Visualization of acoustic streaming produced by lithotripsy field using a PIV method

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Abstract: We visualized the acoustic streaming produced in water by an experimental lithotripter using a particle image velocimetry (PIV) method. Streaming generated around the beam focus has been optically visualized using light scattering particles and was easily noticeable even with naked eye for all electrical settings of the lithotripter. Spatial distributions of velocity vectors are complicated and several local peaks and vortices are observed. Measured streaming velocities are found to be in ranges of 1.5 - 3 cm/s. It should be noted that the measured velocity was averaged over 1/30 sec, the time resolution limited by video frame rate, and the true velocity is expected to be at least 10 times higher. Despite such an underestimation, it was shown that the streaming velocity increased with voltage settings and, as predicted by theory, is proportional to intensity and closely related to the shock-wave pressures generated. In particular, the velocity has almost a linear correlation with peak-negative pressures (r=0.98683, p=0.0018). This suggests that the streaming velocity measured using the PIV technique can be used to estimate the generated peak-pressures without disturbing the field.

1. Introduction

Extracorporeal shock wave lithotripsy (ESWL) has been taken as a revolutionary technique for the clinical treatment of the stone diseases since the middle of 1980’s [1]. It employs high amplitude acoustic pulses, often, called shock waves, generated outside the body, focused onto a target region
at depth within patient tissue where stones are located [2]. It is known that effects such as direct hammering, indirect cavitation and streaming play important roles in disintegrating the stones [3]. Many investigations have been performed on the direct effects as well as cavitation, yet, no measured data has been reported concerning acoustic streaming induced by a lithotripsy pulse.

Acoustic streaming is a bulk material flow generated in a fluid through which acoustic waves propagate. It is caused by the momentum transfer from the acoustic wave to fluid [4]. Theoretical studies shows that acoustic streaming velocity is proportional to the intensity, the attenuation coefficient of the medium, the square of the beam width, the geometric factor, and it is also inversely proportional to the bulk viscosity and the speed of sound in the medium [5].

Among various techniques available for measuring acoustic streaming, particle image velocimetry (PIV) is highly attractive, since it provides a two dimensional image for streaming, without disturbing acoustic field. Particle image velocimetry (PIV) is based on video images of the illuminated fluid flow plane using seeding particles and produces an instantaneous two dimensional velocity vector field [6]. Recently the PIV technique has been applied by Frenkel et al (2001) to investigate ultrasound induced acoustic streaming, and they established a positive linear relationship between the ultrasonic intensity and the peak streaming velocity [7].

Since the lithotripsy pulse has a strong shock front, it is highly difficult to measure the field. Provided that the velocity quantity measured using the PIV technique shows a good correlation with shock wave parameters, it is possible that the PIV technique may be used as a practical means of indirectly characterizing the shock-wave field.

This study considers the acoustic streaming in lithotripsy field visualized using a PIV technique and discusses the relation of the estimated streaming velocity to the driving lithotripsy pulse

2. Material and methods
The experimental setup is displayed schematically in figure 1. It consists of a shock wave generator placed pointing upwards within a cylindrical water tank (diameter 70 cm, height 90 cm). The PIV system includes an image acquisition system based on a CCD camera and a PC based image processing unit.

The shock wave generator in the study made use of a cylindrical membrane acoustic source. When a strong pulse power is supplied, the membrane is forced to vibrate for few cycles by either thermohydraulic or electromagnetic principles and produce cylindrically diverging pulses. These pulses are reflected by a parabolic reflector and focused to the focal point of the parabola. Pulse power supply placed under the water tank (not shown in the picture) is a simple capacitor charge and discharge device including a highly stable switching system. The system used in the study employed a thyratron switch and a 1 μF capacitor to which voltage is charged up to 20 kV and the inductance was about 5-15 μH. The shock wave pressure was controlled through the charging voltage settings (cVs) which, in present study, varied from 10 to 18 kV. For further details relating to the shock-wave source, the reader should refer to Choi’s work [8-9].

The PIV system consists of a Halogen Lamp (150W, PCS-NHS Nihon-Philips Co., Japan), CCD TV camera (Sony, SSC-M370), VTR (Sony, SLV-RS1), frame grabber (DT64, Ditec, Japan) and an image processing software run on a PC. The halogen lamp with a light sheet probe is positioned to illuminate water in the axial plane of the lithotripsy field. Since the optical camera cannot properly
show the water flow, we chose nylon spheres (100-150 µm in diameter, 1020 kg/m³ in density, Sumitomo Chemical Co., Japan) as light scattering particles, which were seeded in water. Tap water was used in the present study and the particle concentration was set to be about 15 mg/litre. The specific gravity of the particle should be as close as that of water as possible, so that the sphere particles are suspended in water and behave identically to water as it moves. The CCD camera captures the images of the particles suspended in water on the plane illuminated by the halogen light at a frame rate of 30 fps for 5 seconds starting from 1 second before the shock-wave is produced. The video images were fed through a frame grabber to a PC during which the analogue images are converted into digital. Digital image processing was performed with a home-made software (version 1.1, Thinker’s EYES) based on the cross-correlation method to obtain the velocity vector map of the image [10-11]. The CCD camera was set so that the image contained the region whose size was 100 mm by 100 mm and whose center is coincident with the focus of the lithotripsy field. For image processing, we took the partial section of the central square (80 by 80 in mm) rather than the entire image captured.

![Figure 1](image)

Figure 1 Overview of the experimental apparatus consisting of an experimental shock-wave generator and the video image acquisition system for fluid flow.

3. Results

Typical video images captured at the moment when the shock-wave generator was triggered are shown in figure 2. The image is 80 mm by 80 mm in size and the beam focus is approximately coincident with its centre. Shock waves propagate in the vertical direction from below upwards and thus the central vertical line represents the beam axis. The first image (figure 2a) is the neutral image without shock-wave radiation and the image shows the randomly distributed white specks representing the visualizing particles. When the shock-wave is generated, it is visible as a bright white region (BWR) along the beam-axis in the shape of a highly elongated ellipsoid. This BWR gets more stronger, namely, larger in size and brighter, with increasing voltage setting. It may be speculated that the strong
BWR is attributed to additional enhanced light scattering by bubbles cavitating in the focal region by shock-wave.

Figure 2. Video images of water containing light-scattering particles captured when a shock-wave is generated at various charging voltages: (a) 0 kV (the one captured before the shock-wave is produced), (b) 14 kV, (c) 16 kV, (d) 18 kV. The shock-wave propagates from bottom to top and the focus is located in the centre of the image, with the central vertical line representing the beam-axis. (image size: 80 mm by 80 mm)

Figure 3. Velocity vector map with time by the minimum interval of 1/30 second for the streaming water induced by the lithotripsy field produced at the charging voltage of 16 kV: (a) 0 sec, (b) 1/30 sec, (c) 10/30 sec, (d) 20/30 sec. (image size: 80 by 80 in mm).
Figure 3 shows the typical velocity vector maps estimated at t=0, 1/30, 10/30 and 20/30 second, at the voltage setting 16 kV. Strong streaming was formed in the direction of the beam-axis immediately after the shock-wave was released (at t = 0 sec), and the spatial distribution of the velocity vector are complex with several local peaks and vortices. Two distinct vortices are seen. On the beam-axis, one of them is positioned before the focus and the other, stronger in appearance, is situated beyond the focus. These vortices disappear after t = 20/30 seconds. The particle group with maximum velocity are found slightly prior to the focus at t = 0 sec, around which the steep gradient of momentum is built. This fast moving fluid leads the streaming and propagates through the focus. The dominant particles lose their energy with time and the velocity field eventually spreads out at 20/30 seconds and dies away.

The velocity profile in radial direction, perpendicular to the beam-axis, is relatively symmetrical and has its maximum at the centre. The narrow band shown in front of the region of velocity maximum may be regarded as a neutral zone where there is no significant net fluid flow. The narrow band is pushed up by the fast moving fluid below and widens until it disappears after 15/30 seconds. After that, the structure of the streaming band through the beam-axis remains relatively unchanged for several seconds, but eventually smears out. It should be noted that, although the shock pulse exists for a 10 µs, resultant streaming lasts for a time period which is longer than 3 seconds. The maximum peak velocity is observed at t=0 and it gradually decreases with time in an exponential pattern.

Variation of the peak streaming velocity (Vp) obtained at t = 0 sec against the charging voltage setting (cVs) ranging from 12 to 18 kV with the interval of 2 kV is plotted in Figure 4. In the figure, Vz and Vr are the axial component (in z direction) and the radial component (r direction) of the velocity Vp, respectively. It is seen that Vp increases with cVs in a sigmoid pattern, namely, Vp is more sensitive to cVs and more rapidly increases between 12-16 kV than the other ranges. As expected from the figure 3, the Vr is far less than Vz. As cVs increases, Vr rises up more rapidly compared to Vz and this indicates that the streaming pattern is more complicated, at the higher settings.

Figure 4. The peak velocity (Vp) of streaming water against voltage settings ranging from 12 to 18 kV with the interval of 2 kV. The symbol Vz and Vr are the beam axial component (in z direction) and the radial component (r direction) of the velocity Vp, respectively.
4. Discussion
In the study, we have observed some characteristic features of the acoustic streaming produced by a lithotripsy field visualized using a PIV method. It is noted that, although the shock pulse exists for 10 μs, resultant streaming persists for periods longer than 3 seconds. The peak streaming velocity (Vp) measured was 1.5 - 3 cm/s and this depends on the charging voltage setting. These values are larger than the acoustic streaming generated by typical diagnostic ultrasound fields (0.3 - 1.3 cm/s) but less than those produced by Doppler ultrasound fields (1.4 - 14 cm/s) [12]. It is noted that the measured streaming velocity is expected to be severely underestimated, since it is averaged over a long time of 1/30 second which is the time resolution limited by the frame rate of the video images.

To gain some insight about the true Vp, some figures are obtained on the basis of the shock wave form measured at the focus (cVs of 16 kV) using a membrane hydrophone. Plane-wave assumption whereby the particle velocity is given by pressure divided by characteristic acoustic impedance, results in 13.4 m/s, maximum particle velocity, and 0.341 m/s, the net particle velocity averaged over the time that shock-wave exists (50 μs). This is the localized particle velocity and considering the effect accumulated with distance, beam focusing, attenuation in particular, enhanced effects resulting from harmonics generated during propagation, the particle velocity through out the focus is expected to be further increased, as indicated by Starritt et al (1989) [12]. Accordingly we may speculate the measured streaming velocity is underestimated by at least a factor of 10.

Despite such a large underestimation, it was shown that the measured Vp describes a reasonable relationship with cVs well as the driving field parameters. As seen in figure 4, Vp increased with cVs in a sigmoid pattern (r=0.97983, p=0034). Based on the pressure measurement at the focus (not shown here), we observed that Vp was proportional to intensity (r=0.94152, p=0.0168), as predicted by theory [5]. It is noted that the negative pressure (P-) was more closely correlated with Vp (r=0.98683, p=0.0018) than intensity, whereas the peak positive pressure (P+) was poorly correlated with Vp. This may indicate that the present PIV method may be used a non-intrusive means to estimate the peak pressure and intensity of the lithotripsy field which is, in general, highly difficult to characterize.

5. Conclusions
Acoustic streaming produced by a lithotripsy pulse was visualized using a PIV technique and features of the streaming velocity map were observed. The measured peak streaming velocities (Vp) were found to be 1 - 3 cm/s, dependent on the charging voltage settings (cVs) ranging from 10 - 18 kV. The measured Vp was significantly underestimated, as it was averaged over a long time period (1/30 second), compared to the shock pulse duration of about 10 μs. Nevertheless, it was shown that the Vp was sensitive to cVs and is closely related to the parameters of the driving lithotripsy field. As predicted by theory, the measured Vp shows an almost linear relationship with intensity (r=0.94152, p=0.0168). The best correlation was found between Vp and the peak-negative pressure, P-. This suggests that the present intrusive PIV technique may provide a practical means of characterizing the lithotripsy field, which is highly difficult to measure directly.

6. Acknowledgements
This study was supported by Korea Science and Engineering Foundation (R05-2002-000-01130-0).
7. References

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