AN EXPERIMENTAL STUDY OF CAVITATION EFFECTS DUE TO SHOCK WAVES

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Abstract

Bubble dynamics, acoustic emissions and sonoluminescences due to cavitation in the focal area of an electromagnetic shock wave lithotripter have been studied. In our experiments we used different repetition rates of the shock waves. For low repetition rates we were able to relate our experimental results to theoretical predictions for a similar shock wave field of an electrohydraulic lithotripter [1]. Using a higher repetition rate, we observed qualitatively different effects, which may be important in therapeutical applications.

Introduction

Cavitation effects play a significant role in medicine for the destruction of concrements accompanying the treatment of bilious complaints and nephropathies [1], [5]. These effects have been investigated by various groups. For the investigation of a single laser-produced cavitation bubble near a solid boundary Vogel et al. used high-speed photography and a schlieren technique [5], [6], [7]. Others have studied the acoustic emissions of bubble clouds with active and passive ultrasonic sensors [2], [3], [4] . As an independent evidence for the presence of cavitation light emissions attributed to sonoluminescences have been detected with a photomultiplier [2]. For cavitation due to an electrohydraulic lithotripter wave the similarities of the obtained acoustic and optical signals were examined [2].

The theory of the dynamics of a single bubble excited by a lithotripter wave has been developed by Church [1] based on the Gilmore-Akulichev formulation for bubble dynamics. Gas diffusion into the bubble was taken into account and the concentration of gas dissolved in the liquid was assumed to be 90 % of its value at saturation. Bubbles with a radius of 1 - 10 μm are known to exist initially. Church modeled the pressure of the shock wave excited by an electrohydraulic lithotripter as follows. The rise time was set to zero, as the bubble response does not depends on this value. The positive pressure maximum p^+ is followed by a decay of 2 μs down to the negative pressure minimum p^-. The ratio p^+/p^- is assumed to be 6.25. The pressure amplitude is set to 0 for $t > 7\,\mu s$.

An initial compression occurs as soon as the compression half cycle of the shock wave arrives at the bubble. With the tensile part of the shock wave the bubble grows rapidly. After the shock wave has passed the bubble, it grows slowly to a maximum radius. Eventually, at the end the so-called quiet period the bubble collapses violently. During this primary collapse 96 % of the energy stored during expansion is converted mainly into acoustical energy. A small amount of energy is emitted as light (sonoluminescence). After collapse the bubble has a radius of about 40 μm.

The aim of our study now is to obtain experimental results for an electromagnetic (EM) lithotripter. For low shock wave repetition rates, we expect that our results can be related to the theoretical and experimental results in [1] and [2]. To assess the effects, which are important in typical therapeutical applications, we observed the cavitation effects at higher repetition rates. So far, for these repetition rates neither theoretical nor experimental results are available.

The Experimental Setup

Cavitation effects were caused by the acoustical shock wave emitted by an electromagnetic lithotripter source placed at the bottom of an acryl-glass basin filled with water. The shock wave was focused by an acoustical lens. We used chemically deionized and filtered not degassed tap water.

The axisymmetrical lithotripter wave propagates vertically through the basin. After 212 - 215 μs the wave reaches the focus.

To observe sonoluminescences we used the same photomultiplier (EMI 9789B) as Coleman [2] with an effective cathode diameter of 10 mm, a spectral window between 200 nm and 700 nm and a maximum quantum efficiency at 400 nm. The basin was darkened with aluminium sheets.

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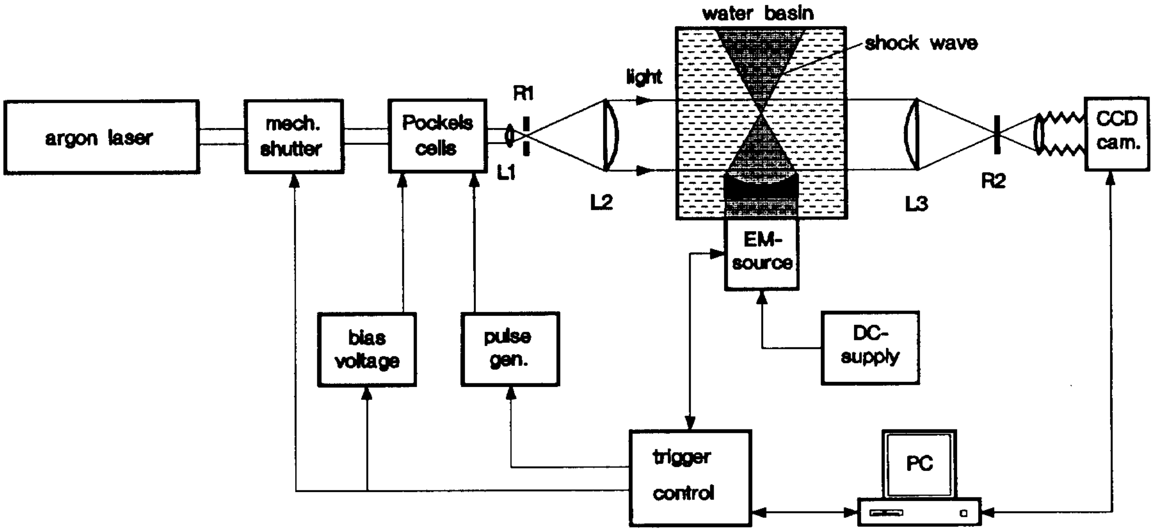

Fig. 1. Experimental setup for high speed schlieren imaging.

The photomultiplier was located on top of the basin and centered on the axis of the acoustic field. We used the photomultiplier with a bias of 1000 V and connected it directly to the 50 Ω input of the LeCroy Oscilloscope 9450.

For the investigation using the schlieren system the aluminium sheets had to be removed.

Fig. 1 shows a diagram of the schlieren alignment. The laser beam is focused by lens L1 and filtered by pinhole R1. After the collimation through the lens parallel light penetrates the water basin and is focused again by lens L3. In the focal plane of L3 a suitable spatial filter is located. Thus the undeflected light passing through the water basin is stopped down. For imaging the objects deviating the light we used a CCD camera module with a sensitive area of 8.8 x 6.6 mm. The scales of the CCD–images could be chosen by varying the focal length of L3. A test section in the region of the shock wave focus was illuminated.

A trigger unit controls the timing of the lithotripter wave, the light pulses and the camera.

The laser worked in C.W.–mode. As the light and the acoustical objects should interact only for a short time, a fast shutter has been realized by two Pockels cells. With our setup light pulse widths between 20 ns and 2 μs and a pulse repetition rate of 300 kHz were possible to generate. As the camera shutter was too slow to sample images at this frequency, we illuminated one image up to three times. An adjustable delay permits to obtain images at different times after excitation of the lithotripter wave.

Different spatial filters were used to visualize the cavitation effects with high contrast. As long as the lithotripter wave itself deviates light in the test section a vertical filament is used as a schlieren stop in order to eliminate this mainly vertically deviated light from the schlieren image. However, deviations caused by cavitation effects could be observed nearly without disturbation. After the lithotripter wave has passed the test section a regular opaque spot was used to stop down the nearly undeflected light.

Results and Discussion

We observed differences between cavitation effects at high and at low shock wave repetition rates. The different results are presented in two separate sections.

A. Low Repetition Rates

At low repetition rates of less than $\frac{1}{20}$ shock waves per second cavitation effects due to a single shock wave

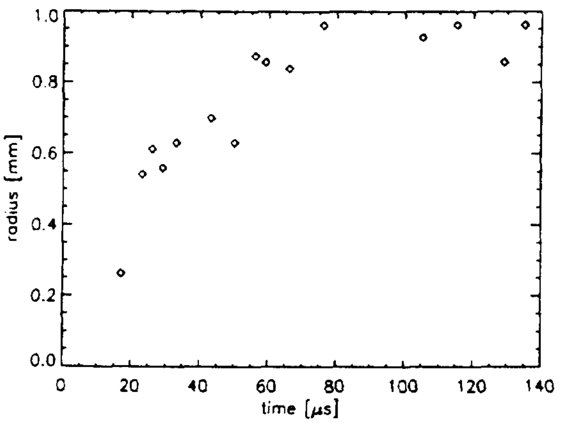

Fig. 2. Time development of maximum radius cavitation bubbels.

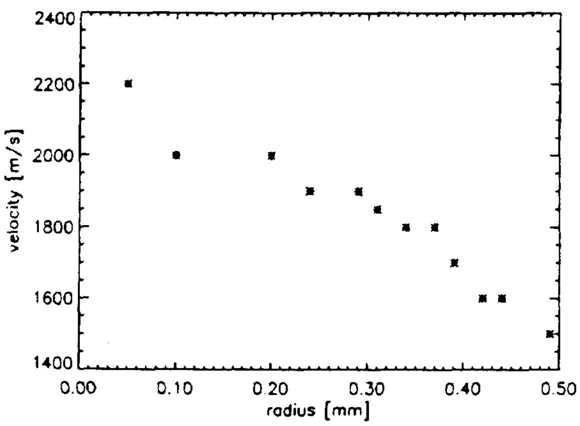

Fig. 3. Propagation velocity of acoustic transients.

have ceased when the next wave is excited. At these repetition rates we detected sonoluminescences 160–200 μs after the shock wave reached the focus area. These can be attributed to the phase of primary collapse. The time span of primary collapse is in accordance with theoretical and experimental values for electrohydraulically excited waves [1],[2]. Also the prolongation of the quiet period due to higher discharge voltages could be proved experimentally. The sonoluminescences indicate a high bubble temperature at collapse.

With our schlieren - system we noticed only a small number of bubbles. We were able to measure the radii of the bubbles during the quiet period over the time for different discharge voltages of the EM-Lithotripter (Fig. 2). The maximum radius attained during this period was 0.78 mm, 0.93 mm and 1.13 mm for 15 kV, 17 kV and 19 kV respectively. As it is known that maximum radii are strongly dependent on the shock wave amplitude they may be used to estimate it.

The velocity of the acoustic emissions was measured by using different pulse widths (Fig. 3). In contrast to the experimental results in [7] we measured a higher maximum velocity of acoustic emission of 2200 $\frac{m}{s}$, but mainly all results are in accordance with other authors [1],[6],[7].

B. High Repetition Rates

Typically , lithotripters in medical applications use higher repetition rates in order of magnitude one shock wave per second. Since for this rates no theoretical background exists, we studied cavitation effects quantitatively.

We observed typical phenomena near the axis of symmetry of the shock wave. First, after four shocks the formation of a cloud of bubbles with high fusion activity can be seen in the lower parts of the test section. During a second set of 2–3 shocks the cloud expands over the whole vertical length of the test section. A third exposure to 2–3 shock waves leads to first implosions, but the highest acoustic activity was observed if then the next shock wave incidence was delayed for 5–7 seconds. After this period of highest acoustic activity subsequent shocks had no observable effects at all. It is very important to note that no sonluminescences were observed in the phase of highest acoustic activity. This indicates lower bubble temperatures at collapse than at lower repetition rates, while the acoustic emissions are still strong. Another important observation is the total lack of any observable bubbles during the time interval between two shock wave incidencies.

This preliminary study may be a basis for further investigations serving better understanding of therapeutical effects of lithotripters.

Conclusions

In our experiments we successfully replaced the expensive high speed photography by multiple light pulse imaging. Additionally, pulses with variable durations were used to analyse the acoustic emissions. According to our observations, we distinguish between low and high repetition rates of shock waves. The cavitation effects in both cases differ qualitatively. At low repetition rates we measured various parameters in accordance to existing theoretical and experimental re-

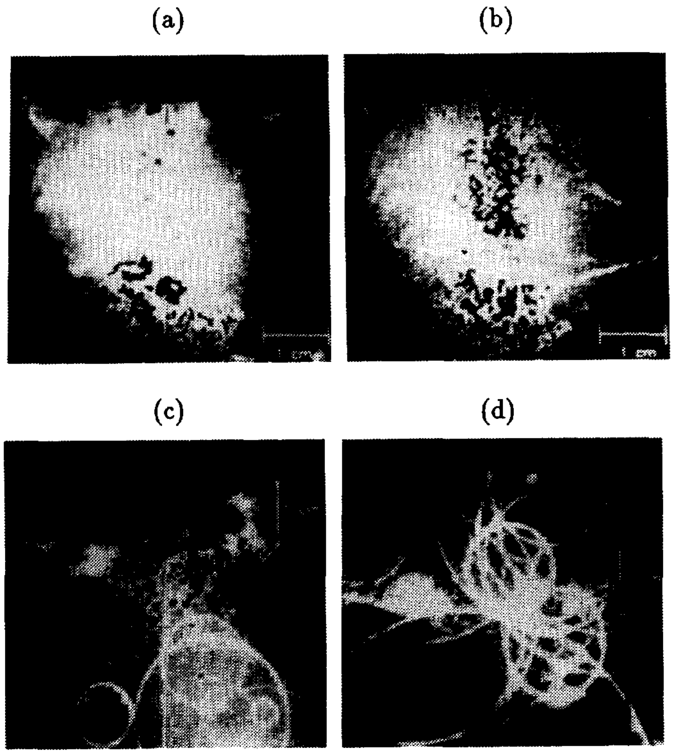

Fig. 4. Schlieren images at high shock wave repetition rates: cloud formation (a), expansion phase (b), first implosions (c) and high acoustic activity (d).

sults. If the bubble dynamics for an EM-lithotriper were theoretically derived, these measurements could serve to obtain parameters of the driving shock wave.

The absence of sonoluminescence at higher repetition rates indicates lower bubble collapse temperature and therefore less damage to healthy tissue during treatment. However, the acoustic activity at this repetition rates is comparable to that at lower rates. Since these effects are of high therapeutical interest it is nessessary to establish a theoretical background in future studies.

Acknowledgement

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