) the positive and negative pressure phases of the pulse temporal profile had the same areas under the waveform curve. Reduction of the tensile stresses by cavitation upset this balance, making the positive area much larger than the negative area; that is, the total momentum of this transient acoustic pulse (red) was no longer zero. Loss of momentum by the acoustic wave should have introduced acoustic streaming along the shock wave path. Indeed, a strong fluid motion was seen along the axis of the lithotripter when cavitation occurred. This compares with virtually no visible fluid motion observed in the absence of cavitation.
Figure 3.- Abundant cavitation typically observed at 2Hz PRF (left) and temporal profiles of the lithotripter pulse (right) recorded with (red) and without (blue) cavitation. Averaged pulses are shown by solid lines. The dotted red trace shows a shock wave for the image shown on the left.

In Fig.3 cavitation bubbles were present virtually everywhere in the acoustic field with a maximum of bubble density observed about 1 cm prefocally to the geometric focus of the lithotripter. Cases when cavitation bubbles were localized at different positions along the acoustic axis of the lithotripter are discussed below.

Three consecutive lithotripter pulses at 0.5Hz are shown in Fig.4. As discussed above, the cavitation cloud drifted along the acoustic axis of the lithotripter (from right to left) with an average velocity on the order of 0.5cm/s in this case. Cloud movement toward the focus of the lithotripter was accompanied by a progressive decrease in the tensile component of the lithotripter pulse, so that the smallest tensile component was observed when the cavitation cloud surrounded the tip of the hydrophone (Fig.4, bottom).

Figure 4.- Cavitation fields and corresponding shock waves (red traces) for three consecutive lithotripter pulses. Dotted lines show recorded signals; solid lines show post-processed waveforms. The blue waveform is an averaged signal without cavitation.
Comparison of waveforms shown in Fig. 4 suggests that cavitation bubbles in the close vicinity of the hydrophone have a greater effect on the attenuation of the acoustic signal than bubbles generated farther away. However, the presence of bubbles around the hydrophone was not a necessary condition for an observed reduction of the tensile component of the wave (Fig. 4, top row). This is further illustrated in Fig. 5. The top row shows a prefocal cavitation cloud which almost completely attenuated the tensile component of the wave. The bottom image was recorded 10 lithotripter pulses after the top frame (shock waves were delivered at 0.5Hz PRF). The cavitation cloud that was captured in the top image drifted along the acoustic axis of the lithotripter (to the left, out of the field of view in the bottom image) and a new cloud was generated prefocally. Note that although the bottom cloud was not very dense, it caused noticeable reduction of the trailing negative-pressure phase of the lithotripter pulse.

Figure 5.- Prefocal cavitation fields and corresponding shock waves (red). Shock waves were separated by 10 lithotripter pulses at 0.5Hz. The blue waveforms show an averaged pulse at minimal cavitation when almost no bubbles were seen in the collected images.

How cavitation reduces the tensile component of the lithotripter shock wave can be understood from the basic principle of energy conservation. Kinetic and potential energy for bubble growth is withdrawn from the tensile component of the acoustic pulse, which causes reduction of its amplitude. Knowing the number and maximum size of cavitation bubbles one can derive a reasonable estimation of the reduction of the tensile component of the wave, as previously described [10]. However, such an approach assumes that all energy lost by the acoustic pulse was spent on bubble growth. Thus, pressure waves re-radiated from the bubbles are neglected. Here we present preliminary results of numerical simulation (by Wayne Kreider) showing that radiation from bubbles can cause reduction of the tensile component of the wave (Fig. 6). This model is based upon an approach for simulating the responses of an arbitrary number of bubbles in an incompressible fluid [11]. For bubbles located in close vicinity to the virtual hydrophone, the compressive pressure bump (caused by radiation of nearby bubbles) temporally overlaps with the trailing negative-pressure phase of the lithotripter pulse, thereby reducing the peak negative pressure of the pulse. Radiation from bubbles located at further distances from the hydrophone would create a delayed positive-pressure wave, which follows the tensile component of the lithotripter pulse. It should be noted that the appearance of a similar positive-pressure bump has been predicted by previous numerical simulations of acoustic propagation in bubbly media [2]. For the results shown in Fig. 6, a cubic grid of 64 bubbles is considered and pressure signals from each of 64 bubbles are added to the incident lithotripter pulse at a location corresponding to the center of the grid. Three values of bubble densities (10, 100, and 1000 bubbles/cm$^3$) are modeled which corresponds to inter-bubble spacing of 4.6mm, 2.2mm, and 1mm, respectively.
Figure 5.- Numerical modelling of acoustic pressure at the center of a bubble cloud. The resulting plots shows superposition of incident wave with waves radiated from the bubbles.

In summary, the present study demonstrates that induced cavitation noticeably reduces the tensile component of lithotripter pulses, while the leading positive-pressure phase propagates without much attenuation. Cavitation bubbles affect the tensile component of the wave regardless of their position along the acoustic axis of the lithotripter; however, bubbles near the hydrophone appear to contribute more noticeably in attenuation of the negative tail than bubbles at greater distances. These results support the idea that cavitation bubbles can significantly distort lithotripter pulses, and this should be taken into account during characterization of the acoustic fields of shock wave lithotripters.

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References:

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