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Experimental setup for evaluation of cavitation effects in ESWL

Abstract: Cavitation is a major fracture mechanism in extracorporeal shock wave lithotripsy (ESWL). However, it can cause tissue trauma and its effects on kidney stones and surrounding tissue are not fully understood. Therefore experimental setups enabling systematic parameter studies are crucial. We developed and evaluated a testing rig comprising three measuring methods in order to examine this mechanism. Our initial evaluation of this setup based on standard components showed promising results. Primary cavitation was displayed by high-speed photography 195 µs after the shock front had passed the focal zone. The effect of different pulse repetition rates (30, 60, 90, 120 SW/min) on the extension of the cavitation area was determined. The lifetime of secondary cavitation was analysed by B-mode ultrasound imaging. In a post processing progress the images showing bubbles were compared to a reference picture for both types of cavitation and the number of pixels that changed colour was counted. Furthermore stone comminution at different pulse repetition rates (30, 60, 90, 120 SW/min) was investigated by fixed-dose fragmentation. We observed an inverse correlation of cavitation and fragmentation. As the pulse repetition rate increases, the area of primary cavitation grows whereas the fragmentation efficiency decreases. B-mode imaging showed that secondary cavitation bubbles persisted between the shocks and can serve as nuclei. The higher the pulse repetition rate is, the more of these nuclei remain and thus facilitate formation of primary cavitation. The experimental setup provides reproducible results regarding the development of primary and secondary cavitation on the one hand and the fragmentation of phantom stones on the other hand. Therefore it can be utilized to further investigate the effect of different boundary conditions and shock wave parameters on cavitation and stone comminution. The impact of different focal sound fields is subject of ongoing research.

Keywords: shock wave lithotripsy, pulse repetition rate, cavitation, stone fragmentation, high-speed photography

1 Introduction / Background

Extracorporeal shock wave lithotripsy (ESWL) is a commonly used treatment for patients suffering from urinary stones smaller than 20 mm [1]. One therapy session comprises from 1000 up to more than 5000 shock waves [2], often fired at a rate of 120 SW/min due to time constraints in clinical routine [3–5]. There are five effects governing the fracture mechanisms of shock waves in lithotripsy: spallation, quasistatic and dynamic squeezing, erosion and cavitation [1,6,7]. It is still controversially discussed, whether cavitation bubbles rather enhance fragmentation by collapsing close to the stone’s surface [1] or attenuate the following shock waves [4,8]. At the same time, cavitation can cause tissue trauma and rupture of blood vessels and therefore can be associated to severe risks [1,9,10]. Although the lifetime of the primary cavitation bubbles is shorter than the interval between the consecutive shock waves, smaller secondary cavitation bubbles remain and can serve as nuclei for the next shock front depending on the pulse repetition rate [4,11].

Since the effects and side effects are not fully understood, it is necessary not only to examine when cavitation is useful or obstructive but also to analyse how to intensify or mitigate the bubble clusters. For a quantitative experimental evaluation of cavitation caused by different shock wave parameters and boundary conditions a testing rig is needed.

In literature different measuring methods to investigate the characteristics of cavitation are described. Thus, the impact of bubble growth on the waveform can be shown by fibre-optic hydrophones [4]. However, this method is limited to one spot, e.g. the focal point, and moreover intense cavitation can lead to breakage of the fibre. The acoustic...
emission of cavitation bubbles collapsing is recorded by passive cavitation detectors (PCD) [12,13], which do not deliver any visual information. High-speed cameras on the other hand can be utilized to take images of primary cavitation and to assess the spatial extent of bubble clusters at a certain time [4,8,9,12], but are very expensive. B-mode ultrasound imaging is used in order to analyse bubble dynamics [12]. However, it is limited to the in-vivo and in-vitro investigation of temporal and spatial development of secondary cavitation only [14]. The impact of the bubble collapse on surrounding solid bodies can be estimated by shooting on aluminium foil targets [15]. Nevertheless the results of these experiments cannot be transferred offhand to artificial kidney stones as the aluminium target interferes with the shock waves in another way than stones made of gypsum do. Pishchalnikov et al. [11] developed a quite comprehensive experimental set up with highly sophisticated components comprising a fibre-optic hydrophone, a high-speed camera and B-mode ultrasound. The main objective of our work was to provide a test-setup based on standard components.

2 Material and Methods

A testing rig was configured including a high-speed photography setup based on a standard digital camera and an externally triggered digital flash light, a B-mode ultrasound probe and the possibility of fixed-dose stone fragmentation. The shock waves were generated using a customized piezoelectric lithotripter with 6300 V charging voltage enabling the generation of different acoustic fields. The central water tank was filled with degassed ultrapure water (20°C) and a stone fixture made of liquid latex (XUR® - FlüssigLatexCouture, Berlin, Germany) was positioned in the acoustic focus of the lithotripter.

Primary cavitation was examined using high-speed photography. A camera (Nikon d80, Nikon Corporation, Tokyo, Japan) and a flash (Metz 58 AF-1, Metz mecatech GmbH, Zirndorf, Germany) were placed in a darkened room on opposite sides of the water tank, both facing the empty latex fixture (see Figure 1). A sheet of paper was used as a diffuser in order to attenuate the backlight and avoid overexposure. The flash with 30 μs duration was triggered 195 μs after the shock front had passed the focus. Cavitation at four different pulse repetition rates (30, 60, 90, 120 SW/min) was investigated by taking n = 6 pictures at each setting.

Secondary cavitation was made visible by a B-mode ultrasound scanner (z.one ultra, Zonare Medical Systems, Inc., Mountain View, CA, United States). The sonic head covered by ultrasound gel and a thin plastic bag was placed inside the water tank, facing the empty latex fixture. With this experimental setup the lifetime of cavitation clusters was examined. Therefore n = 3 videos of 30 s duration were recorded with a framerate of 3.8 fps. To evaluate the effect of cumulative cavitation based on the remaining nuclei of the previous shock wave 10 shock waves were fired at a rate of 60 SW/min and recording started right before the last shock wave was triggered.

Both, the pictures of the primary cavitation and the videos of the secondary cavitation were evaluated by Python and Scilab programs. A reference picture without any bubbles was subtracted from the pictures and the frames of the videos, respectively (see Figure 2). The number of pixels that changed - showing cavitation activity - was counted and therefore the size of the cavitation area was determined.

For the fragmentation hemispherical stone phantoms made of BegoStone plaster (BEGO Bremer Goldschlägerei Wilh. Herbst GmbH & Co. KG, Bremen, Germany) with a mixing ratio of 4:1 (gypsum : ultrapure water) were used. The stones were saturated with gypsum water, degassed and placed in the latex fixture at the acoustic focus of the lithotripter. They were divided into five groups (n = 6) and exposed to 500 shocks at rates of 30, 60, 90, and 120 SW/min, respectively. After each shock wave treatment the fragments were filtered, dried and their grain size...
distribution was determined using a sieve tower. The efficiency of stone comminution was measured by the fragmentation coefficient $f = \frac{100 \times m_1}{m_2}$, where $m_1$ is the total weight of all fragments and $m_2$ is the weight of all fragments smaller than 2 mm.

### 3 Results

![Figure 3: Size of the area covered by primary cavitation at $t = 340\mu s$ at different pulse repetition rates (30, 60, 90 and 120 SW/min)](image)

There is significantly more cavitation activity at higher pulse frequencies (see Figure 3). At a repetition rate of 30 SW/min the area of cavitation covered only $1034 \pm 166$ pixels whereas the area was largest at 120 SW/min extending to $2662 \pm 874$ pixels. There was no statistical significant difference ($p > 0.05$) between the size of the cavitation area at 90 SW/min and 120 SW/min.

B-mode imaging indicated that secondary bubbles stayed in and around the latex fixture, which was positioned in the acoustic focus of the lithotripter. A bigger cluster remained for 1s after the shock wave passed the focal zone, while the lifetime of individual bubbles was 5 s (see Figure 4).

![Figure 4: B-mode images of secondary cavitation at $t = 0 \text{s}$, $t = 1 \text{s}$ and $t = 5 \text{s}$](image)

The stone comminution experiments showed that the fragmentation efficiency decreases as the pulse repetition rate increases (see Figure 5). Stone fragmentation was most efficient at a pulse repetition rate of 30 SW/min with $f = 25.6 \pm 1.6\%$ and least efficient at 120 SW/min with $f = 21.0 \pm 1.8\%$.

![Figure 5: Fragmentation coefficient $f$ (fragments smaller than 2 mm) for different pulse repetition rates (30, 60, 90 and 120 SW/min)](image)

### 4 Discussion

The testing rig enables us to evaluate the formation and evolution of cavitation on the one hand and its consequences for stone comminution on the other hand. An inverse correlation of cavitation and fragmentation was shown. With increasing pulse repetition rates primary cavitation increases while the fragmentation efficiency decreases. Likewise, other works have shown the effects of higher pulse repetition rates facilitating cavitation [4,12] and impairing stone comminution not only in-vitro [4,8,16] but also in pig models [5,17] and in clinical studies [18,19]. Even though the lifetime of primary cavitation is too short to impact subsequent shock waves [4], secondary cavitation clusters stayed for 1 s and individual secondary bubbles remained even longer. Therefore they can work as nuclei for the following shocks. Similar results have been shown by Pishchalnikov et al. [11]. A smaller pulse repetition rate, hence a longer interval between the pulses, minimizes the probability of a shock wave hitting a nucleus and thus reduces the cavitation affinity.

The results presented above indicate, that cavitation in front of the focal zone impairs stone comminution on the one hand, while literature has shown the advantage of this mechanism for stone comminution on the other hand. Therefore not only the lifetime and the size of the area covered by bubbles but also the place where cavitation develops should be subject of research in the future. The experimental setup described in this work can be utilized to examine the effects and side effects of cavitation as well as the influence of different waveforms on cavitation and stone comminution.
**Author Statement**

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**References**


