TANDEM SHOCK WAVES FOR EXTRACORPOREAL SHOCK WAVE LITHOTRIPSY

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ABSTRACT

Extracorporeal shock wave lithotripsy (SWL) has become the standard treatment for patients with renal calculi; however, shock waves are not innocuous when focused on the kidney. This paper reports the design of a novel piezoelectric tandem shock wave generator for SWL. The system generates two shock waves with an adjustable time delay (50 - 950 μsec) to enhance cavitation–induced damage to the kidney stone, without increasing tissue trauma. Pressure measurements and fragmentation tests with standardized kidney stone models were compared to that of a conventional generator. Results using tandem shock waves show enhanced stone comminution.

INTRODUCTION

Disintegration of urinary calculi is possible by extracorporeally induced shock waves. Hundreds of focused shock waves penetrate the body disintegrating the concrements into small enough particles to pass spontaneously through the urinary tract. This technique, known as extracorporeal shock wave lithotripsy (SWL) has been successful for more than twenty years,[1-5] nevertheless, basic research is still necessary to define SWL techniques that minimize tissue damage while improving treatment efficacy. Pancreatic, gallbladder and salivary stones have also been treated with ESWL.[2,4] The objective of our study is to propose improvements to SWL devices (extracorporeal lithotripters) in order to enhance stone comminution without increasing tissue trauma.

Lithotripsy shock waves consist of a nonlinear high pressure impulse (up to 150 MPa) with a rapid rise (less than 10 ns) forming the shock front, followed by a "negative" phase of up to about –20 MPa. They have a wide spectrum of frequencies ranging from a few hundred kHz to a few hundred MHz. Due to their nonlinear acoustic behavior, high-pressure impulses may become shock waves on transmission. Their velocity in water and tissue is about 5% faster than sound waves.

So far, three main shock wave generation principles have been developed for medical applications: electrohydraulic, piezoelectric and electromagnetic.[3-5] For this study, only piezoelectric shock wave generation was used. Piezoelectric lithotripters produce shock waves by a fast DC high voltage (5 - 10 kV) discharge through a set of about 3000 piezoelectric crystals. The crystals change their external dimensions because of the electric discharge, producing a compression wave in water. Tensile or "negative" pressure results fom the return of the crystals to their original shape. Focusing of the energy is obtained by spherical alignment of the piezoelectric crystals. This is necessary to achieve maximum energy at a small volume, ensuing minimal tissue damage. Shock wave coupling is achieved by a water cushion together with coupling ultrasound gel (Fig. 1). Water is degassed to remove dissolved air and microscopic bubbles which absorb shock wave energy due to acoustic mismatch. To localize the stone, X-ray or ultrasound imaging systems are used. Details on piezoelectric lithotripters are given elsewhere.[2-5]

Kidney stones fracture mainly due to cavitation, internal crystalline-matrix layer separation, and spalling around the stone.[6-8] A cloud of cavitation bubbles is generated in the vecinity of the focus *F* by the tensile phase following the positive peak of each shock wave. It also may appear by reflection of the shock wave at the concretion. These bubbles expand in about 50 - 100 µs, stabilize for 200 – 500 µs, and finally collapse, creating stone-damaging high energy secondary shock waves and high velocity (up to 300 m/s) microjets of fluid.[9-13] The larger the bubbles grow, the more violent their collapse will be. Several authors have shown that if a second shock wave is sent during or shortly after the stable phase of these bubbles, their collapse can be intensified, enhancing stone damage significantly. So far this has been tested using either two electrohydraulic shock wave generators facing each other or using composite reflectors for electrohydraulic lithotripters;[14-21] however, retrofitting a second shock wave generator or composite reflectors on an electrohydraulic lithotripter may be complicated or expensive.

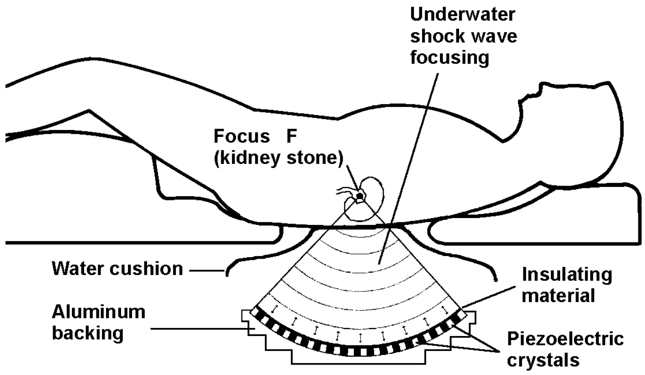


Fig. 1. Schematic diagram of piezoelectric shock wave generation and focusing for extracorporeal kidney stone disintegration

We designed and tested a novel piezoelectric tandem shock wave generator capable of producing two shock waves at an adjustable delay between 50 and 950 µs. An important feature of this highly versatile system is the possibility of varying the amplitude of each shock wave independently as well as changing the phase. Inverted pressure waveforms that start with a tensile pulse followed by a compressive one, can be generated independently, switching the system to "inverse mode." Pressure measurements and standardized kidney stone model disintegration tests obtained with the tandem system at different settings were compared with that of the conventional lithotripsy system.

MATERIAL AND METHODS

The electric circuit of a *Piezolith 2300* (Wolf GmbH, Knittlingen, Germany) lithotripter was modified. Conventional piezoelectric shock wave generators (Fig. 2) only have one capacitor charging system and one spark gap (SG). Figure 3 shows the tandem system, consisting of two independent high voltage power supplies charging two 0.5 µF capacitors (C1 and C2). Both capacitors remain charged until their spark gap (SG1 or SG2) is fired. This is achieved sending a

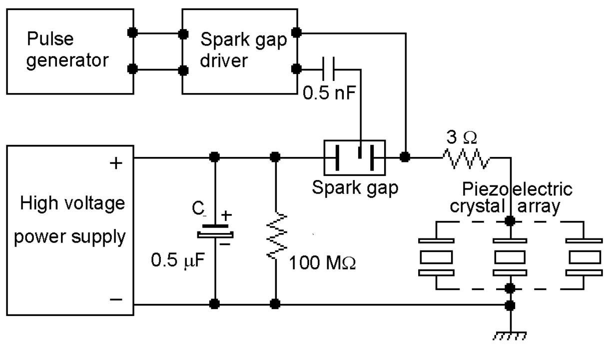


Fig. 2. Simplified diagram of the conventional piezoelectric generator.

12 kV low current pulse to fire the trigger electrode (TE1 or TE2) of each spark gap, inducing electric breakdown between main electrodes and discharging either C1 or C2 through the piezoelectric array.

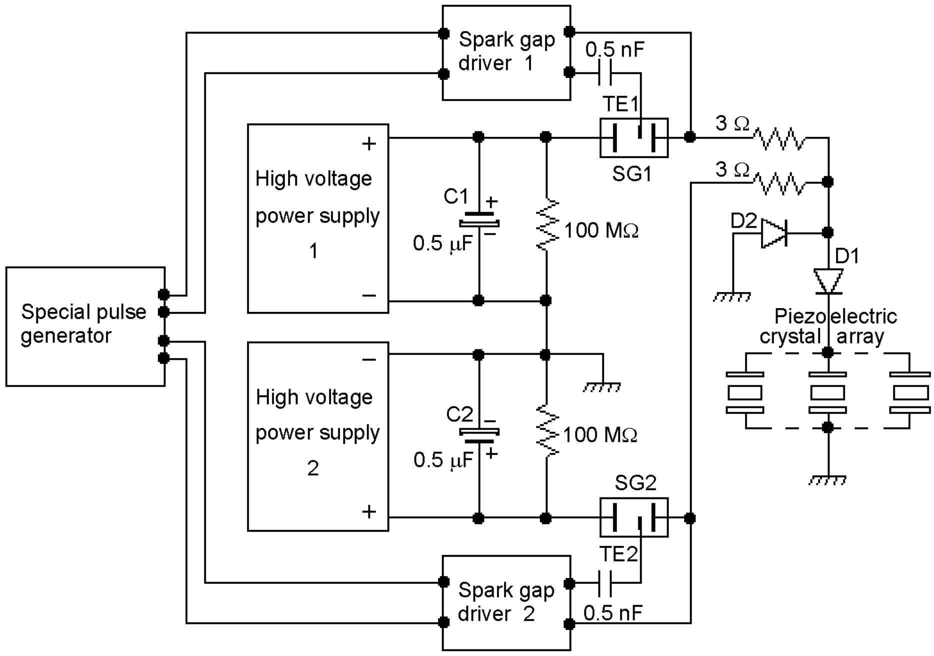
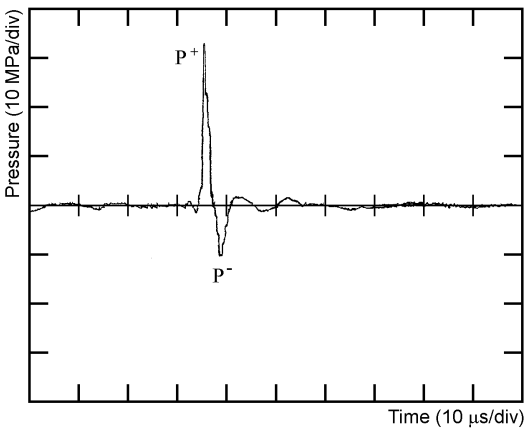


Fig. 3. The novel tandem shock wave generator

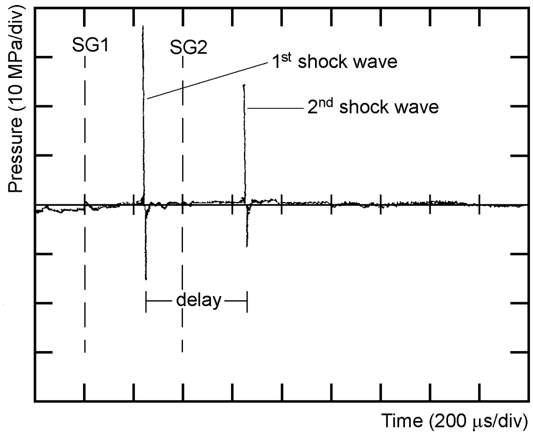
The tandem circuit may be operated in manual or repetition mode. Repetition mode offers either conventional or tandem shock wave generation at an adjustable time delay between 50 and 950 μs. Conventional lithotripter pulses, followed by phase inverted pulses, or vice versa, may be selected (Fig. 4). Either two conventional or two inverted shock waves can be generated at the desired delay. Since for experimental purposes the complete lithotripter was not needed, only the shock wave generator was mounted on a bench and a cylindrical 45 cm high Lucite water tank placed on top of it. An X-Y-Z positioner was used to fasten the pressure gauge or a kidney stone model at the focus *F*.

Pressure waveforms were registered at *F* with polyvinylidene difluoride (PVDF) needle hydrophones (Imotec GmbH, Würselen, Germany) and fed into a digital oscilloscope (Tektronix, Inc., Beaverton, OR, USA, model 2430A). Water temperature, water level and discharge voltage were set to 25 °C, 44 cm and 7.5 kV, respectively. Ten pressure waveforms were obtained with the conventional single pulse system and ten records were registered at each time delay with the dual-phase system. All pressure measurements were done using the manual mode.

Three standardized (30 x 30 x 14.3 ± 0.1 mm) rectangular kidney stone models (High Medical Technologies, Kreuzlingen, Switzerland) were exposed, one by one, to 600 shock waves at each delay, centering them horizontally at the focus *F* of the piezoelectric array. The fragmentation efficiency coefficient, defined as $F = 100(W_i - W_f)/W_i$ was obtained selecting 17 different delays. W_i and W_f are the average initial and the average final (shock wave-exposed) model weights. Models were saturated in water for 10 minutes before shock wave application.

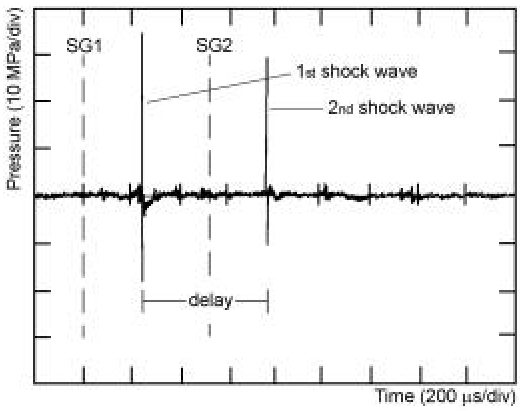


(a)



(b)

Fig. 4. Pressure waveform obtained at the focus of a) the conventional, and b) and c) the novel tandem shock wave generator at a delay of 400 and 500 μs, respectively. SG1 and SG2 correspond to the instant when the first and second spark gap was fired.



(c)

RESULTS

Average amplitudes of the positive and negative peak obtained with the conventional single shock wave system were about 38 and –18 MPa respectively. No statistically significant difference ($p \leq 0.01$) was obtained between these values and the amplitudes of the first shock wave when using tandem shock wave generation at any delay. The amplitudes of the positive and negative pressure peaks of the second shock wave (about 32 and –15 MPa) were always significantly lower ($p \leq 0.01$) than those corresponding to the first shock wave. Figure 4a shows a typical lithotripter shock wave obtained at *F* with the conventional system. Figure 4b and c correspond to tandem shock waves generated at a delay of 400 and 500 μs, respectively. For simplicity, the spark gap discharge signals seen on the screen of the oscilloscope are indicated only as vertical dotted lines. All shock waves reached the hydrophone approximately 230 μs after the spark gaps were fired. This time corresponds to a shock wave velocity of about 1500 m/s.

Fragmentation efficiency is shown in Figure 5. Increased efficiency was obtained at a delay of 350 μs. This is about 23% higher than the efficiency observed for the double number (1200) of conventional single lithotripter pulses.

DISCUSSION

Our results show that tandem shock wave generation at a delay of 350 μs increases stone phantom disintegration efficiency. We believe this to be due to enhanced cavitation. A 350 μs delay is in accordance with bubble collapse times reported by other authors.[22] No statistically significant difference was obtained for the disintegration efficiency at 350, 400, and 450 µs. At these delays the second positive pressure wave seems to accelerate bubble collapse, intensifying damage to the stone phantoms. If the second positive peak arrives after bubble collapse, no additional damage is produced to the models. At delays between 100 and 250 µs the second shock wave apparently arrives during the growing phase of the bubbles generated by the first shock wave. Because of this, bubbles collapse before reaching their maximum size and damage is reduced, being even lower than using the conventional system.

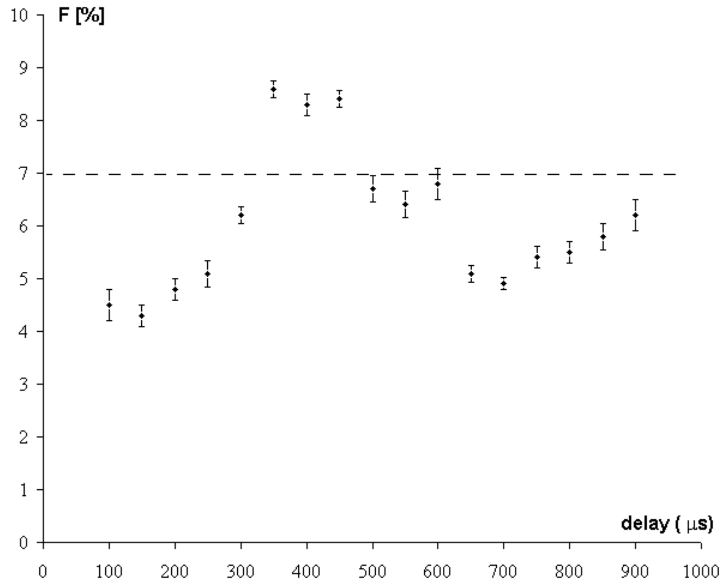


Fig. 5. Fragmentation efficiency of rectangular kidney stone models exposed to 600 tandem shock waves generated at 7.5 kV. The dotted line corresponds to the fragmentation efficiency obtained with 1200 single (conventional) shock waves.

We suppose that since the bubble cloud produced by the passage of the first shock wave is still present as the second shock wave arrives, the second positive and negative pressure amplitude is always smaller than the first.

More experiments using different kidney stone models as well as *in vivo* models will be helpful to decide whether tandem shock wave generation should be used for SWL. Due to its versatility, the tandem shock wave generator described here could also be very useful as a research device to increase knowledge of stone fragmentation mechanisms. Since shock wave cytotoxicity is related to cavitation, this system could also be used for research in oncology, shock wave mediated macromolecule delivery,[23] and during exposure of isolated microorganisms to shock waves.[24]

A concern about tandem shock waves for SWL could be cavitation-induced tissue damage; however, other authors have shown that bubble collapse *in vivo* is less violent than in water, because bubble expansion is constrained by the tissue.[25] In contrast to other tandem shock wave systems that have been proposed, our circuit could be installed in clinical piezoelectric lithotripters at relatively low cost.

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