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Impact of voltage and capacity on the electrical and acoustic output of intracorporeal electrohydraulic lithotripsy

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Summary. The electrical and acoustic output created by the spark discharge for electrohydraulic lithotripsy at the tip of a 3.3-F probe was evaluated. Spark generation was achieved by variable combinations of voltage and capacity. The effective eletrical output was determined by means of a high-voltage probe, a current coil and a digital oscilloscope. Peak pressures, rise times and pulse width of the shock waves were recorded using a polyvinylidene difluoride needle hydrophone in 0.9% NaCl solution at a distance of 10 mm. The effective electrical output is lower than the calculated output, due to inductivities, capacities and resistances of the cables and plugs. The life of the probes is markedly shorther when a combination of high voltage and low capacity is used than with low voltage and high capacity corresponding to the same energy. The peak pressure and the slope of the shock front depend solely on the voltage, while the pulse width is correlated with the capacity. The pulse intensity integral of the shock wave is likely to be the best equivalent to the applied energy.

Key words: Intracorporeal electrohydraulic lithotripsy – Ultrasonics – Shock wave energy – Endourology – Ureteroscopy

Several lithotripter devices are used in clinical practice to fragment calculi under direct vision. Flexible or semirigid ureteroscopes are now available, which are smaller and less traumatic than the earlier rigid ones. The smaller channel sizes and the flexibility of these endoscopes mean that lithotripsy provided by a pulsed laser or electrohydraulic lithotripsy (EHL) are the only appropriate techniques. In both cases, energy can be transferred through small and flexible probes. Thus, the already well-known technique of EHL is again gaining more importance [2, 6, 11, 16].

The principle of EHL is based on the effect of an electrical discharge causing a spark in a liquid medium, which vaporizes the fluid and creates a rapidly expanding plasma bubble. This generates a hydraulic shock wave, which can fragment solid objects in its path. In this regard EHL is very similar to lasertripsy, which also creates a shock wave by inducing a plasma bubble.

The energy for any electrical discharge depends on the voltage and the capacity applied. This study was performed to evaluate the impact of different voltages and capacities on the electrical and acoustic output and also on the shape and pressure profile of the shock wave generated.

Materials and methods

Electrical discharge was provided by a variable insulating transformer and three different capacitors of 50, 100 and 270 nF, which were connected in parallel. Voltages of between 1 and 6 kV and capacities between 50 and 420 nF were possible. Electrical discharge was initiated using a trigger transformer and a spark gap. A 3.3-F EHL probe (Richard Wolf Knittlingen, FRG) was connected to the generator with a standard contact cable 1 m long (Richard Wolf). The probe is made of two tiny parallel copper wires. These electrodes end at the tip of the probe embedded in insulating material in a metal case, which prevents the electrodes from separating during discharge (Fig. 4).

In a first trial, the electrical end-of-cable energy was evaluated using a current coil and a high-voltage probe. The electrodes of the EHL probe were partially separated, and one of them was led through the current coil. A LeCroy 9400 Dual 125 MHz digital oscilloscope was employed to display the current intensity and the voltage. For single-shot waveform recordings, the LeCroy digitizer has a maximum sampling rate of 100 Msample/s (giving a minimum sampling interval of 10 ns). The intensity of current was used for triggering. The end-of-cable energy reaching the probe was computed by the oscilloscope to the equations:

$$P = U\,I\,[W] \quad \text{and} \quad E = \int P\,dt = \int UI\,dt\,[Ws].$$

In a second trial, the resulting shock waves were recorded. For this a shielded polyvinylidene difluoride (PVDF) needle hydrophone (Imotec, Karlsruhe, FRG) was used, which has a 0.5-mm-diameter sensitive element at it's tip. The voltage waveform from the hydrophone was displayed on the oscilloscope. The hydrophone cable (194 cm) was directly connected to the oscilloscope, whose input has a capacity of 50 pF and was set at a resistance of 50 Ω. The sensitivity of the hydrophone was 425.85 µV/bar. This represents

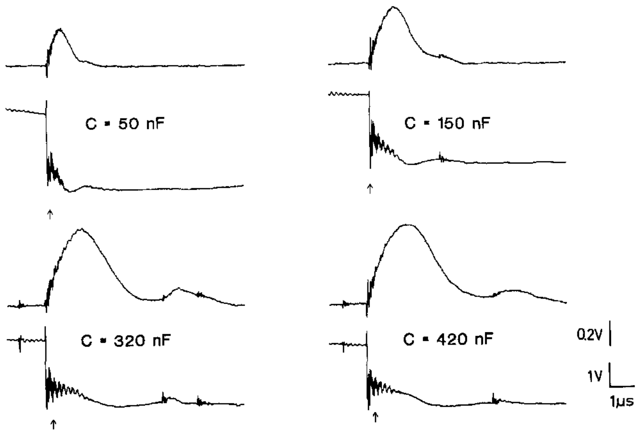

Fig. 1. Oscillographic traces of current and voltage drop representing the electrical end-of-cable energy during discharge, using the same voltage (3 kV) but increasing capacities

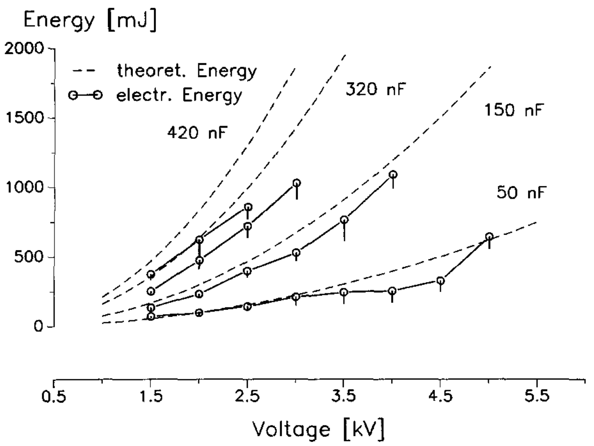

Fig. 2. The actually measured electrical end-of-cable energies of four different capacities plotted against the theoretic energies *(dotted lines)*

the end-of-cable sensitivity of the hydrophone with an electrical loading correction applied to account for its own capacity (213 pF) and the input capacity of the oscilloscope (50 pF). It was calibrated in degassed, deionized water at 20°C, using frequencies between 0.19 and 4.26 MHz at the Institut für Höchstfrequenztechnik und Elektronik, University of Karlsruhe, Germany.

Both the probe and the hydrophone were immersed in a tank filled with a 0.9% NaCl solution at 20°C. The sensitive element of the hydrophone was positioned exactly in the longitudinal axis at a distance of 10 mm from the tip of the EHL probe, using a micromanipulator for all three dimensions.

The durability and the reproducibility of measurements performed with different probes were evaluated. For this purpose, ten probes were tested with two different parameters of energy. Five probes each were fired at 4.5 kV/50 nF and at 2.6 kV/150 nF.

According to the equation $E = \frac{1}{2} CU^2$, this is equivalent to 507 mJ for both constellations. Values were recorded five times every fifth discharge, up to the point when either the results showed a significant decrease in peak pressure, the wave form became noticeably different, and/or damage to the probe could be seen.

The impact of voltage and capacity on the pattern of the shock wave generated was evaluated using ten probes, each fired 75 times at the most, according to the results of the above tests. The maximum energy applied per shot did not exceed 1300 mJ. This was the limit given by the manufacturer of the probes for their stress resistance. The voltage applied ranged from 1.5 kV up to a maximum of 5.8 kV. The minimal capacity was 50 nF and the maximal capacity, 420 nF. Each energy setting was tested with each probe at least 15 times alternately, to rule out any burn-down effect of the probe.

Peak pressure, rise time of the shock front and pulse width were recorded (Fig. 3). Peak pressure was said to be equivalent to the maximum voltage level obtained from the voltage curve rising from the zero line. Rise time was defined as the time needed for the voltage curve to reach 90% of its maximum pressure value, starting from the 10% value. The slope of the shock front (S) is according to the differential of pressure (Δ p) to rise time (Δ t)

$$S = \frac{\Delta p\,[\mathrm{bar}]}{\Delta t\,[\mathrm{ns}]}$$

It can be given in degrees assuming a triangle according to the equation

$$S\,[\mathrm{deg}] = \arctan\left(\frac{\Delta p\,[\mathrm{mV}]}{\Delta t\,[\mathrm{s}]}\right) \cdot \frac{180}{\pi}$$

The pulse width was determined as the time interval between the point at which the shock wave first reaches 50% of it's maximum level and the point at which the descending curve first reaches this value again. The integral of the voltage curve or the pulse intensity integral was determined as the integral over the area under the pulse width. The integral was computed by the digitizer.

Statistical evaluation was performed using bi-variance and one-way-variance analysis and Scheffe's test.

Results

The energy [E] for a spark discharge provided by different ratios of voltage [U] to capacity [C] has to be calculated according to the equation $E = \frac{1}{2} CU^2$. Figure 1 shows the actual end-of-cable currents and the voltage drop with a setting of a constant voltage but various capacities. The voltage drop occurs at the moment of spark generation, and the increased capacities lead to broader current curves in keeping with a longer duration of the spark, because current can only flow as long as the spark bridges the two electrodes. Up to 1500 mJ the theoretical energies for four different capacitors are shown in Fig. 2 by the dotted lines. The electrical end-of-cable energies actuallly measured are plotted against the calculated energies. A reasonable loss of energy is obvious. This is probably due to so called parasitic inductivities, capacities and resistances of the cables and plugs between the generator and the probe. Another plausible explanation is incomplete capacitor loading and/or discharging, which accounts mostly for the inconstant reproducibility of the applied energy. The variation coefficient of the end-of-cable values actually measured at the same energy setting was 10%.

The durability of the probes was measured at voltage and capacity settings that result in an equal energy value of 507 mJ by calculation. All the probes lasted at least 100 shots. Thereafter, the peak pressure was significantly reduced and the shape of the pulses became irregular. With lower voltage and corresponding higher capacity, however, the durability was markedly longer, i.e. up to 200 shots. This might be because higher voltages result in higher peak pressures, as shown below. The small copper

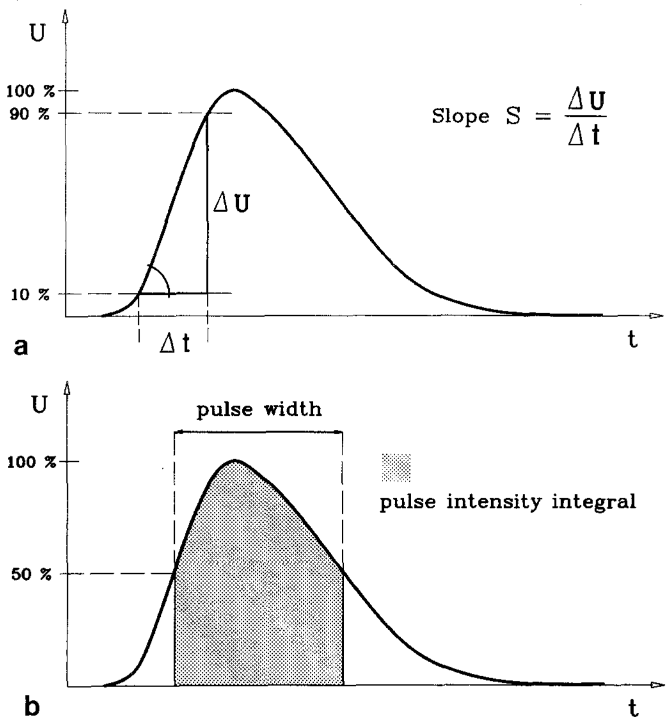

Fig. 3 a, b. Sketches of a pressure curve and the measured features: *a* peak pressure (P = 100%), rise time (Δ t), and *b* pulse width and pulse intensity integral

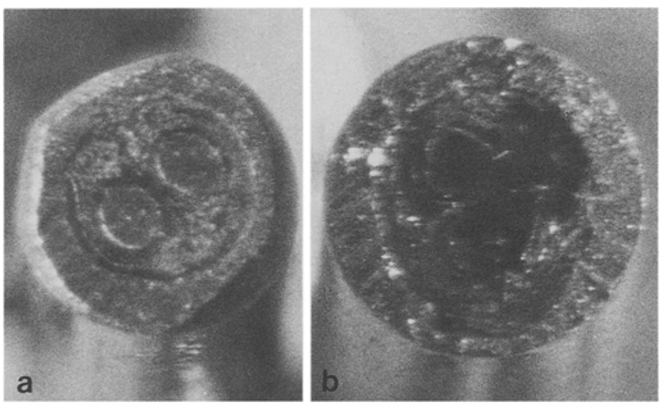

Fig. 4. a, b. Tip of the electrohydraulic probe *a* before and *b* after 100 discharges; the copper wires are burned down and remnants of the insulating material are lying in the wave path

wires were burned down and retracted in some cases. Remnants of the insulating material between the small electrodes stayed in the wave path (Fig. 4). These remnants are likely to be responsible for the pressure decrease and the irregular shape of the pulses that we noted when the probes were used to the extent mentioned. With the exception of a slight increase in peak pressure over the first 30 shots, no other tendency was noticeable. There was no significant variance between different probes (P=0.01). But, as stated before, there was a variance of the measured shock wave parameters of the same probe, which is not a property of the probe but a consequence of the inconstant energy supply.

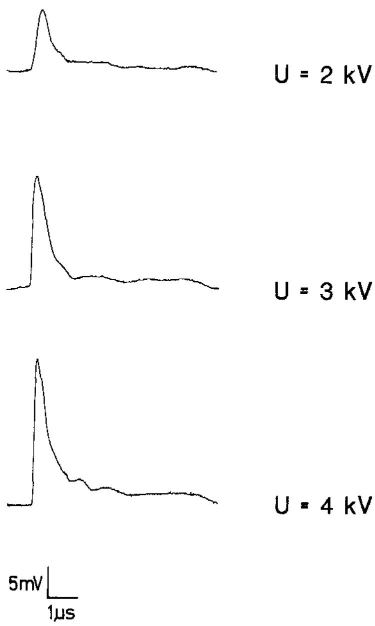

Fig. 5. Pressure curves obtained with the same capacity (50 nF) but increased voltages

To generate a spark under water the voltage applied must be sufficient to overcome the resistance between the electrodes at the probe tip. This resistance is dependent on the gap between the electrodes and the specific resistance of the fluid, in this case 0.9% salt solution. Different concentrations of NaCl solution have no impact on the shape and pressure profile of the shock waves (unpublished data). In principle, the same features are specific for the spark gap switch used in the device to trigger the discharge. The lowest voltage necessary to create a spark under these circumstances was 1.5 kV. A voltage setting of over 6 kV induced an uncontrollable repeated discharge.

In general, it has to be stated that the peak pressure and the slope of the shock front are strictly a function of the voltage (P=0.005). If the voltage was increased using the same capacity then a higher peak pressure and a steeper shock front resulted (Fig. 5).

The relation of voltage and capacity to the peak pressure and the steepness of the shock front is shown in Fig. 6. It is obvious that a wide range of peak pressures can be obtained with different voltages. Since the slope of the shock front is an exponential function of the voltage, the most intensive increase of steepness is between 1.5 and 3.0 kV. When more energy was supplied by a higher capacity, the creation of a broader shock pulse was the only result, correspoding to a greater pulse width of the shock wave. Figure 7 shows several pulses with increased capacities but the same voltage.

A possible way of estimating the energy transferred by each shock wave is to evaluate the area under the pressure curve. This so-called impulse or pulse intensity integral was calculated in the way described. In Fig. 8 the intensity integrals of the shock waves at different voltages and capacities are plotted against the calculated energy. The similarity of these values to the trends of the calculated or

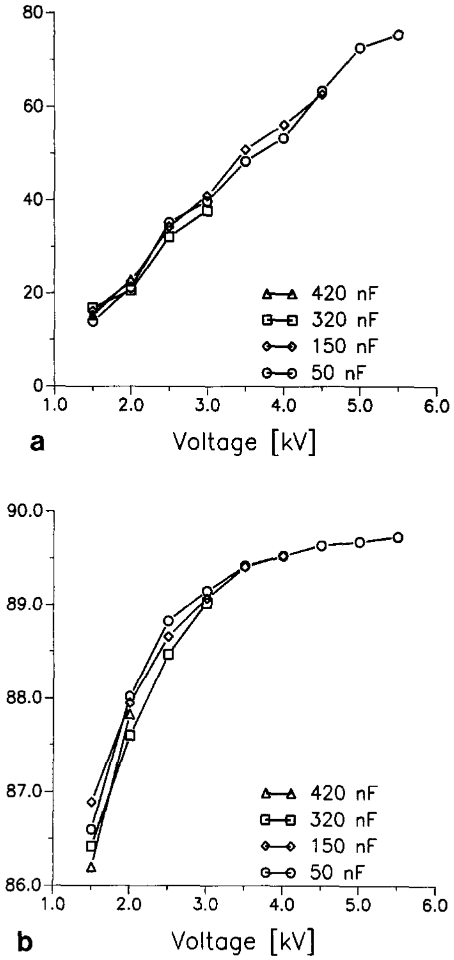

Fig. 6 a, b. Relation of **a** peak pressure [bar] and **b** [deg] of the shock front to voltage using four different capacities

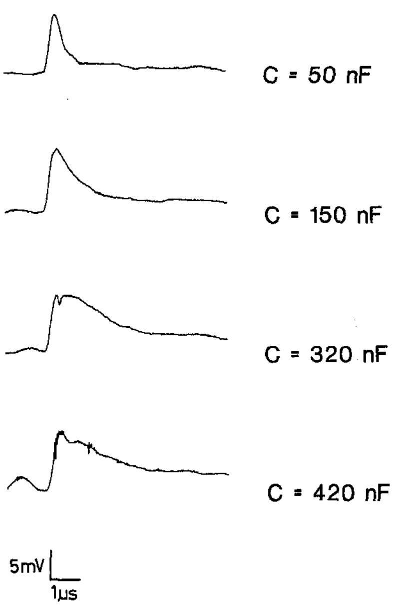

Fig. 7. Pressure curves obtained with the same voltage (2 kV) but increased capacity

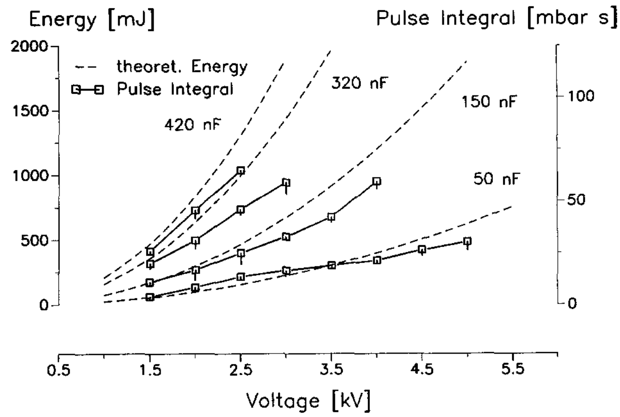

Fig. 8. The pulse intensity integrals of four different capacities plotted against the theoretic energies *(dotted lines)*

the electrical end-of-cable energies shown in Fig. 2 is striking, thus indicating that the pulse intensity integral is the best equivalent to the applied energy transferred by the different types of shock waves.

Discussion

The actual electrical end-of-cable energy measured for electrohydraulic lithotripsy is less than that calculated from different ratios of voltage to capacity. In this regard the specified values of energy per discharge given by different manufacturers of EHL devices should be critically reviewed. Inductivities, capacities and resistances of contact cables, plugs and probes from various manufacturers affect the end-of-cable energy of the equipment and are likely to be different. Therefore, it does not make sense to compare different lithotripters with reference to their ability to destroy stones if the comparison is based simply on the specified energy.

As we were able to show, a higher capacity leads to current of longer duration, which means that the spark is also of longer duration. There is good reason to suppose that the plasma bubble induced by the spark also has a longer existence, whilst the velocity in creation of the bubble is not influenced. This correlates with the pressure profiles of the corresponding pulses, which just show an increased pulse width if only a higher capacity is applied.

All available devices for *extra*corporeal electrohydraulic lithotripsy provide energy with various voltages but a fixed capacity. Thus, the resulting shock waves differ in the peak pressure [3]. In contrast, most electrohydraulic devices for *intra*corporeal lithotripsy have a fixed voltage level and the option of a higher capacitor to increase the energy per shot. Hence, the peak pressure of the shock wave created is always the same and the resulting pulse is merely broader [12].

Although EHL is commonly used to destroy bladder stones [1, 4, 9], its use in the narrow ureteral lumen has often been reported to be associated with a considerable rate of complications, such as ureteral perforations and resulting strictures [5, 7, 8, 10, 14, 15]. The lack of these is said to be a special advantage of the laser [15].

On the other hand, it is obvious that the traumatic potential of any shock wave depends mainly on its energy. The previously cited results of traumatic endoureteral EHL were obtained without endoscopic control and with energy of over 1500 mJ per discharge, which is nearly ten times the maximum energy per pulse provided by the laser.

As shown by the results of this study EHL can provide a wide range of energy to be applied per shot. But most of the commercially available lithotripters still permit none or very few modifications of the energy per single discharge, especially for use in the narrow ureter [12]. Once the energy of the single electrohydraulic discharge is reduced to a level of under 300 mJ its traumatic potential is also reduced. This was proven by the clinical use of several prototypes designed on the basis of our results [13].

On the other hand, the energy transferred by the electrohydraulic shock wave can be increased if the hardness of the stone or its mass requires a more powerful impact per shot. Regarding this option, EHL might be superior to laser lithotripsy, which can provide only a limited energy per pulse due to the confined ability of the fiber to transfer the energy.

It should be pointed out that measuring the shock wave at a distance of 10 mm merely provides general information on the pressure profile, since the actual values of pressure and energy are much higher at the point of action. In the clinical situation the EHL probe is used in direct contact with the stone. We were able to show that the peak pressure of the shock wave decreases in an exponential way with increasing distance between stone and probe tip (unpublished data), whereas shape and pressure profile may be quite different with a distance of 1 mm or less. To avoid damage of the hydrophone when high energies are used, however, there has to be at least some safety margin in the distance to the probe tip. This is a general problem in measuring and characterizing shock waves and cannot be definitely excluded.

The aforementioned results further indicate that the well-known technique of EHL can be used to generate a wide range of patterns of shock waves. It remains to be seen whether a different type of shock wave transferring the same energy has a different impact on various stones or on tissue. The trial in which several probes were fired at the same energy level but with different ratios of voltage to capacity may give a hint. The earlier breakdown of the probes firing with a higher voltage and a corresponding lower capacity indicates that a higher peak pressure created by the voltage means more stress on the probes' tip. Assuming that a steeper shock front is more likely to be able to break up harder stones, it should be taken into account that the most intense increase in the slope of the shock front occurs between 1.5 and 3 kV.

At the moment further studies are in progress, including defined tissue tests and various stone models. Considering the relatively low costs of EHL and its implications, the investment of further effort in the development of this technique should be worthwhile.

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