Urol Res (1996) 24:167–170

ORIGINAL PAPER

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First temporal and spatial quantification of single-shot electrohydraulic lithotripsy in vitro

Received: 9 December 1994 / Accepted: 6 December 1995

Abstract Single electrohydraulic lithotripsy (EHL) discharges from a human ureter were analyzed with a mechanical high-speed motion analysis camera. We found a cavitation bubble, at 650 mJ, 4–11 mm in size, with a lifetime of 400–500 μs. Varying sizes and lifetimes were found using single-shot analysis, as well as in different shot-sequences. This supports similar observations by recent investigations of cavitation bubble size with high-shutter-speed videofilm, which have depicted events at shutter speeds of 4000/s, i.e., an approximate exposure time of 250 μs. Due to the occurrence of high-voltage interference from the EHL high-voltage generator, no other technical electronic event timing equipment has so far been available capable of mechanical high-speed film motion analysis, while at the same time avoiding high-voltage interference.

Key words Endourology · Ureteroscopy · Ureteral calculi fragmentation · Intracorporal electrohydraulic lithotripsy · Space-occupying side effect · Mechanical high-speed motion analysis

Introduction

Recently, intensive research has been conducted on electrohydraulic lithotripsy (EHL) during ureterorenoscopy (URS) for ureteral calculi fragmentation [2, 6, 11, 13, 19]. The primary choice of treatment is extracorporal shock wave lithotripsy (ESWL). However, about 20% of all ureteral calculi fragmentations performed by ESWL are unsuccessful, thus requiring an alternative method of treatment.

EHL has been known as a very efficient method of bladder stone fragmentation since the 1950s [1, 4, 9]. As the space-occupying side effects causing ureteral rupture and lesion have so far not been sufficiently investigated, it has been assumed to be inadequate for blind intra-ureteral use. This drawback has so far led urologists to reject the use of EHL during URS completely.

Laser, mechanical systems (i.e., Lithoclast, ultrasound) and others, were developed for use with miniaturized probes during URS as a minimally invasive endoscopic method. Laser methods are inefficient, due to technical limitations of energy application, and are uneconomic because of their high cost. Ultrasound requires rigid probes placed in direct firm contact with the stones, rendering it unsuitable for use in this capacity.

Photographs and high-shutter-speed videofilms of EHL events demonstrate that the cavitation bubble is responsible for ureter rupture. Size depends on energy input. This has been measured by changing the video picture rate versus the EHL shot series (phase shift) (publication in preparation). Although the measurement of the size of the bubble itself has seemed correct, there have been two difficulties: first, it has not been possible to specify the bubble's lifetime absolutely. Second, there has been no means of proving the reliability of the measured extension with regard to the "temporal location" of the frame interval. An additional obstacle has been the high-voltage interferences produced by the generator. Thus, electronic monitoring of the experiments for the purpose of obtaining temporal information has been impossible. The only solution to the problem of obtaining reliable data is to film EHL with a *mechanical* high-speed motion analysis camera.

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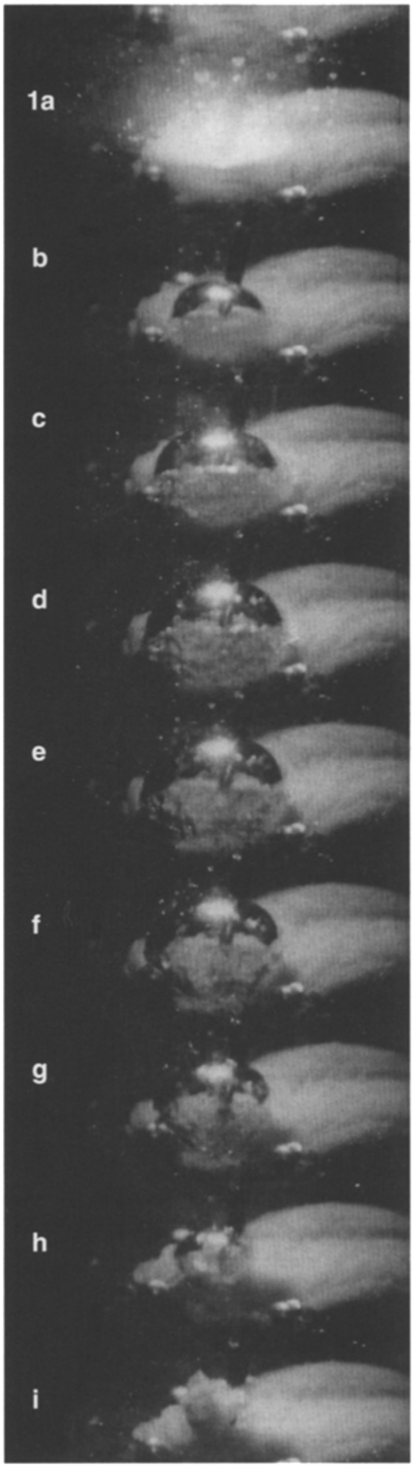

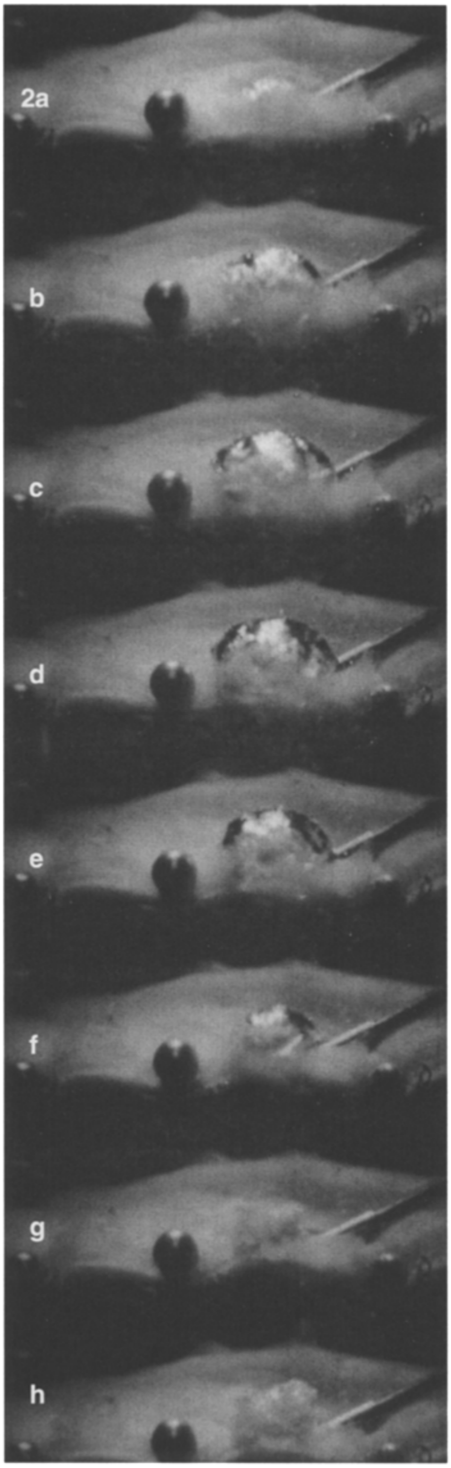

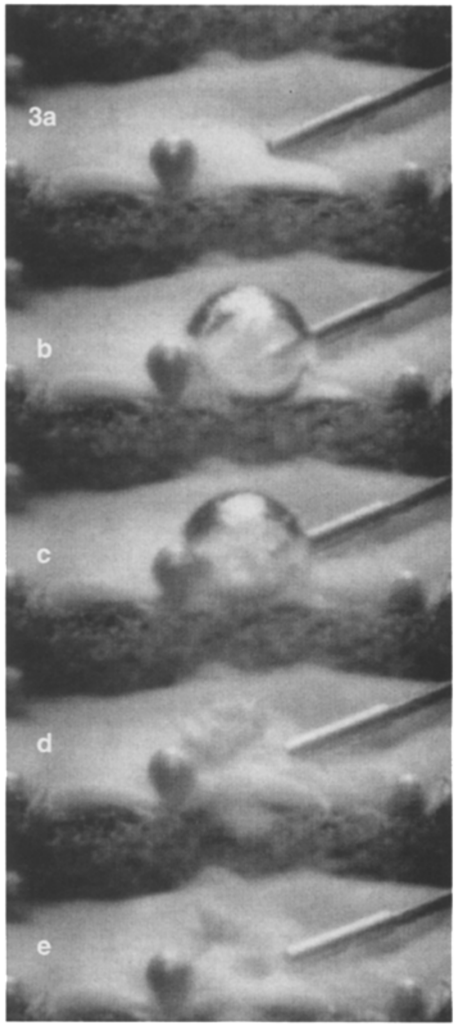

Fig. 1a–i EHL discharge of 675 mJ filmed at 16 000 fps (1 frame ≅ 62.5 μs). **a** Initial flash, **b, c** increasing cavitation bubble, **d** maximum expansion of cavitation bubble, **e–h** decreasing cavitation bubble, **i** imploding cavitation bubble

Fig. 2a–h EHL discharge of 675 mJ filmed at 10 000 fps (1 frame ≅ 100 μs), **a** Time before shot, **b, c** increasing cavitation bubble, **d** maximum cavitation bubble, **e, f** decreasing cavitation bubble, **g, h** imploding cavitation bubble

Fig. 3a–e EHL discharge of 675 mJ filmed at 5000 fps (1 frame ≅ 200 μs), **a** Time before shot, **b, c** motionless cavitation bubble, **d, e** imploding cavitation bubble

Materials and methods

We had access to a 16HD Hitachi high-speed motion analysis camera at the German Forces University, Department of Electrical Engineering and Communication Processing (Prof. Dr. Ing. B. Morgenstern, Holstenhofweg 85, D-22043 Hamburg, Germany). We used Kodak RAR (rapid access recording) 2498 film on an Estar AH base, pushed through development to 400 ASA. We developed prints of representative parts of the film, which enabled counts and measurements to be made.

The camera was placed in front of the experimental basin filled with 0.9% NaCl solution. For close-up pictures accessories such as C-mount extension rings placed between the camera body and the lenses were needed. For illumination we used 12-V low-voltage halogen reflector lamps. Specimens of human ureter were taken postoperatively for our experiments from hypernephroid renal cell carcinomas. They were pinned onto a sponge at the bottom of the basin. Using our film material, illumination and camera, picture-taking rates of up to 16 000 fps (frames per second) were possible. One picture represents one part of the process within 62.5 μs ($= 1$ s/16 000 $= 62.5 \times 10^{-6}$ s). Camera and experimental EHL generator (Firma Richard Wolf, Knittlingen, Germany) were operated simultaneously by hand. The energy applied was 675 mJ at 150 nF and 3.0 kV. The size of the cavitation bubble was measured in relation to the defined size of the tip of the probe. The probe diameter was exactly 1 mm.

Results

Space occupation takes place when a cavitation bubble with a clear surface and sharply defined edges appears. Due to the dynamic extension of the cavitation bubble, we found maximum/minimum ratios of 7/3 mm, 9.3/5 mm, 11/4 mm (Figs. 1b–h, 2b–f). Continuously varying space occupation, i.e., clear cavitation bubbles differing in size, were observed during expansion and implosion of one single EHL shot, as well as during different EHL shot sequences. Therefore, an absolute size of cavitation bubble cannot be predicted, but a maximum size can be concluded or deduced. At 5000 fps, we were unable to find any variations in size of cavitation bubble. Therefore, we can postulate that the observed extension corresponds to the maximum size of the cavitation bubble (Fig. 3b, c).

Lifetimes of the cavitation bubble were as follows:

- At 16 000 fps: 7 frames $\times$ 62.5 μs $\rightarrow$ 437.5 μs
- At 10 000 fps: 5 frames $\times$ 100 μs $\rightarrow$ 500 μs
- At 5000 fps: 2 frames $\times$ 200 μs $\rightarrow$ 400 μs

The duration of a space-occupying cavitation bubble can therefore be extrapolated to be 400–500 μs.

Discussion

We were able to show that the cavitation bubble varied dynamically in size. These variations were a natural physical effect of EHL during the expansion and implosion process. The slight variation in cavitation bubble size from one shot sequence to another may be explained by the slightly varying energy output of the generator. A varying condensor discharge at high-voltage discharge is a well-known physical effect.

Conclusions

The high mechanical energy potential and efficacy of EHL in regard to bladder stone lithotripsy is well known [1, 4, 9]. Vorreuther et al. have performed video investigations to prove that EHL stone fragmentation and its side effects [5, 7, 8, 10, 17, 18] depend on energy input. Energy input control will render this system applicable for usage with URS [2, 3, 13, 16]. In this way, we can prove that measurements of cavitation bubble size with high-shutter-speed videofilm and phase shift are reliable. The problem of variation is not caused by the video method but is typical of EHL discharge. The variations in maximum sizes obtained with the video investigation are thus in a similar range and are not due to errors of measurement in the technical equipment. These variations are negligible under the clinical conditions used for endoscopy. As the bubble represents a space-occupying side effect, it is of the utmost importance that the maximum size be taken into account.

The benefit of video investigations is their low cost and immediate on-screen availability. There is no need for expensive film development. The reliability of counts is substantially improved by the increased number of measurements. In contrast mechanical high-speed motion analysis is more precise than videofilm but not as efficient in respect to cost, man power required, availability of technical equipment, and the limited number of repetitions required for improved reliability. Video analysis is definitely to be preferred. In any case, only through high-speed motion analysis do we know that video analysis produces equally valid data. The high degree of precision achieved with high-speed motion analysis is not necessary to obtain the desired data of clinical interest but is indispensable for proving the reliability of video analysis data.

There is an additional advantage besides the high energy potential of this therapeutic technique: the energy can be applied through flexible and perfectly miniaturizable wires to the point of interest. The wire itself is not a significant limitation in the effective application of energy, unlike fiber optics or rigid ultrasound probes [12, 14]. Direct firm stone contact is not required.

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