FREQUENCY ANALYSIS OF SHOCK WAVE SCATTERING TO IDENTIFY KIDNEY STONE FRAGMENTATION IN SHOCK WAVE LITHOTRIPSY

PACS: 43.20.Fn, 43.90.Vj, 43.80.Qf

Owen, Neil1,2; Bailey, Michael2; Sapozhnikov, Oleg2,3; Crum, Lawrence2
1INSERM, 151 cours Albert Thomas, 69424 Lyon Cedex 03 – France, nrowen@gmail.com
2University of Washington, 1013 NE 40th ST, Seattle, WA 98105, USA, bailey@apl.washington.edu
3Department of Acoustics, Faculty of Physics, Leninskie Gory, Moscow 119992, Russia, oleg@acs366.phys.msu.su

ABSTRACT
Currently there is little feedback available in shock wave lithotripsy (SWL) to determine kidney stone fragmentation. The identification of fragmentation would aid a urologist in deciding to continue or stop treatment, and it could potentially reduce SW dose. Lithotripsy SWs strike stones with a broadband mechanical load. Reverberations excited within the stone are transmitted to surrounding fluid; a process termed resonant acoustic scatter (RAS). The frequency of RAS is inversely proportional to stone size. In experiment, variable SW treatments were applied to two types of stone models in vitro to produce different levels of fragmentation, which were measured by sieving dehydrated fragments and normalizing their mass to intact stone mass. RAS from selected SWs was measured with a broadband receiver and a new frequency analysis method was applied to display the redistribution of spectral energy. Mean percent mass for fragments smaller than 2 mm increased proportionally to the number of SWs applied. Amplitude of the frequency analysis output was directly proportional to fragmentation, and peak frequencies were inversely proportional to stone size. Results show promise that frequency analysis of RAS might provide feedback on fragmentation in SWL.

INTRODUCTION
Shock wave lithotripsy (SWL) is an acoustic method to remove kidney stones, and it has been in clinical practice for more than two decades. [1] Today, SWL is the most frequently used method to treat kidney stones sized between 2 mm and 20 mm. [2,3] Tissue damage accompanies most if not all SWL treatment, which can lead to acute and chronic complications. [4,5,6] Further, damage to renal tissue in the form of hemorrhagic lesion is proportional to SW dose, which is measured in part by the number of SWs applied. [7,8] However, there is currently little feedback available to urologists during SWL to help reduce SW exposure. Fluoroscopy imaging is used intermittently during SWL to target the stone, but the duration is limited by the associated radiation dose and it can be difficult to distinguish between an intact stone and a collection of stone fragments. B-mode ultrasound imaging is also used, but not all stones are detectable with ultrasound imaging and small stones can be difficult to distinguish from speckle. [9] The identification of stone fragmentation could aid a urologist in screening stones that are resistant to SWs and in determining the endpoint of SWL treatment. However, there is currently no method available during SWL to quantify stone size.

Some work has been completed to provide feedback during SWL. Many systems have been proposed to account for stone mobility, which can cause many SWs to miss the stone [10], by tracking the stone with a novel lithotripter design or stone detection system. [11,12,13] In those in vitro works, the number of SWs necessary to fragment a stone is reduced because more SWs hit the stone. Less work has been completed to identify stone fracture and fragmentation. Fedele et al. [14] describe a diagnostic sensor and signal processing technique to assess the degree of stone fragmentation and stone location. The technique uses cavitation signals, where the secondary acoustic emission from bubble collapse and rebound is dependent on stone size. They are pursuing their method in vivo but that data has yet to be published.
Reported here is a passive acoustic method to assess stone fragmentation during SWL. In previous work [15] it was shown through numerical calculation and experimental measurement that the frequency of SW scattering by model stones in water was related to stone size. In this work, a variable number of SWs was applied to cement stone models in water, and resonant acoustic scatter from selected SWs was measured by a broadband receiver. After experiment, stone fragmentation was measured by percent mass, and detected acoustic signals were post-processed. Through frequency analysis, it was possible to assess the extent of stone fragmentation.

**Frequency of Resonant Acoustic Scatter**
In previous work, the frequency of RAS from stone models was related to the sound speed of the stone and the size of the stone by

$$f = \frac{c}{2d}.$$  \hspace{1cm} (Eq. 1)

In Eq. 1, $f$ is frequency, $c$ is sound speed of the stone model, and $d$ is the diameter of the stone model. Equation 1 is a 1D approximation to a 3D system, and it is accurate to first order.

**MATERIALS AND METHODS**
Figure 1 shows the experimental arrangement used to measure SW scattering by model stones in water. Stones were held in a low density polyethylene pipette (LDPE) and placed at the focus of a research electrohydraulic lithotripter. [16] Acoustic scatter was measured by a broadband, spherically focused receiver placed outside the aperture of the lithotripter. The inset photograph shows a stone in the pipette, the SW axis, and the axis of the receiver. Detected signals were high-pass filtered at a corner frequency of 100 kHz, digitized at a sampling rate of 50 MHz, and saved to a computer.

Spherical stone models of two types were used in this work, and both are standard models for testing SWL devices. The first stone type, obtained from Nihonkia Medical (NM), Japan, had 5 mm radius, 2.7 mm/µs sound speed, and 1.15 g/cm³ density. The second stone type, made with Ultracal-30 (U30) gypsum, had 4.7 mm radius, 2.84 mm/µs sound speed, and 1.7 g/cm³ density. [17] The U30 stones were generally more robust to SWs than the NM stones.

Similar experimental protocols were followed for both stone types (see Table I). The goal was to measure scatter before and after SW treatment, and to establish different levels of fragmentation. The lithotripter charging potential was 18 kV and 22 kV for the NM and U30
Table 1.- Experimental protocol to establish different levels of fragmentation and to measure scatter from selected SWs.

<table>
<thead>
<tr>
<th>Step</th>
<th>NM Stones</th>
<th>U30 Stones</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 SW at 1/60 Hz</td>
<td>10 SWs at 1/60 Hz</td>
</tr>
<tr>
<td>2</td>
<td>0 SW (Control), 20 SW, or 50 SWs at 0.5 Hz</td>
<td>0 SW (Control), 100 SW, or 200 SWs at 0.5 Hz</td>
</tr>
<tr>
<td>3</td>
<td>5 minutes inactivity</td>
<td>5 minutes inactivity</td>
</tr>
<tr>
<td>4</td>
<td>5 SWs at 1/60 Hz</td>
<td>10 SWs at 1/60 Hz</td>
</tr>
</tbody>
</table>

stones, respectively. For the NM stones, 10 stones were used for each exposure level, and for the U30 stones, 5 stones were used for each exposure level. All stones were hydrated for at least 48 hours prior to SW exposure. In Step 1, scatter was measured to collect data from the intact stone before the SW treatment. Step 2 was a SW treatment in which SWs were triggered at 0.5 Hz. The control for this experiment was to apply 0 SW during Step 2. Step 3 was a 5 minute period of inactivity. In Step 4, scatter was measured to collect data from the fragmented stone after SW treatment. Slow rates in Steps 1 and 4, and the period of inactivity in Step 3 were used to reduce cavitation, and to reduce whatever effects cavitation might yield.

After experiment, fragmentation was measured by percent mass. Each stone was removed from the pipette and placed in a container to dehydrate over a period of 5 days. Once dry, fragments were sieved with 3 mm, 2 mm, and 1 mm screens. The mass of fragments, separated by size, was normalized by the mass of the intact stone measured prior to experiment,

\[
\text{Percent Fragmentation} = \frac{m_f}{m_i} \times 100.
\]  

(\text{Eq.2})

In Equation 2, \(m_f\) is the mass of stone fragments, and \(m_i\) is the mass of a dry, intact stone.

Several steps were used to process the measured scatter signals. First, inverse filtering, or deconvolution, was used to remove the transient effects of the high pass filter used during experiment. [18] Next, each signal was aligned to have zero time coincide with arrival of the SW at the pipette surface. Reflection of the SW off the pipette surface was an artifact present in all measured signals and was used to identify the beginning of the scatter signal. Then, a 5 µs segment starting at zero time was retained and all other segments of the sequence were discarded. The power spectrum of each signal was calculated and normalized to unit energy using Parseval’s Theorem. Next, the mean power spectrum was calculated for signals measured before SW treatment, and for signals measured after SW treatment. Last, the mean spectrum for signals measured after SW treatment was normalized to the mean spectrum for signals measured before SW treatment, \(E_f[f]/E_i[f]\), where \(E_f[f]\) is spectral energy scattered by the fractured stone at frequency, \(f\), after SW treatment, and \(E_i[f]\) is spectral energy scattered by the intact stone before SW treatment. Normalizing to the mean power spectrum displays the change in the spectral energy of the scattered signals after fragmentation. With the number of stones used for each SW exposure level and the number of measured scatter signals, a two-tailed t-test was used to calculate the frequencies at which the ratio of spectra was statistically significant. The null hypothesis was that the mean spectrum measured before SW treatment was equal at all frequencies to the mean spectrum measured after SW treatment.

RESULTS

Figures 3 and 4 show experimental data for the NM stones and U30 stones, respectively. Data in the left hand columns are mean percent fragmentation, and one standard deviation, measured after experiment using Eq. 2. Data in the center columns are photographs of stone fragments that were sieved with the 3 mm, 2 mm, and 1 mm screens. The horizontal black lines separate fragments that were larger or smaller than 2 mm. Data in the right hand columns are the ratio of spectra, \(E_f/E_i\), calculated from acoustic scatter measured with the broadband receiver. Peak ratio values have been labeled with levels of significance based on a two-tailed t-test.

The SW treatment protocols produced distinct levels of fragmentation which increased with the number of SWs applied. The percentage of stone mass smaller that 2 mm, the size urologists consider passable, for the NM stone type was 3.0%, 24%, and 54% for the total exposure of 10 SW, 30 SW, and 60 SW, respectively. Values for the U30 stone type were, 0.14%, 1.3%, and
Figure 3 – Fragmentation data and signal processing output for the NM stones. The left hand column is percent fragmentation measured after experiment. The center column is photography taken after experiment of stones from each SW treatment group: 0 SW (Control), 20 SW, or 50 SW (scale in mm). The right hand column is the ratio of spectra calculated using the mean spectrum of scatter measured before SW treatment and the mean spectrum of scatter measured after SW treatment.

10% for the total exposure of 20 SW, 120 SW, and 220 SW treatments, respectively. Total exposure is the sum of SWs used for measurement and treatment (see Table I).

Peak ratio values increased with the number of SWs applied. For the NM stone type, peak ratio values were 2.3, 3.0, and 6.0 for the 0 SW, 20 SW, and 50 SW treatments, respectively. For the U30 stone type, peak ratio values were 1.2, 2.2, and 2.9 for the 0 SW, 100 SW, and 200 SW treatments, respectively. Using the sound speed for each stone type in Eq. 1, the frequency of RAS for a fragment with 2 mm diameter is 675 kHz and 710 kHz for the NM and U30 stone types, respectively. In Fig. 3, peak frequencies occur above 675 kHz, and in Fig. 4, peak frequencies occur above 710 kHz.

DISCUSSION AND CONCLUSIONS
Fragmentation was indicated by the ratio of spectra, $E_r/E_i$, which clearly shows the shift of spectral energy to higher frequencies if the stones were fragmented. Peak ratio values increased linearly with percent fragmentation for both stone types, and peak frequencies agreed well with frequencies estimated by Eq. 1 for fragments smaller than 2 mm.

Fragmentation increased linearly with the number of SWs applied, and the U30 stones were more robust to SWs than the NM stones. This result compares well with previous work [17] in which fragmentation and SW exposure are proportional in vitro. The robustness of the two
stone types reflects the range of stones encountered during clinical SWL [19], and using both here is a more rigorous test of the measurement and signal processing method.

For the NM stones, the mean percentage of fragments smaller than 2 mm were 3%, 24%, and 54%, and peak ratio values were 2.3, 3.0, and 6.0 for the 0 SW, 20 SW, and 50 SW groups, respectively. The correlation coefficient between these values was R=0.96. For the U30 stones, the mean percentage of fragments smaller than 2 mm were 0.14%, 1.3%, and 10% and peak ratio values were 1.2, 2.2, and 2.9 for the 0 SW, 100 SW, and 200 SW groups, respectively. The correlation coefficient was R=0.87. These correlation coefficients are high and the trend indicates that peak ratio value could be a simple predictor for percent fragmentation for fragments smaller than 2 mm.

Peak frequencies in Figs. 3 and 4 agreed well with the frequencies of RAS estimated for the two stone types using Eq. 1. Peaks in Fig. 3 occurred above 675 kHz, which was the estimated frequency range for NM stone fragments that were 2 mm, or smaller. Similarly for the U30 stones, peaks in Fig. 4 occurred above 710 kHz, which was the estimated frequency range for scatter from stone fragments that were 2 mm, or smaller. In both Figs. 3 and 4 the peaks also increased in amplitude as the percentage of stones smaller than 2 mm increased. Signal
processing output therefore was sensitive to the frequency of RAS estimated for fragments smaller than 2 mm, and sensitive to the percentage of fragments smaller than 2 mm.

In this in vitro study, a strong trend was shown between the frequency analysis of SW scattering and the size of stone fragments for two types of stone. Though in vivo experimentation is necessary, the measurement and analysis of SW scattering by stones is a promising method to provide feedback on stone size to urologists during SWL. [This work was supported by NIH DK43881, NSBRI SMS00402, RFBR 05-02-16987.]

References: