Quantification of the Range of Motion of Kidney and Ureteral Stones During Shockwave Lithotripsy in Conscious Patients

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Abstract

Effective shockwave lithotripsy requires accurate targeting of the stone throughout the course of treatment. Stone movement secondary to respiratory movement can make this more difficult. *In vitro* work has shown that stone motion outside the focal region reduces the efficacy of stone fragmentation; however, there are few clinical data on the degree of stone movement in patients during treatment. To investigate this, X-ray fluoroscopic images of the kidney and ureteral stones at the upper and lower limits of the normal respiratory cycle were acquired during shock wave lithotripsy of 58 conscious patients, and stone excursion was calculated from these images. In addition, the respiration rate and patient perceived pain were recorded during the course of the treatment. It was found that stone motion secondary to respiration was 7.7 ± 2.9 mm for kidney stones and 3.6 ± 2.1 mm for ureteral stones—less than has been reported in studies with anesthetized patients. There was no significant change of motion over the course of treatment although pain was found to increase. These data suggest that stone motion in conscious patients is less than in anesthetized patients. Furthermore, it suggests that lithotripters with focal regions of 8 mm or greater should not suffer from a marked drop in fragmentation efficiency due to stone motion.

Introduction

SHOCK WAVE LITHOTRIPSY (SWL) is the most commonly performed treatment for nephrolithiasis in the United Kingdom and the United States.^{1,2} Effective stone fragmentation is dependent on accurate targeting of the stone in three dimensions—particularly in the plane normal to the acoustic beam—and on maintaining the stone targeting during the course of treatment. After initial targeting, SWL is delivered at a regular rate (1–2 Hz). Most patients receive a full course of up to 4000 shocks because currently there are no established endpoints for treatment. SW delivery is stopped at regular intervals during the treatment to confirm targeting, typically every 500 SWs at our center. Excessive stone movement during lithotripsy will reduce the number of incident shocks resulting in reduced stone comminution rates; for example, motion exceeding 10 mm has been demonstrated to reduce fragmentation efficacy *in vitro* on a lithotripter with a nominal 4.5 mm focal zone width.³ Furthermore, if a large fraction of the shock waves do not interact with the stone, then

this will result in more shock waves being delivered to the patient, which would suggest a greater potential for collateral tissue damage.⁴

Previous imaging studies have reported superior–inferior displacement of the kidney due to respiration ranging from 5 to 50 mm.^{5–8} Many factors might influence this range of movement, including anesthesia, pain, respiratory pathology, and body habitus, all of which affect respiratory patterns. Although it has been proposed that anesthesia might reduce respiratory movement and improve stone targeting,⁹ respiratory motion during anesthesia has also been reported to be greater than in conscious subjects.¹⁰ A recent study in anesthetized patients suggests that stone movement due to respiration is ~ 15 mm and may result in 40% of shock waves missing the stone.¹¹ Kidney movement due to respiration in conscious subjects has been reported to be less. In a recent study in which kidney motion secondary to respiration was measured using images acquired by magnetic resonance imaging (MRI), it was shown that displacement of the kidneys during normal respiration of conscious, healthy volunteers

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FIG. 1. Example fluoroscopy images taken at inspiration (**A**) and expiration (**B**) during lithotripsy. Images were overlaid and the distance between the centroids of the two outlines and the distance from the nominal focal point calculated (**C**). Color images available online at www.liebertpub.com/end

had a mean of 8.9 mm for the right kidney and 8.48 mm for the left.⁸ To our knowledge, there are no data on stone motion of nonanesthetized patients undergoing SWL. Given that one of the main attractions of lithotripsy as a treatment modality is that it can be performed on conscious patients and in an outpatient setting, quantifying stone motion would provide insight into whether targeting is of greater concern in these patients. In addition, improved understanding of stone motion during SWL will be necessary to develop stone tracking and triggered firing systems to maximize comminution efficacy and minimize renal parenchymal damage.

Patients and Methods

Between January and February 2013, 58 patients (40 men, 18 women, mean age 53) undergoing elective outpatient lithotripsy for ureteral or renal stones were evaluated. All lithotripsy treatments were performed on a Storz Modulith SLX-F2 fixed-site lithotripter at the Churchill Hospital, Oxford, UK, as described previously.¹¹ All patients were treated in a supine position using fluoroscopic guidance only. Patients needing ultrasound targeting or treatment in the prone position were excluded. All patients received the same pre-procedure analgesia, antiemetic, and prophylactic antibiotics a few minutes before treatment (pethidine 100 mg intramuscularly, diclofenac 75 mg per rectum, prochlorperazine 12.5 mg intramuscularly, and ciprofloxacin 100 mg orally). All patients were fully conscious throughout their treatment and were offered audiovisual distraction to reduce pain perception.¹¹ The operator aimed to deliver 4000 shocks in each treatment in total but reduced this if the patient could not tolerate the treatment or if the stone was adequately fragmented. Stones were visualized at regular intervals to ensure alignment of stone. Follow-up data (radiographs) were available for 29 patients (15 renal stones and 14 ureteral stones), and were graded in a blinded manner to assign outcomes as no change, remaining calculus but reduced in size, or stone free.

During lithotripsy, stone movement was evaluated at four time points (0 [baseline], 500, 1500, and 3000 shocks) by recording fluoroscopic images taken at the limits of stone excursion due to respiratory motion, one at the furthest point travelled during inspiration and one at the furthest point travelled during expiration. The respiratory rate (determined by measuring number of breaths in 30 s) and verbal pain score (0-none to 10-worst possible) were also recorded at each time point. For each image, the outline of the stone was drawn manually. Paired fluoroscopic images were overlaid and the distance between the centroids of the two outlines and the distance of the outlines from the nominal focal point were

calculated using ImageJ software (Fig. 1). If the stone disintegrated during the course of treatment, measurements were performed from the center of the visible stone fragments. Fluoroscopy images of a coin taken in the plane of the focal zone were used to calibrate the pixel size of the images.

The stone position data were used to estimate the acoustic energy delivered to the stone due to motion. Because only images at the extrema of respiration were captured, it was necessary for a model of respiratory motion to be used to determine the stone location at all times. The equation proposed by Lujan et al.¹² was used

$$z(t) = z_0 - b \cos^{2n}\left(\frac{\pi t}{\tau}\right) \quad (1)$$

where $z(t)$ is the position of stone at time t , z_0 the position at expiration, b the amplitude of motion (i.e., $z_0 - b$ the position at inspiration), τ the period of motion, and n the degree of asymmetry. The degree of asymmetry accounts for the longer time period spent in expiration than inspiration and a value of $n = 3$, as suggested by Lujan et al., was used in the modeling here.

The incident energy on the stone throughout its motion was calculated using a bespoke computer simulation written in MATLAB (The Mathworks, Natick, MA), which carried out the following operations. A pressure map in the focal region was assumed to follow a Gaussian profile with a $1/e$ radius of 3.6 mm, which corresponds to the manufacturer specified 6-mm diameter of the precise focus. A normalized energy flux density map was then created by squaring the pressure map, and this step assumes no significant change in waveform shape across the focal region.¹³ The outline of each stone was imported from fluoroscopic images and converted into an image mask for the energy flux density map. The stone was translated, by assuming it moved in a straight line between the location of inspiration and expiration according to Equation 1. The energy delivered to the stone was calculated at each location by integrating the energy flux density over the projected area of the stone. The energy was then normalized to the energy that would be incident on the stone if it were located exactly at the focus of the lithotripter. From the simulations, the following quantities were calculated over an entire respiratory cycle: the average energy delivered to the stone, the mean distance of the stone from the lithotripter focus, and the minimum distance of the stone from the focus.

Statistics

Overall effects on motion of the stones were tested using generalized linear modeling. Treatment outcomes were also

FIG. 2. Stone movement due to respiration as a function of the number of shock waves delivered. Ureteral stones demonstrated less movement than stones in the kidney ($p < 0.05$) at all time points throughout treatment. Overall, the range of stone movement did not change as treatment progressed for either kidney or ureteral stones. Color images available online at www.liebertpub.com/end

assessed using generalized linear modeling for the 29 patients for whom follow-up data were available. Repeated measures analysis of variance (MANOVA) was used to assess data on a within-subject basis and two-way ANOVA was used to evaluate data by shock-wave number and location in the kidney or ureter. Correlations were tested using the conventional least-squares method. All statistics were calculated using JMP (SAS, Inc., Cary, NC), and significance was assumed when $p < 0.05$.

Results

Of the 58 stones that were analyzed, 41 (70.7%) were kidney stones and 17 (29.3%) were ureteral stones. The mean kidney stone size was 8.53 mm (range 4–23 mm) and the mean ureteral stone size was 8.05 mm (range 3–22 mm). In four cases, the lithotripsy was concluded before 3000 SWs had been delivered and so fluoroscopic image data sets were incomplete.

Figure 2 shows the total motion (distance between inspiration and expiration) of kidney and ureteral stones at the four

time points. The mean kidney stone motion was 7.7 ± 2.9 mm (range 2.2–14.7 mm) and was greater than the motion of ureteral stones 3.6 ± 2.1 mm (range 0.5–7.8 mm). Using a full model, or using only a two-way ANOVA with SW-number, motion differed between renal and ureteral stones, $p < 0.0001$. The stone motion did not change over the course of treatment (by repeated measures $p = 0.56$).

Figure 3 shows pain and respiratory rate at the four time points. Pain was found to increase at 500 and 1000 shock waves but without a significant further increase at 3000 shock waves. By repeated measures, pain increased on average with every patient, $p < 0.0001$. There was no effect of stone location (renal vs. ureteral, $p = 0.73$). The respiratory rate did not change significantly with the number of shock waves ($p = 0.96$) nor with stone location ($p = 0.38$). These data indicate that even though pain increased during the treatment, it did not have a measurable effect on motion or respiration.

Figure 4 shows a scatter plot of the mean distance of the stone from the focus (as calculated by the MATLAB program) against the straight-line distance between inspiration-to-expiration distance. The correlation of these two measures is significant ($p < 0.0001$), with no effect of location ($p = 0.53$). The outliers in the scatter plot do not represent specific patients, so it appears that this relationship is independent of subject; similarly, repeated measures analysis of the distance to the focus showed no significant variation within subjects ($p = 0.60$). However, the overall slope of the scatter plot is relatively shallow, as motion in the stone due to respiration has a minor effect on the total distance that the SW travels.

Figure 5 shows a scatter plot of the energy delivered to a stone and the average distance between the stone and the geometric focus of the lithotripter for all the measurements. It can be seen that the two are well correlated ($p < 0.0001$) and that for more than 50% of the energy to be delivered to a stone, the stone should have an average distance from the focus of < 4 mm, which is similar to the 3-mm radius of the focal zone.

For the 29 patients where follow-up data were available, in 48% of the cases no change in the stone was apparent by radiography, in 28% the stone showed visible diminution of stone size, and in 24% of the cases the patient was deemed to be stone free. Full model analysis of outcome showed no correlation with any measured parameters ($p = 0.45$); specifically, there was no correlation between outcome and any measure of stone motion in the patients.

FIG. 3. Reported pain and respiratory rate during lithotripsy treatment. Although reported pain score increased as shock wave lithotripsy treatment progressed, it was not significant enough to impact on respiratory rate or stone movement. Color images available online at www.liebertpub.com/end

FIG. 4. Scatter plot of mean distance to focus against inspiration-to-expiration distance. In general, the mean distance is about one-third of the inspiration-to-expiration distance, however, the correlation is not strong. Color images available online at www.liebertpub.com/end

Discussion and Conclusions

To our knowledge, this is the first study to measure stone movement due to respiration in conscious patients undergoing lithotripsy. This study found that the mean stone movement was 7.7 mm for kidney stones and 3.6 mm for ureteral stones. This degree of movement is consistent with data from MRI of kidney movement during conscious respiration⁸ but less than the approximately 15 mm of stone movement previously reported in anesthetized patients undergoing lithotripsy.¹⁰ This suggests that the range of motion may be less in conscious patients than those who are anesthetized, although we acknowledge that this comparison is across patient groups from different countries. However, in the study in anesthetized patients, one patient was performed under sedation and had the least amount of respiratory-related motion (10 mm) but at a higher respiratory rate,¹⁰ which is consistent with the hypothesis that patients who are more conscious have less respiratory motion. The reasons for the difference in stone motion between anesthetized and conscious patients is likely to be predominantly due to ventilator tidal volumes but may also be due to patient positioning. In our study, using the Storz Modulith F2, the patient is positioned in a plastic

FIG. 5. Relative energy delivered to the stone for each condition and the average distance the stone was from the focus. Color images available online at www.liebertpub.com/end

hammock that creates a spinal kyphosis, which may further limit respiratory excursion.

Analysis of stone motion suggested that just measuring the distance between expiration and inspiration is not a robust measure of the mean distance the stone is from the focus. In general, the mean distance between the stone and the focal point of the lithotripter was about one-third of the measured inspiration-to-expiration distance. However, there was substantial scatter in the data and, therefore, measuring inspiration-to-expiration distance should not be used as a proxy for the distance between the stone and focus, rather the distance should be determined by direct measurement.

We had hypothesized that during the treatment patient pain would increase and that this would result in more stone motion and a change in respiration rate. We did find that the pain score increased during treatment over the first 1500 SWs. However, the data did not show a change in either stone movement or respiratory rate during treatment. This suggests that the pain patients felt did not affect their respiration activity during lithotripsy.

Data on stone movement are important because previous *in-vitro* work has suggested that increased movement results in a significant reduction in fragmentation efficiency.³ Lithotripsy systems with a small focus may produce more powerful fragmentation at the expense of some shocks missing the stone if there is significant movement. Even with the relatively small range of movement observed in our study, modeling suggests that on average, stones in the kidney were subject to 55% of the energy that they would have had if they were not moving. For stones in the ureter, where the motion was less, on average received 73% of the energy they would be subject to if they did not move. These values are not sensitive to the respiration rate, as long as breathing and shock wave delivery are not synchronized. The lithotripter used in these studies has the capability to be used with either a narrow focus or a broad focus. The data are supportive of the manufacturer's statement for this, particularly that the narrower focus be used for ureteral stones due to the lower amount of motion and the broader focal zone for kidney stones that had greater motion.

There are several limitations to this study. As can be seen from the data, stone motion secondary to respiration varies between the kidney and ureter. While the magnitude of stone motion will vary along the length of the ureter, the number of ureteral stones examined in this study is too small to draw any conclusions from subgroup analysis. Furthermore, the impact of factors such as body-mass index (for conditions such as obesity hypoventilation) and the presence of respiratory conditions, which may affect the rate and depth of breathing, were not assessed. These variables may need to be considered in future studies. Images were taken by several different radiographers during the course of the study and measurements performed by two individuals—a potential source of interobserver variation.

In summary, kidney stone motion was measured to be less than reported in anesthetized patients, which suggests that more shock wave energy may be incident on the stone for conscious patients. For the patients studied, the respiratory motion was not correlated with stone fragmentation outcomes, suggesting that the range of motion did not affect stone fragmentation for this lithotripter. However, we estimated that about half the available energy was incident on stones in the kidney, which suggests that a system that tracks and triggers shock wave delivery in real time based on stone

location could almost double the energy delivered to the stone, which presumably would result in better fragmentation and less collateral damage.

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Abbreviations Used

ANOVA = analysis of variance
 MRI = magnetic resonance imaging
 SWL = shock wave lithotripsy