INNOVATIONS IN SHOCK WAVE LITHOTRIPSY TECHNOLOGY: UPDATES IN EXPERIMENTAL STUDIES

YUFENG ZHOU, FRANKLIN H. COCKS, GLENN M. PREMINGER AND PEI ZHONG*

From the Department of Mechanical Engineering and Materials Science (YZ, FHC, PZ), and Duke Comprehensive Kidney Stone Center, Division of Urology (GMP, PZ), Duke University, Durham, North Carolina

ABSTRACT

Purpose: We developed innovations in shock wave lithotripsy (SWL) technology.

Materials and Methods: Two technical upgrades were implemented in an original unmodified HM-3 lithotripter (Dornier Medical Systems, Inc., Kennesaw, Georgia). First, a single unit ellipsoidal reflector insert was used to modify the profile of lithotripter shock wave (LSW) to decrease the propensity of tissue injury in SWL. Second, a piezoelectric annular array (PEAA) generator (f = 230 kHz and F = 150 mm) was used to produce an auxiliary shock wave of approximately 13 MPa in peak pressure (at 4 kV output voltage) to intensify the collapse of LSW induced bubbles near the target stone for improved comminution efficiency.

Results: Consistent rupture of a vessel phantom made of single cellulose hollow fiber (i.d. = 0.2 mm) was produced after 30 shocks by the original HM-3 reflector at 20 kV. In comparison no vessel rupture could be produced after 200 shocks using the upgraded reflector at 22 kV or the PEAA generator at 4 kV. Using cylindrical BegoStone phantoms (Bego USA, Smithfield, Rhode Island) stone comminution efficiencies (mean ± sd) after 1,500 shocks produced by the original and upgraded HM-3 reflectors, and the combined PEAA/upgraded HM-3 system, were 81.3% ± 3.5%, 90.1% ± 4.3% and 95.2% ± 3.3%, respectively (p < 0.05).

Conclusions: Optimization of the pulse profile and sequence of LSW can significantly improve stone comminution while simultaneously decreasing the propensity of tissue injury during in vitro SWL. This novel concept and associated technologies may be used to upgrade other existing lithotriptors and to design new shock wave lithotriptors for improved performance and safety.

Key Words: lithotripsy, ultrasonics, calculi, soft tissue injuries

In the last 2 decades shock wave lithotripsy (SWL) technology has evolved significantly in terms of the means of shock wave generation, focusing, patient coupling and stone localization. However, the fundamental principle of SWL remains unchanged. Independent of the technologies used almost all commercial lithotriptors produce a similar pressure waveform at the focus which can be characterized by a leading shock front with a compressive wave followed by a trailing tensile wave. The acoustic fields produced by different lithotriptors differ only in terms of peak amplitudes of the pressure waveform, pulse duration, beam size, total acoustic energy and, therefore, overall performance. To a large extent technical improvements in the second and third generation lithotriptors were made based on empirical experience to provide user convenience and device multifunctionality rather than a mechanistic understanding of stone comminution and tissue injury in SWL. Furthermore, the evolution of lithotripter design thus far has overwhelmingly, and perhaps mistakenly, relied on the importance of the compressive wave component of the shock wave with almost total neglect of the contribution of the tensile component of the waveform.

In contrast, significant progress in the basic research of SWL has been made in the last 5 years to improve our understanding of the primary mechanisms of stone comminution and tissue injury in SWL. It is now recognized that the disintegration of renal calculi in a lithotripter field is the consequence of dynamic and synergistic interaction of 2 fundamental mechanisms: stress wave induced dynamic fracture in the form of nucleation, growth and coalescence of preexisting micro-cracks inside the stone, and cavitation erosion caused by the violent collapse of bubbles near the stone surface. Similarly, 2 different mechanisms have been proposed for SWL induced tissue injury: shear stress due to shock front distortion and cavitation induced inside blood vessels, especially the expansion of intraluminal bubbles. Based on these improved understandings various strategies have been proposed to improve the effectiveness and safety of SWL. A secondary pulse that can be produced by either a piezoelectric annular array (PEAA) generator or a second electrohydraulic shock wave generator has been used to intensify the collapse of cavitation bubbles near a stone surface for improved comminution efficiency. Moreover, modification of the lithotripter shock wave (LSW) pulse profile to suppress intraluminal bubble expansion has been proposed to decrease the propensity of vascular injury in SWL. However, all these previous studies were either performed in research lithotriptors or, when used individually, they could not improve stone comminution while simultaneously decreasing tissue injury in SWL.

Therefore, in this study we developed innovative SWL technologies that can be upgraded on a Dornier HM-3 lithotripter, the current gold standard in clinical SWL. Specifically a new PEAA generator that is completely compatible with an HM-3 lithotripter and a single unit reflector insert to suppress intraluminal bubble expansion were designed and fabricated. Using phantom systems we have demonstrated in vitro that the performance and safety of the HM-3 lithotripter can be significantly improved by these technical upgrades.
MATERIALS AND METHODS

Lithotriptor and technical upgrades. The basic experimental system used in this study was an unmodified Dornier HM-3 lithotriptor (80 nF capacitor with a truncated brass elliptoidal reflector of semimajor axis a = 138 mm, semiminor axis b = 77.5 mm and half-focal length c = 114 mm). Two technical upgrades were implemented on the HM-3 lithotriptor. First, a single unit reflector insert that has the same geometry as the 8-segment reflector insert we developed previously,12 was fabricated and retrofitted inside the original HM-3 reflector (fig. 1). The inner surface of the new reflector insert fits on an ellipsoidal surface with a’ = 132.5 mm, b’ = 71.5 mm and c’ = 111.5 mm, and the lower edge of the reflector insert was 4 mm higher than the focal plane at F1. Second, a new PEAA generator consisting of 6 spherically concaved segment transducers made of 1–3 piezocomposite material (IMA022, IMASONIC, Besançon, France) was fabricated. The new PEAA generator has a central resonant frequency of 230 kHz, a focal length of 150 mm and was driven by a high voltage pulse generator of local design.13 The 6-segment transducers were mounted axis-symmetrically on a carrier surrounding the outer surface of the HM-3 reflector (fig. 1). Together these technical upgrades were intended to improve the performance and safety of the HM-3 lithotriptor, ie the reflector insert is used to modify the profile of the lithotriptor pressure waveform to minimize tissue injury, while the PEAA generator can be used in tandem with the HM-3 lithotriptor to intensify cavitation activity at the stone surface for improved treatment efficiency.

System integration. To determine the optimal time delay to trigger the PEAA generator after each spark discharge from the HM-3 lithotriptor a pair of 2.25 MHz focused transducers (V395-SU, Panametrics, Waltham, Massachusetts) with a focal length of 150 mm and a nominal element size of 35 mm were also installed on the PEAA transducer carrier (fig. 1, B) to serve as passive cavitation detectors (PCD). The dual PCD transducers which are aligned at 82.6 degrees from each other, can be used together to determine cavitation activity in a confined volume around the lithotriptor focus, such as the collapse time (tC) of cavitation bubbles induced by the LSW.14 Using the Field II package, the axial and lateral resolution of the dual PCD system were determined to be 5.2 and 4.4 mm, respectively.13 Previous studies have shown that significant improvement in stone fragmentation can be achieved when the PEAA pulse impinges on the LSW induced cavitation bubbles during their primary collapse.9 To streamline the operation of the PEAA generator, a computer program written and run in LabVIEW 5.0 (National Instruments, Austin, Texas, fig. 2) was used to determine automatically the inter-pulse delay between the PEAA generator and the HM-3 lithotriptor. After each spark discharge the dual PCD system was used to detect the acoustic emission (AE) signals associated with LSW induced cavitation bubbles around F2. After amplification and band-pass filtering in a Pulser/Receiver (PR5052, Panametrics, Waltham, Massachusetts), the AE signals were registered on

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Fig. 1. A, schematic diagram and B, photograph of HM-3 lithotriptor upgraded with single unit reflector insert and PEAA generator. PEAA generator consists of 6 spherically concaved segment transducers mounted on spherical carrier aligned coaxially and confocally with HM-3 reflector. Pair of PCD transducers is also mounted on carrier.

Fig. 2. A, operation flow chart and B, graphic user interface of control program written and run in LabVIEW 5.0 on personal computer. This computer program is used to determine collapse time of cavitation bubbles at lithotriptor focus during SWL based on acoustic emission measurements and, subsequently, it sets appropriate interpulse delay between triggers of PEAA generator and HM-3 lithotriptor.
The potential of vascular injury caused by shock waves was evaluated using blood vessel phantoms produced by the HM-3 lithotriptor using either the original or upgraded reflector. At each location at least 4 waveforms were recorded. Pressure waveform measurements. The pressure waveforms produced by the HM-3 lithotriptor and the PEAA generator were measured by using a fiber optic probe hydrophone (FOPH-300, University of Stuttgart, Germany). The hydrophone was attached to a 3-axis translation stage tilted at 14 degrees so that the fiber optic probe was aligned parallel to the lithotriptor axis. To map the acoustic field of the PEAA generator, the hydrophone was scanned at 1 or 2 mm steps, transverse and along the lithotriptor axis, respectively. At each location at least 4 waveforms were recorded.

Performance evaluation. The potential of vascular injury produced by the HM-3 lithotriptor using either the original or the upgraded reflector was evaluated using blood vessel phantoms made of single cellulose hollow fibers of 200 μm inner diameter following our established protocol. Although the cellulose hollow fiber cannot mimic the broad mechanical response of different blood vessels to LSWs, as a phantom material it provides a consistent means to assess the propensity of vessel rupture in SWL in vitro (as a prelude to more complex and expensive animal experiments). The vessel phantom aligned to F2 was immersed in a test chamber filled with freshly poured castor oil while degassed water seeded with ultrasound contrast agents serving as cavitation nuclei was circulated inside the vessel phantom. Shock waves were delivered to the vessel phantom at a pulse repetition rate of 0.1 Hz and the number of shocks needed to cause a rupture within the first 200 shocks was recorded.

Two types of stone phantoms were used to compare stone comminution produced by the original and upgraded HM-3 lithotriptors. One was a spherical phantom (D = 10 mm) made of plaster-of-Paris (Bemis, Crossett, Arkansas) with a powder-to-water mixing ratio of 2:1, which mimics soft struvite stones. The other was a cylindrical phantom (D = 6.8 mm and L = 11.4 mm) made of BegoStone with a powder-to-water mixing ratio of 5:1, which mimics hard calcium oxalate monohydrate stones. The fragmentation tests were performed using our established phantom system that mimics stone comminution in the renal pelvis during SWL. Before shock wave exposure each stone phantom was immersed in water for at least 20 minutes and then placed in a plastic holder with disposable finger cot at the end and aligned to F2 with the aid of the biplanar fluoroscopic imaging system of the HM-3 lithotriptor. After every 100 shocks the positions of the residual stone phantom and fragments in the lithotriptor field were checked fluoroscopically. If necessary repositioning was performed to align the largest fragment to F2. At the end of each experiment all fragments were removed from the holder and air-dried at room temperature for 24 hours. The dry fragments were then filtered through a series of American Society for Testing and Materials standard sieves (No. 5, No. 10, No. 18, No. 35, W. S. Tyler, Mentor, Ohio) with 4, 2, 1 and 0.5 mm grids, respectively. Stone comminution efficiency was determined by the percentage of fragments less than 2 mm that can be discharged spontaneously in urine after clinical SWL therapy. Six samples were used with each test configuration.

RESULTS

Pressure waveforms. The pressure waveforms produced at F2 by the original HM-3 reflector at 20 kV and the upgraded reflector at 22 kV are shown in figure 3. In these measurements tissue mimicking materials were placed along the shock wave propagation path to simulate the attenuation effect of interposing tissues on LSW. Using the original HM-3 reflector at 20 kV, the peak positive pressure of the LSW (mean ± s.d.) was measured to be 31.2 ± 3.0 MPa, which represents a 34% decrease from the corresponding value (47.0 ± 2.6 MPa) measured in water. Using the upgraded reflector at 22 kV, a modified pressure waveform containing 2 distinct compressive peaks with an inter-peak delay of 3.8 μs was measured. The peak positive pressure of the leading LSW and the second compressive wave were found to be 36.0 ± 2.4 and 13.3 ± 2.3 MPa, respectively. The use of a higher output kV for the upgraded reflector compensates for the decrease in effective reflecting surface of the LSW when the reflector insert is used.

The typical pressure waveform produced in water at the beam focus of the PEAA generator operating at 4 kV is shown in figure 4, A, which contains essentially 2 pressure pulses separated from each other by about 6 μs. The first pressure pulse has a leading tensile wave with a peak negative pressure of −6.1 MPa and a tensile pulse duration of 2.0 μs, which is followed by a stronger compressive wave of 13.2 MPa in peak positive pressure, 330 ns in rise time and 1.3 μs in compressive pulse duration. The second pressure pulse, generated by the back surface of the transducer during high voltage pulse excitation, has a reversed pulse polarity and smaller peak pressure amplitudes compared to the first pulse. The maximum peak positive and peak negative pressures produced by the PEAA generator are linearly related to the output voltage of the PEAA generator within the approximate range of 3 to 5 kV (fig. 4, B). In these experiments the output voltage of the PEAA generator was set at 4 kV to ensure a secondary shock wave strong enough for in vivo applications while minimizing the risk of transducer damage.

The −6 dB beam width of the PEAA generator in the lateral directions was determined to be 3.5 (from left to right) and 2.1 mm (from head to foot), respectively (fig. 5, A). This
asymmetric distribution is caused by the absence of PEAA transducers on the lateral side of the HM-3 reflector to accommodate the dual PCD transducers and a pair of air balloons for fluoroscopic imaging (fig. 1, B). Along the axial direction, the depth of the focus of the PEAA generator is about 19 mm (fig. 5, B), which is much smaller than the corresponding values for the original and upgraded HM-3 reflectors. \(^{11}\) Therefore, the new PEAA generator can be used to produce forced and intensified collapse of cavitation bubbles near the target stone while avoiding potential tissue injury in the interposing tissues due to its small overlap in acoustic field with the HM-3 lithotripter.

**Cavitation activity.** Figure 6 shows the representative AE signals associated with cavitation bubbles induced at \(F_2\) by the PEAA generator, the upgraded HM-3 reflector in free field, and near a stone phantom. Each AE signal contains a characteristic double burst structure, with the first burst (1°) corresponding to the initial compression and expansion of cavitation nuclei by the incident shock wave and the second burst (2°) corresponding to the subsequent primary collapse of the bubbles. \(^{16}\) Previous studies have shown that the \(t_C\) of the bubble cluster, defined by the time delay between the 2 pressure bursts, correlates with the maximum bubble expansion. \(^{16}\) For the PEAA generator at 4 kV the values of \(t_C\) in free field and near a stone phantom were found to be 63.3 ± 4.7 and 67.0 ± 6.8 \(\mu\)s, respectively, which are not statistically different from each other (\(p > 0.05\)). However, for the upgraded reflector at 22 kV, the values of \(t_C\) (631 ± 36 \(\mu\)s) for bubbles induced near a stone phantom were found to be almost 2.5 times of that in free field (253 ± 20 \(\mu\)s). These results suggest that wave reflection from a stone surface could significantly influence the duration of the bubble activity depending on the pressure waveform and amplitude.

**Rupture of vessel phantoms.** Using the original HM-3 reflector at 20 kV, rupture of the hollow fiber vessel phantoms could be produced consistently at \(F_2\) (fig. 7). The average number of shocks needed to cause a rupture was found to be 31 ± 10. In comparison using the upgraded reflector at 22 kV no rupture of the vessel phantom was observed after 200 shocks, indicating a significantly decreased risk of vascular injury by the upgraded reflector. Similarly no rupture of the vessel phantom was observed after 200 shocks produced by the PEAA generator at 4 kV.

**Stone comminution.** In the stone comminution experiments 2 different strategies of combining shock waves from the PEAA generator and the HM-3 lithotriptor were tested. In the first strategy shock wave from the PEAA generator was used to induce small cavitation bubbles near the stone...
surface which were then collapsed by HM-3 generated LSW. An inter-pulse delay of 30 μs was used to ensure that the shock wave-bubble interaction occurred near the maximum size of PEAA induced bubbles. Conversely, in the second strategy PEAA generated shock waves were used to collapse cavitation bubbles induced by the HM-3 lithotriptor. Based on previous experience, the inter-pulse delay was set to equal the collapse time of the LSW induced cavitation bubbles near a stone surface for maximum improvement in stone comminution.

Figure 8 shows the results of stone comminution assessed by the spherical plaster-of-Paris phantoms after 200 shocks by PEAA generator at 4 kV, HM-3 with original reflector at 20 kV and combined PEAA/HM-3 with upgraded reflector at 22 kV. Inter-pulse delay, Δt, indicates difference between arrival time of PEAA pulse and HM-3 shock wave at lithotriptor focus. Thus, for Δt = −30 μs, PEAA pulse was used to induce microbubbles near stone surface before arrival of HM-3 shock wave. For Δt = t_c, PEAA pulse was used to boost collapse of cavitation bubbles induced near stone surface by HM-3 shock wave. In these experiments spherical stone phantoms (D = 10 mm) made of plaster-of-Paris with powder-to-water mixing ratio of 2:1 were used.

To assess stone fragmentation further under clinically relevant shock wave exposure, cylindrical BegoStone phantoms were treated with 1,500 shocks generated by the original HM-3 reflector at 20 kV, the upgraded HM-3 reflector at 22 kV or the combination of the upgraded HM-3 reflector at 22 kV with the PEAA generator at 4 kV. For the combined system the PEAA generator was applied only during the first half of the treatment (ie the initial 750 shocks). It was found that the comminution efficiencies produced by the original and upgraded HM-3 reflectors are 81.3% ± 3.5% and 90.1% ± 4.3%, respectively, with the difference being statistically significant (p < 0.05, fig. 9). Using the combined system the comminution efficiency was further improved to 95.2% ± 3.3%, which is significantly better than that produced by the upgraded reflector (p < 0.05). Altogether, the results of stone comminution and blood vessel phantom studies demonstrate that the reflector insert and the PEAA generator can significantly improve the performance and safety of the HM-3 lithotriptor.

DISCUSSION

In the last 2 decades, although various technical improvements in shock wave lithotripsy have been introduced by different lithotriptor manufacturers, the overall performance of modern shock wave lithotriptors has not reached the standard that was set by the original Dornier HM-3. This result has been attributed to the fact that technical improvements in the newer shock wave lithotriptors may have been made with the aim of providing user convenience and device multifunctionality rather than a mechanistic understanding of stone comminution and tissue injury in SWL. Therefore, the need for a better shock wave lithotriptor with significantly improved performance and safety is clearly warranted.

Basic research in recent years suggests that stone comminution among the different strategies tested. When only the PEAA generator was applied, stone comminution was almost negligible (1.3% ± 0.2%), confirming again that it is the shock wave-bubble interaction that contributes to improved stone comminution using the combined PEAA/HM-3 system.

Figure 6 shows typical acoustic emission signals associated with cavitation bubbles produced at lithotriptor focus by using A, PEAA generator at 4 kV, B, upgraded reflector at 22 kV, in free field and C, upgraded reflector at 22 kV near stone phantom. Collapse time of bubbles is determined by time delay between peak pressure of first (1°) and second (2°) burst.

Figure 7 shows the relationship between number of shocks (N_r) needed to cause rupture of cellulose hollow fiber (i.d. = 0.2 mm) vessel phantom and shock wave exposure condition. Six samples were used for each test configuration.
Acoustic cavitation has an important role in stone comminution and tissue injury in SWL. However, the underlying mechanisms by which cavitation contributes to stone comminution and to tissue injury are different, making it possible to manipulate bubble dynamics selectively in different regions of the lithotriptor field to enhance stone comminution while decreasing tissue injury. By upgrading an original Dornier

culum in SWL is a multifaceted, progressive process that involves a synergistic interaction of LSW induced stress waves and cavitation. In addition 2 mechanisms have been proposed that may be responsible for SWL induced collateral tissue injury, namely shear stress and, more importantly, intraluminal cavitation. Therefore, a rational strategy to improve SWL technology should be the optimization of these critical factors (stress waves and cavitation) for maximal therapeutic gain with minimal side effects. Practically, however, control of cavitation in SWL is much easier to implement than optimization of stress waves. This is because cavitation induced in tissue or fluid surrounding the target stone is directly determined by the tensile component of the LSW. Moreover, bubble activities in SWL can be monitored acoustically and they can be enhanced or suppressed by an auxiliary shockwave with appropriate pulse profile and interpulse delay. In contrast, stress waves induced in the target stone are influenced by many factors such as the size, geometry, internal structure and physical properties of the stone, many of which cannot be readily determined before SWL. Based on these considerations we have developed 2 technical upgrades (reflector insert and PEAA generator) that can be integrated with an HM-3 lithotriptor to suppress cavitation selectively in tissues along the propagation path of LSW to decrease vascular injury and to intensify the collapse of cavitation bubbles near the target calculi for improved stone comminution. Using established phantom systems we have demonstrated in vitro that stone comminution and safety of the upgraded system are significantly improved from the original HM-3 lithotriptor, the current gold standard in SWL. Compared to other proposed technical improvements (Twinheads lithotriptor\textsuperscript{18} and dual-pulse lithotriptor\textsuperscript{19}), our technologies are much easier and less expensive to implement under clinical SWL conditions.

It should be noted that although the reflector insert and PEAA generator are both used for cavitation control, their objectives and mechanisms of action are quite different. The reflector insert is used to produce a weak compressive shock wave in about 4 $\mu$s from the leading shock front to cancel the trailing tensile component of the LSW partially and, thus, decrease the propensity of small blood vessel rupture during SWL.$^{11,12}$ To reduce vascular injury, a short inter-pulse delay is important because the expansion of a LSW induced intraluminal bubble can significantly dilate a small blood vessel within $10\mu$s after the passage of the leading shock front.$^7$ Moreover a unique advantage of the reflector insert is that as the output voltage of the lithotriptor is increased, the 4 $\mu$s delayed compressive wave also becomes stronger, thus exerting a self-regulated control on the tensile wave of the LSW. The modification of the pulse profile by the reflector insert is analogous to adding a safety lock on the LSW.

It should be emphasized that the reflector insert does not eliminate cavitation, rather it only significantly weakens the expansion of LSW induced cavitation bubbles. In comparison to cavitation in tissue, LSW induced bubbles in the aqueous medium surrounding a stone are usually larger because of strong wave reflection and bubble aggregation, and the enlarged bubbles on the stone surface usually collapse within several hundred microseconds after the passage of the shock front.$^{19}$ Therefore, the PEAA generator can be used to produce a significantly delayed auxiliary shock wave to intensify the collapse of LSW induced bubbles near the stone surface for improved comminution efficiency.$^9$ Because of its relatively small pressure amplitude, minimal beam overlap with the HM-3 shock wave, and long inter-pulse delay, the auxiliary shock wave from the PEAA generator will presumably not increase cavitation damage in the interposing tissues between the shock wave source and the target stone.

In this study passive cavitation detection was used to determine the collapse time of the cavitation bubbles during SWL to set the appropriate inter-pulse delay between the triggers of the HM-3 lithotriptor and PEAA generator. Real-time monitoring of bubble activities near the stone surface is important because several factors, including stone type (harder stones produce a stronger wave reflection and, thus, larger bubbles), lithotriptor output voltage, electrode condition, and size and distribution of residual fragments could all change the collapse time of the bubbles. Therefore, the interpulse delay should be adjusted accordingly during the course of SWL to achieve maximum improvement in stone comminution.

Finally, because of the flexibility of the PEAA generator, this device can be used in different combinations with the HM-3 pulse to produce desirable shock wave-bubble interaction during SWL. We have shown that the auxiliary shock wave produced by the PEAA generator can be used to seed microbubbles at the lithotriptor focus before the arrival of the LSW or to boost the collapse of LSW induced large bubbles near the stone surface. Although both approaches produced significantly enhanced stone comminution (fig. 8), the latter approach was found to be more effective. This finding, together with observations from other recent studies,$^{13,20}$ suggests that treatment strategy in SWL can greatly influence the final outcome of stone fragmentation. Further studies including in vivo animal experiments are needed to explore the potential of a combined PEAA/HM-3 lithotriptor fully with upgraded reflector to achieve significantly improved stone comminution with simultaneously decreased tissue injury in SWL. It is worth noting that although the present study was performed on a Dornier HM-3 lithotriptor, the concept and technologies developed in this work can be used to upgrade other existing lithotriptors and to design new shock wave lithotriptors for improved performance and safety.

**CONCLUSIONS**

**FIG. 9.** Stone comminution efficiency produced after 1,500 shocks by original HM-3 reflector at 20 kV, upgraded reflector at 22 kV, combined PEAA/HM-3 with upgraded reflector at 22 kV. Cylindrical BegoStone phantoms of 6.8 $\times$ 11.4 mm (D $\times$ L) were used. PEAA generator was operated at 4 kV and was used only in first half of results. Significance levels ($p$ values) are shown.

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<th>Stone Comminution Efficiency (%)</th>
<th>HM-3 @ 20 kV</th>
<th>Upgraded @ 22 kV</th>
<th>PEAA @ 4 kV</th>
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HM-3 lithotripter with a reflector insert and a PEAA generator, we have demonstrated in vitro that the overall performance and safety of the resulting lithotripter system can be significantly improved. These findings support our general hypothesis that innovations in SWL technology can be achieved via optimization of the pressure waveform profile, distribution, and pulse sequence in a lithotripter field. Further work to confirm the advantages of this novel SWL technology by in vivo animal studies is warranted.

Thomas Dreyer and Marko Liebler from the University of Karlsruhe, Germany collaborated on the measurements of pressure waveforms of the PEAA generator using a fiber optical probe hydrophone (FOPH 300).

REFERENCES