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The impact of the geometry of the lithotriptor aperture on fragmentation effect at extracorporeal shock wave lithotripsy treatment

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Abstract The aim of this study was to determine the impact of the aperture size of an electro-hydraulic lithotriptor on the fragmentation effect. We also wanted to investigate whether a potential change in the capacitance of the pulse forming network (PFN), at a certain energy level, might have an impact on fragmentation rate. Two different apertures with a diameter of 23 and 17 cm respectively were compared using two different values of total PFN capacitance: 50 nF and 80 nF. Model stones of similar size and weight were fragmented. The number of shots for complete fragmentation or the grade of fragmentation after a certain number of shots was measured. This study shows that for the shock wave system used, the 23-cm aperture seems to provide more effective fragmentation as function of the number of shots compared with the 17-cm aperture at the same energy level. Furthermore, a minor change in the PFN capacitance between reasonable limits does not affect the fragmentation efficiency. This article also highlights the fact that it is not relevant simply to compare the *voltage* level given in the shots in extracorporeal shock wave lithotripsy treatment between different lithotriptors.

Key words ESWL · Lithotriptor · Aperture · Ellipsoidal reflector · Electro-hydraulic · Stone fragmentation

Introduction

In an electro-hydraulic lithotriptor the shock wave is released through a high-voltage discharge over an electrode-gap placed in liquid coupling medium. The coupling medium is pre-conditioned water containing saline. Water is a suitable coupling medium since its acoustic properties are very like those of soft tissues. The water is degassed in order to remove dissolved air and thereby reduce transmission losses [8].

The electrode-gap is mounted at the first focus of a truncated ellipsoidal reflector. The shock wave, initially isotropically radiated from the source, is reflected in a cone shape onto the stone target, placed in the second ellipsoidal focus (Fig. 1). Due to the cone-shaped beam, the −6 dB focal volume will be hourglass-shaped when not distorted by a stone target. About 10% of the released pressure pulse will not be reflected but forms instead a diverging cone, as indicated in Fig. 1. The non-reflected pulse will arrive at the focus a little earlier than the reflected pulse. The target is fragmented by a combination of elastic blasts and cavitation effects which appear when the shock wave passes near the focal volume [2].

The design of the reflector parameters is a very delicate matter. The properties of the reflector can be varied in many ways: length of the ellipsoid axis, truncation height, focal distance, possible electrode-holder parts shadowing the shock wave path, etc. The truncating level must be balanced by the amount of non-reflected beam and the demands on the maximal treatment depth. The size of the aperture, i.e. the acoustic window, and the shape of the reflector have impact on parameters important for the outcome of the treatment, for example the non-linear shocking factor and the focal volume. A simple estimation of the acoustic gain of the lithotriptor can be achieved by dividing the aperture cut-area by the radial cross-section of the focal volume.

The high voltage is charged and stored in a *pulse forming network* (PFN). The PFN consists of distributed capacitance, inductance and resistance. The time t in seconds (s) to fully charge the PFN to U volts (V) equals

$$t = \frac{CU}{i}$$

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where C is the total capacitance in farads (F) and i is the charging current in amperes (A). The electrical energy E in joules (J) or watt seconds (W s) in each shot then becomes

$$E = \frac{1}{2}CU^2$$

As the energy is dependent on the voltage squared, a change in voltage may result in a larger change in energy. A common error today is simply to compare *voltage* values between different lithotriptors and to express the energy given in an extracorporeal shock wave lithotripsy (ESWL) treatment only in terms of voltage [3, 7]. This is, however, not relevant, since the relationship above shows that a certain energy level could be reproduced with any voltage level, as long as the total C-value is correctly matched (Fig. 2) and as long as the voltage level is high enough to result in an efficient explosive-like discharge; the spark-gap impedance hence becomes heavily non-linear. In practice this means that at low discharge energy the impedance becomes pure resistive, i.e. there is a low amount of acoustic emission.

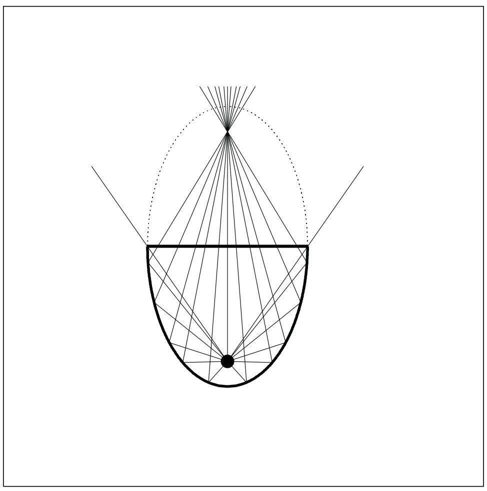


Fig. 1 Schematic sketch of a lithotriptor reflector, consisting of a truncated ellipsoid. The shock wave is released at the first ellipsoidal focus and then reflected towards the second. Note the diverging non-reflected pulse. All the *reflected* paths have exactly the same length. The focal contribution will hereby be phase linear

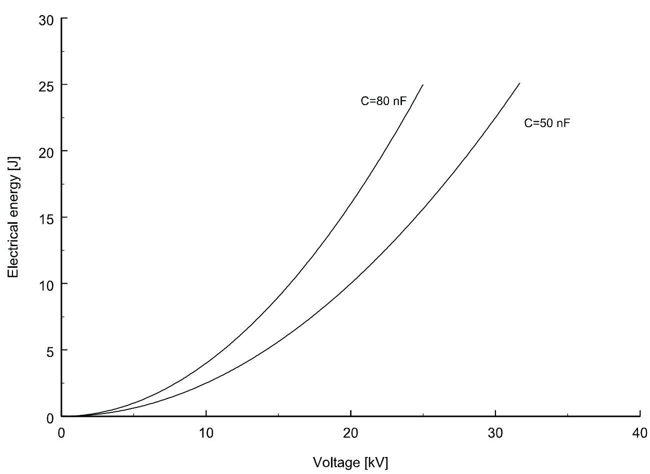


Fig. 2 Electrical energy as a function of voltage at two different pulse forming network (PFN) capacitance values: 50 nF and 80 nF

The aim of the present study was to determine how the fragmentation rate depends on the aperture size and to determine whether a slight change in the PFN capacitance at a certain energy level has an impact on the fragmentation efficiency.

Materials and methods

Lithotriptor

We used the electro-hydraulic lithotriptor Lithocut (Comair, Sweden) [1, 4] with the bellows removed and replaced with rigid plastic wrapping with an opening at the top. The electrode-gap distance was adjusted to 0.3 mm according to the manufacturer's recommendation.

Two reflectors with different apertures were compared:

(i) A 23-cm diameter reflector with aperture area of 416 cm^2 and a maximal treatment depth of 13 cm. This is the model conventionally used in the Lithocut system.
(ii) A specially constructed 17-cm diameter experimental reflector with aperture area of 227 cm^2 and a maximal treatment depth of 13 cm.

The two apertures were compared regarding fragmentation effect at the electrical energy levels of 10.0 J and 15.7 J. The experiments were run with two different PFN capacitances, 50 nF (5×10^{-8} F) and 80 nF (8×10^{-8} F), which are both common levels used.

Model stones

Leca spheres, which are normally used for flower conditioning, were used as model stones. They have a suitable quality for the purpose and are often routinely used for ESWL test fragmentation. We selected stones of roughly the same size (approximately 1.5 cm^3) and comparable weight (400–440 mg) to maintain the model stone density as constant as possible in each experiment.

To determine the water absorption capacity of the model stones, dry stones were weighted and thereafter immersed in 0.9% NaCl solution. The stones were soaked for some time and then weighed again. In this way we found that the model stones were saturated with water after 30 s. When soaked for a longer time, the stones did not increase in weight. When the stones were dried they resumed their initial dry weight. We could hence assume that the total weight of the dried fragments of a fragmented model stone should weigh the same as the dry weight of the stone before fragmentation.

All model stones in the present experiments were soaked for at least 30 s before they were placed in the lithotriptor focus. The stones and the fragments were weighed on a precision scale with an accuracy of 10 mg.

Experimental set-up

The two reflectors were used with experimental set-ups which were identical with respect to the triggering events. Each model stone was placed in a vinyl condom filled with approximately 4 ml 0.9% NaCl solution. The condom was placed in the lithotriptor focus using a calibrated laboratory clamp set-up. The coupling water was filled up to 6 cm above the focal point in order to avoid interacting reflexes from the water surface.

The coupling water was degassed by boiling and the saline content was kept constant at the level recommended by the manufacturer [8]. The pause time between shots was chosen as 1.2 s in all our experiments, since this is the minimal pause time needed to re-condition the coupling water [11] and will also ensure that each shot is given with a fully charged PFN.

The coupling medium was often changed during the experiments since particle fragments tended to diffuse through small cavitation-induced holes in the condom and contaminate the water and thereby increase the transmission losses. Frequent changing of the coupling medium also kept the degree of degassing at a fairly constant level. This was monitored by a polarographic O_2-meter (Model 55, YSI, USA) [10]. The electrode-gap distance was checked between each experiment and adjusted as necessary. A couple of times the electrodes had to be replaced due to wear of the electrode tip.

Degree of fragmentation

After drying, the stone fragments were strained through two gratings. Grating A had a rectangular mesh with the side 2.7 mm (mesh area 7.3 mm^2) and grating B a rhombic mesh with the side 1.5 mm (mesh area 1.5 mm^2). The fragments were classified according to the following system: group 1, fragments passing through both gratings; group 2, fragments obstructed by grating B; group 3, fragments obstructed by grating A. The weight of the fragments in each group was used for comparison.

In clinical ESWL treatment, the size of a fragment is deemed to be acceptable when its maximal diameter is smaller than 4 mm, as calculi of that size will mostly be discharged spontaneously. Complete fragmentation in our tests was thus defined as when all fragments of a fragmented model stone were in groups 1 and 2.

Results

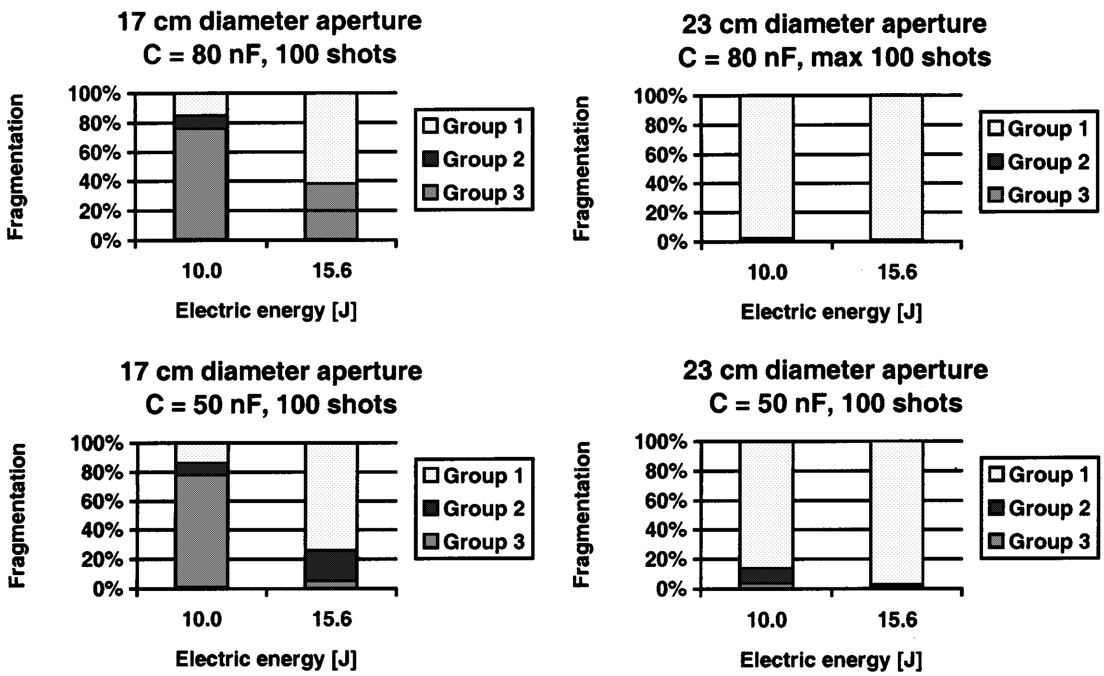
Stones were fragmented in both apertures using either 50 nF or 80 nF with an electrical energy of either 10.0 J or 15.6 J. At least ten stones were fragmented at each combination of energy and PFN capacitance level. The stone fragmentation efficiency as a function of the number of shots was far better using the 23-cm diameter aperture ($P < 0.001$, Student's *t*-test) (Fig. 3). With, for example, a capacitance of 80 nF and an electrical energy of 10 J, 100% of the calculi fragments were in groups 1 and 2 compared with 23% using the 17-cm aperture at the same energy and capacitance level. Moreover, no statistical difference in fragmentation efficiency was seen between stones fragmented with different PFN capacitances at a certain energy level in a certain aperture. Figure 4 shows the number of shots needed for complete fragmentation with both the apertures.

The reproducibility was good in all experiments. The small variations detected can be explained by variations in dissolved gasses and impurities of the coupling medium, variations in the electrode condition and variations in the density and composition of the model stones. We also found that air hidden in closed spaces in the model stones was released when the stones were fragmented, and this might have affected the acoustic impedance.

Discussion

In this study the better stone fragmentation with the larger aperture can most probably be explained by the principle that the higher is the ratio of aperture diameter D to focal length f, D/f, the higher will be the pressure amplification from relflector edge to focus [5]. More-

Fig. 3 **a** Degree of fragmentation for stones fragmented in the 17-cm ellipse with capacitance $C = 80$ nF. One hundred shots. **b** Degree of fragmentation for stones fragmented in the 23-cm ellipse with capacitance $C = 80$ nF. Maximum 100 shots. **c** Degree of fragmentation for stones fragmented in the 17-cm ellipse with capacitance $C = 50$ nF. One hundred shots. **d** Degree of fragmentation for stones fragmented in the 23-cm ellipse with capacitance $C = 50$ nF. One hundred shots



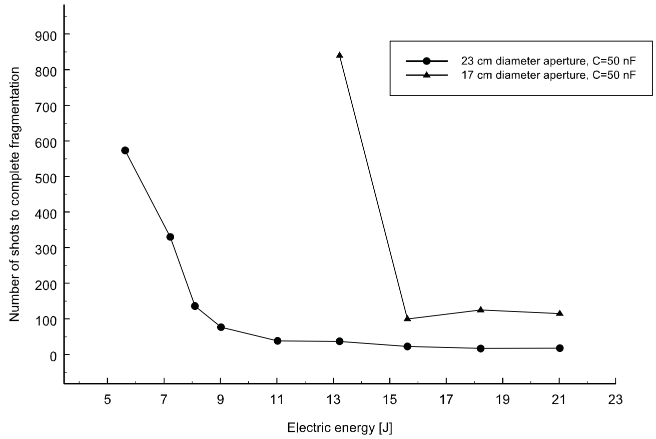


Fig. 4 Number of shots to complete fragmentation for each aperture

over, the smaller a reflector is, the longer and larger will be the focal −6 dB volume. A larger focal volume means that the energy density will be dispersed over a larger area and the focal pressure consequently decreased. We have, in these experiments, shown that the 17-cm reflector provides a significantly larger focal volume compared with that of the 23-cm reflector. This verification could be performed using a PVDF-hydrophone or a coaxial cable sensor [9] or simply by manually holding the model stone condom in the focus and then moving it a few millimetres. On the other hand a smaller focal volume demands more exactness of aim.

In the present experiments we used capacitances of 50 nF and 80 nF at the voltage levels 20 kV and 25 kV or 15.8 kV and 19.8 kV, producing an electrical energy of 10.0 J and 15.7 J. In this limited range we did not observe any significant differences in the fragmentation rate at the same energy level. Hence, a small change in PFN capacitance, within reasonable limits, does not change the fragmentation efficiency. In principle, the higher the capacitance, the higher will the discharge current become and the discharge voltage will thereby be reduced. On the other hand, a very low capacitance will put unacceptable demands on the internal high-voltage insulation and increase the resonance frequency of the damped electrical oscillation.

According to an earlier report, the number of shots to complete fragmentation should be approximately proportional to the inverted value of the electrical energy squared [6]. Our results seem to be in good agreement with this hypothesis (Fig. 4).

In conclusion, the 23-cm diameter aperture provides better fragmentation as a function of the number of shots than the 17-cm aperture. A small change of the PFN capacitance, within reasonable limits, does not significantly affect the fragmentation efficacy. It is not relevant to compare the electrical energy in terms of voltage levels between different lithotriptors if the PFN capacitance value is not also given.

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