Optimizing Shock Wave Lithotripsy: A Comprehensive Review

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Shock wave lithotripsy is a commonly used procedure for eradicating upper urinary tract stones in patients who require treatment. A number of methods have been proposed to improve the results of this procedure, including proper patient selection, modifications in technique, adjunctive therapy to facilitate elimination of fragments, and changes in lithotripter design. This article assesses the utility of these measures through an analysis of contemporary literature.

[Rev Urol. 2013;15(2):49-60 doi: 10.3909/riu0568]

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KEY WORDS

Shock wave lithotripsy • Upper urinary tract stones • Comminution

Shock wave lithotripsy (SWL) is commonly utilized to treat patients with upper urinary tract stones. It is now clear that proper patient selection, modifications in treatment technique, and employment of adjunctive measures can be utilized to optimize SWL results. In addition, certain future changes in lithotripter design may prove to be beneficial. Herein, we review methods to improve SWL results.

Patient Selection

Stone Size

It is well documented that, as stone size increases, SWL success rates decrease. Investigators have demonstrated that patients with stones $>$ 2 cm are less apt to be rendered stone free. Abdel-Khalek and associates[1] performed an analysis on 2954 patients with single or multiple radio-opaque renal stones

< 30 mm who were treated with SWL utilizing a Dornier MedTech MFL-5000 lithotripter (Weßling, Germany). Stone size significantly impacted treatment success. A multivariate analysis demonstrated that, at a stone size of < 15 mm, the probability of being rendered stone free was 1.94 times greater than for stones > 15 mm. Others have clearly demonstrated that stones > 2 cm are less likely to be cleared after SWL.[2]

Skin-to-Stone Distance and Body Mass Index

Body mass index (BMI) and its surrogate, skin-to-stone distance (SSD), have been demonstrated to influence stone-free status after SWL. Pareek and associates[3] performed the first study that assessed BMI as an independent predictor of SWL outcomes. In this study, 100 SWL patients with 5- to 10-mm renal or upper ureteral stones who had pretreatment noncontrast computed tomography (NCCT) imaging were analyzed using binary logistic regression. A Medstone electrohydraulic lithotripter (Aliso Viejo, CA) was utilized, and patients were divided into stone-free or residual fragment groups. Results revealed that BMI was a significant predictor of stone-free status. The mean BMI for those who failed was 30.8, as compared with 26.9 in those with successful treatment outcomes. Nakada and colleagues[4] were the first to use SSD to predict success with SWL when they analyzed 64 patients with 5- to 15-mm lower pole kidney stones treated with a Doli S lithotripter (Dornier MedTech). The investigators then measured the length from the skin to the center of the stone at 0°, 45°, and 90°, and used the average of these values as the SSD. The reported results illustrated that an SSD > 10 cm was a strong predictor of SWL treatment failure. Others have demonstrated similar findings. In a multivariate analysis of 111 SWL patients with 5- to 20-mm renal stones, Perks and colleagues[5] illustrated that an SSD > 9 cm predicted failure. Park and colleagues[6] analyzed a cohort of 43 patients with 5- to 20-mm renal stones treated with a Sonolith Praktis electroconductive lithotripter (EDAP TMS, Vaulx-en-Velin, France) and reported that an SSD > 7.8 cm was associated with failure. Patel and associates[7] performed a study of 83 patients with 5- to 15-mm renal stones treated with an electromagnetic Doli 50 lithotripter (Dornier MedTech) and found an SSD > 8.3 cm was associated with failure. Wiesenthal and colleagues[8] performed a multivariate analysis of patients with renal and ureteral stones treated with a Philips LithoTron lithotripter (Andover, MA) and found that, although SSD was predictive of success for patients with renal stones, it did not discriminate for those with ureteral calculi.[8] Hammad and associates[9,10] demonstrated that, although SSD predicts SWL success for patients with renal stones, the type of tissue in the SSD pathway—fat or muscle—did not impact results. Thus, the SSD appears to be a valid predictor of SWL stone-free outcome for patients with renal stones < 2 cm.

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Hounsfield Unit Attenuation Values and Stone Composition

Stone attenuation measured on NCCT has been demonstrated to impact SWL results; this metric is quantified as Hounsfield units (HU). Pareek and associates[3] assessed HU attenuation values as an independent predictor of SWL outcomes. In this study, 100 SWL patients with renal or upper ureteral 5- to 10-mm stones who had pretreatment NCCT imaging were analyzed using binary logistic regression. A Medstone electrohydraulic lithotripter was utilized, and patients were categorized as stone free or having residual fragments. Stone attenuation was demonstrated as a significant discriminator with a mean HU of 910.4 for those with residual fragments and 577.9 HU for those rendered stone free. This group performed another study in which 50 patients with 5- to 10-mm renal calculi were treated with the same device and categorized as treatment success (stone free or fragments ≤ 3 mm) or failure. The mean attenuations for success and failure were 551.20 and 926.2, respectively.[11] Perks and colleagues[5] performed a multivariate analysis of 111 patients with 5- to 20-mm renal calculi undergoing SWL with a Philips LithoTron Ultra. Stone attenuation was again shown to predict success (stone free or < 5 mm fragments); the mean value for the failure group was 1092 HU and the mean value was 837 HU for the successful treatment group. Subsequently, Joseph and associates[12] studied 30 patients with renal calculi ≤ 20 mm subjected to SWL with a Siemens Lithostar Multiline lithotripter (Munich, Germany). They segregated results by HU values into three groups: < 500, 500-1000, and > 1000. Success (stone free or ≤ 3 mm) was 100%, 85.7%, and 54.5%, respectively.[12] Gupta and associates[13] reported on 112 patients with 5- to 20-mm renal or ureteral calculi undergoing SWL utilizing an electromagnetic Lithostar Shock Wave System C. Their results demonstrated a mean attenuation of

750 HU for successfully treated patients (stone free or fragments ≤ 5 mm). Another multivariate analysis by Wang and colleagues[14] assessed 80 adult patients with ≤ 25-mm renal stones that were treated via a Philips LithoTron electrohydraulic lithotripter. Success (stone free or fragments ≤ 4 mm) was associated with calculi HU values < 900.

It is clear that stone attenuation influences results with SWL. The cutpoint for predicting failure is not clearly defined, but a liberal estimate is 1000 HU. A more conservative estimate would utilize an HU value of 750. These thresholds may be impacted by the type of lithotripter utilized, the lithotripsy techniques employed, and stone internal architecture.

Reducing the Rate of Shock Wave Delivery

There is in vitro, in vivo, and clinical evidence that reducing the rate of shock wave delivery enhances fragmentation and thus stone clearance. Vallancien and associates[15] performed in vitro studies assessing fragmentation of stones using various SWL delivery rates of 75 to 600 shock waves per minute (SW/min). An EDAP LT-01 piezoelectric device was used. Fragmentation was more efficient with slower shock wave delivery. Greenstein and Matzkin[16] delivered shock waves at ceramic phantom stones using an electrohydraulic Econolith 2000 device (Medispec, Germantown, MD). They reported that fragmentation to < 2.2 mm was significantly quicker when the rate was 30 or 60 SW/min as compared with rates of 90, 120, and 150 SW/min. There were no significant differences between rates of 30 and 60 SW/min, whereas there was an inverse relationship in fragmentation success and rate for these three higher delivery rates. In another study, Weir and colleagues[17] delivered shock waves at artificial plaster stones at rates of 60, 80, and 117 SW/min using an electrohydraulic Dornier MFL-5000. Fragmentation took significantly longer at the highest rate.

In vivo studies were subequently undertaken that again demonstrated that better fragmentation was achieved at a slower rate. Paterson and colleagues[18] implanted gypsum stones into the lower pole of swine using a percutaneous approach. Shock waves were subsequently delivered at these stones using an electrohydraulic Dornier HM3 device at rates of either 30 or 120 SW/min, a kilovoltage of 20, and total shocks of 400 shock waves were used for both rates. Fragmentation expressed as a percent increase in stone fragment surface area was significantly higher at 30 SW/min (327% ± 63% vs 135% ± 136%).

Fragmentation was more efficient with slower shock wave delivery.

Several clinical trials have assessed the impact of shock wave delivery rates on outcomes. The first was reported by Robert and associates.[19] In this trial, 114 patients with ureteral stones were treated with a piezoelectric EDAP LT-02 lithotripter at shock wave frequencies of 60 or 240 SW/min. Lower ureteral stone-free rates were greater utilizing the more rapid sequence. Madbouly and associates[20] performed a trial involving 156 patients harboring renal or ureteral stones. Participants were randomized to receive either 60 or 120 SW/min; success was defined as stone free or fragments < 2 mm. Their data analysis showed a success rate that was 8.7% higher in the slow wave group, as well as a decreased total number of shock waves required for success, at the cost of a longer treatment time—all of these results were statistically significant. Two additional trials in the following year also produced similar results. A 349-patient study with two shock wave groups receiving 70 to 80 or 120 SW/min, respectively, resulted in a 19% greater stone-free rate in the slow wave group.[21] Similarly, a 134-patient study, in which success was defined as stone free or fragments < 4 mm, revealed effective fragmentation of 65.2% in the slow group (60 SW/min) compared with 47.1% in the fast group (120 SW/min).[22] Similar to the results of Robert and associates,[19] Davenport and colleagues[23] reported a study of 100 patients with renal stones who were randomized to be treated at 60 or 120 SW/min using an electromagnetic Dornier Lithotripter S. They did not demonstrate differences in success rates as defined by a combination of stone-free status or fragments < 4 mm.[23] However, patients in this study had rather small solitary renal stones with a mean stone area of 60 mm². Pace and associates[24] also found no difference in treatment success—defined as fragments < 5 mm or stone-free status—using these two rates for smaller stones (< 1 cm), but success was 14% higher for patients with larger stones (> 1 cm) treated at a rate of 60 SW/min. Yilmaz and colleagues[25] randomized 170 patients with renal stones to be treated with an electrohydraulic Stonelith Lithotripter (PCK Medical Systems, Ankara, Turkey) at rates of 60, 90, and 120 SW/min. Success was significantly higher (stone free or < 3 mm fragments) for those being treated at rates of 60 and 90 minutes; there was no significant difference between these latter rates. Kimura and associates[26] treated 1291 patients with either renal or ureteral stones at rates of 90 or 120 SW/min using a Siemens Lithostar Multiline electromagnetic device. A significant increase in the stone-free rate at 3 months was demonstrated in those with ureteral stones treated at the slower rate, but there were no differences for those with renal calculi. Honey and colleagues[27] performed a study in which subjects with proximal ureteral stones were randomized to be treated with a Phillips electrohydraulic LithoTron at rates of 60 or 120 SW/min. The stone-free rate was significantly higher in those treated at a slower rate. Koo and associates[28] performed a study in which patients harboring renal stones were treated with an electromagnetic Dornier Lithotriptor S and randomized to 70 or 100 SW/min. Success (stone free or < 3 mm fragments) was significantly higher with the slower rate. Mazzuchi and coworkers[29] undertook a randomized trial of patients with renal and ureteral stones who were treated with a Dornier Compact Delta device at rates of 60 or 90 SW/min. No significant differences were found with regard to treatment success. Semins and associates[30] performed a meta-analysis of four of the aforementioned randomized, controlled clinical trials. They utilized a fixed-effect model and found that patients who were treated with rates of 60 SW/min had a 10.2% (95% confidence interval, 3.7-16.8) increased likelihood of a successful treatment outcome, which was highly significant. The limitations of this analysis included lack of uniformity among the four trials with regard to variation in stone size criteria, location of stones, lithotripter type, anesthesia techniques, and definitions of successful treatment.

The mechanism behind the effect of shock rate on stone fragmentation is not entirely clear. The leading theories currently are that a decreased shock rate improves bubble dynamics due to reduced water and gas content surrounding the stone, decreases acoustic impedance mismatch, or optimizes the production of cavitation bubbles on the surface of stones.[31] As early as 1989, it was demonstrated that SWL causes the development of cavitation bubbles on the surface of stones.[31] More cavitation bubbles accumulate at the stone surface with increasing shock wave delivery rates and are thought to attenuate the impact of subsequent shock waves. In addition, microbubbles are generated with collapse of the cavitation bubbles which serve as cavitation nuclei. The latter can lead to "cavitation debris or bubble clouds" that further reduce the delivery of shock wave energy.[24,32] Pishchalnikov and colleagues[33] supported this theory when they illustrated in in vitro studies that bubble clouds are enhanced with increasing shock wave delivery rates. The presence of this bubble cloud has also been demonstrated in a porcine model by Bailey and colleagues.[34] The cloud was shown to reflect shock waves and limit the collapse of cavitation bubbles.

A reduction in the shock wave delivery rate may also limit renal damage that can occur when this energy is delivered to the renal parenchyma. This has been shown by Evan and associates[35] in a porcine model in which 2000 shock waves at 24 kV were delivered at rates of 30 or 120 SW/min using a Dornier HM3 lithotripter. Hemorrhagic renal lesions involving 4.7% of the functional renal volume were present in the 120 SW/min group, whereas they were present in just 0.08% in the 30 SW/min group. The reasons for reduced injury with a slower rate have not been fully elucidated, but the aforementioned research group has proposed two mechanisms. The first is that a slower rate allows cavitation nuclei to be more effectively cleared from the vascular space, thus limiting the impact of cavitation bubble collapse and vessel rupture. The other hypothesis is that stress within the renal parenchyma can accumulate if the rate of shock wave delivery is faster than the displacement relaxation time of this tissue. The latter mechanism is feasible at this increased rate and could lead to vascular damage.

The aforementioned results strongly suggest that stone fragmentation is enhanced at slower shock wave delivery rates. Therefore, a practical approach is to use rates of 60 to 90 SW/min, as this should result in improved fragmentation as compared with a more rapid delivery. Furthermore, this has the theoretical advantage of limiting renal injury.

Ramping Up Voltage

A strategy of ramping up shock wave energy to improve fragmentation and stone clearance and limit renal damage has been proposed. In vitro and in vivo studies suggest that this may be beneficial, whereas clinical results have been discordant.

An in vitro study demonstrated that better fragmentation occurred with a ramping up sequence. Zhou and colleagues[36] performed a study in which 1500 shocks were delivered to spherical Bego stone phantoms (Bego USA, Smithfield, RI) at 60 SW/min using an unmodified electrohydraulic Dornier HM3 lithotripter. Three different treatment strategies were utilized: increasing output voltage from 18 to 20 to 22 kilovolts (kV) every 500 shocks, decreasing output voltage from 22 to 20 to 18 kV every 500 shocks, or maintaining a constant output voltage of 20 kV. The ramping up voltage sequence resulted in the best final comminution efficiency.

In vivo studies have assessed both the impact of energy sequences on fragmentation and renal injury. Maloney and colleagues[37] implanted Bego stone phantoms into the renal pelvis of 11 swine, which were subsequently divided into the three following groups for treatment with a Dornier HM3 lithotripter: group 1 was subjected to 600, 600, and 800 shocks at 18, 20, and 22 kV; group 2 received 800, 600, and 600 shocks at 22, 20, and 18 kV; and group 3 received 2000 shocks all at 20 kV. The rate was 60 SW/min for all groups. The ramping up strategy used in group 1 resulted in significantly higher mean comminution efficiency, determined by percentage of stone fragments < 2 mm posttreatment. Willis and associates[38] utilized a porcine model in which an electrohydraulic Dornier HM3 lithotripter was used to deliver shock waves to kidneys. They demonstrated that pretreatment of the targeted kidney with low-voltage energy with as few as 100 shock waves and a 3-minute interval before proceeding to full energy delivery reduced renal injury. Similarly, Connors and associates[39] treated 19 porcine kidneys with a Dornier HM3 electrohydraulic lithotripter at a rate of 120 SW/min utilizing distinct protocols for three groups. Group 1 received 2000 24-kV shock waves, group 2 received 100 shock waves at 18 kV followed by 2000 shock waves at 24 kV, and group 3 was treated with 100 shock waves at 24 kV followed by 2000 shock waves at 24 kV; both pretreatment cohorts included a 3- to 4-minute protective pause. The mean hemorrhagic lesion size expressed as a percentage of renal volume was significantly smaller in both pretreatment groups compared with the group without pretreatment, whereas there was no significant difference in mean lesion size between the respective pretreatment groups. The authors concluded that, although voltage ramping reduces renal injury, the initial pretreatment voltage does not significantly affect renal lesion size.

Demirci and colleagues[40] performed the first clinical trial studying voltage ramping in a cohort of 50 patients with renal or ureteral stones < 20 mm. Patients were randomized to receive either a constant treatment energy of 13 kV or increasing output voltage every 500 shocks at 11, 12, and 13 kV, respectively. The shock wave delivery rate was not reported by these investigators. All SWL was performed with a Dornier Compact Delta electromagnetic lithotripter with a total of 3000 shock waves per patient in each group. The stone-free rate was significantly higher in the stepwise treatment group (96% vs 72%). A limitation of this study was that a significant number of subjects in both groups underwent multiple SWL treatment sessions. In addition, secondary stone removing procedures were performed more frequently in the stepwise treatment group. Honey and coworkers[41] conducted a randomized controlled trial in 160 patients with renal calculi utilizing a Phillips LithoTron electrohydraulic lithotripter at a rate of 120 SW/min. In the immediate treatment group, the starting voltage of 15 kV was increased by 1 kV every 10 shocks to a maximum of 23 kV. In the delayed treatment group, the starting voltage of 14 kV was increased after 10 shocks to 15 kV for the first 1500 shocks—thereafter, the voltage was increased by 1 kV every 10 shocks to a maximum of 23 kV. The overall success rate at 3 months, defined as stone free or fragments ≤ 4 mm, was 18% higher with immediate voltage escalation. However, the actual stone-free rates at 2 weeks and 3 months after treatment were not significantly different. One wonders if the results would have been different if a lower shock wave delivery rate was used in this study. Lambert and colleagues[42] prospectively randomized 45 patients with renal stones to receive SWL for renal stones (median size 8 mm) with an escalating strategy of 500 shocks at 14 kV, 1000 at 16 kV, and 1000 at 18 kV, or a conventional strategy of 2500 shocks at 18 kV. A Dornier Doli 50 electromagnetic lithotripter was utilized. The shock wave delivery rate of both groups was 60 to 80 per minute. A significantly higher stone-free rate at 1 month in the escalating voltage group was demonstrated (81% vs 48%). In addition, urinary microalbumin and β2-microglobulin levels, indices of renal injury, were significantly decreased 1 week postoperatively in the escalating voltage group, suggesting a renoprotective effect with voltage ramping.

Explanations have been proposed as to why a ramping-up strategy may optimize fragmentation and limit renal injury. If high energy is delivered to the stone initially, fragmentation is quite efficient, and several small stone fragments accumulate in front of the remaining stone mass, potentially attenuating the ensuing shock waves. Increased energy output at the end of treatment as with a ramping-up sequence may better overcome this barrier. A gradual increase in energy may enhance cavitation and its synergistic interaction with stress waves. The renoprotective effects of pretreatment are attributed to an increase in the renal vascular resistive index thought to be induced by constriction of renal blood vessels.

There may be stone fragmentation benefits with a ramping-up strategy, but the strength of evidence is less than that for slower shock wave delivery rates. Further better-designed studies are needed to determine if this is a beneficial strategy. A practical approach to such strategies is suggested. There is little downside to delivering a pretreatment dose, delaying further shock wave delivery for 3 minutes, and proceeding with shock wave delivery, as this strategy may be renoprotective. Many patients who undergo SWL under intravenous (IV) sedation are currently being treated using a dose escalation strategy, and this should not be altered.

It is possible that some of the differences between IV sedation and general anesthesia can be explained by a greater variability in patient response to IV sedation.

Anesthesia

It has been suggested that anesthesia modality may influence SWL outcomes. Eichel and associates[43] studied a population of 370 patients with renal or ureteral stones treated within a 6-month span with a Dornier Doli U50 electromagnetic lithotripter; 49% of patients in group 1 received IV sedation, whereas all patients in group 2 underwent general or regional anesthesia. Comparison of SWL success rates, defined as stone free or fragments < 3 mm, revealed a significantly higher success rate in group 2 (78% vs 51%). Similarly, Sorensen and colleagues[44] reported a study of 295 patients with renal or upper ureteral stones < 2 cm who were treated with a Dornier Doli U50 electromagnetic lithotripter. The patients underwent IV sedation (92 patients) or general anesthesia (203 patients). At 3 months, the stone-free rates were significantly higher in the group receiving general anesthesia (87% vs 55%).

It is possible that some of the differences between IV sedation and general anesthesia can be explained by a greater variability in patient response to IV sedation. Specifically, it is possible that IV sedation could provide insufficient analgesia, resulting in decreased patient cooperation, erratic breathing, and concomitant inaccurate stone localization. Several studies have been performed, therefore, to provide strategies for optimizing IV sedation during SWL, with variable techniques and results. Stone fragmentation outcomes utilizing these techniques, however, have not been reported.[45-47]

Studies have demonstrated that a stone may move up to 50 mm during respiration and such motion may impact SWL efficacy. An in vitro model mimicking respiratory stone motion showed a significant reduction in stone comminution with stone motion as small as 10 mm; in fact, greater variation in stone motion can result in up to 75% of shock waves missing the stone entirely.[48,49] Sorensen and colleagues[50] performed an analysis of 10 patients who underwent SWL for treatment of 13 renal stones with a mean size of 10.5 mm (range, 5-18 mm) using either a Healthtronics LithoTron electrohydraulic lithotripter (Healthtronics, Atlanta, GA) or a Dornier Compact Delta II electromagnetic lithotripter. Commercial diagnostic ultrasound was used to record images of the stone during treatment. Two independent observers reviewed ultrasound videos and determined shock wave accuracy (defined as the proportion of shock waves that resulted in stone motion) as well as respiratory stone motion. It was found that 60% ± 15% of delivered shock waves were accurately delivered and the average respiratory stone motion was 1.5 ± 0.3 cm. Image-based renal stone tracking software that automatically adjusts lithotripter targeting during shock wave treatment has been developed, but this technology has not been adapted or promoted.[51] Modifications of general anesthesia have also been utilized in an attempt to limit respiratory stone motion. Mucksavage and coworkers[52] studied a cohort of 112 patients who underwent SWL with conventional anesthesia or high-frequency jet ventilation (HFJV). The HFJV group required significantly fewer shocks and total energy to achieve comminution.

We believe that the utilization of general anesthesia during SWL may promote better targeting and efficient fragmentation when a third-generation lithotripter is used. Increased respiratory motion compromises shock wave delivery, and strategies such as tracking software and HFJV are being assessed to address these concerns. It is hoped the further development of stone tracking technology will improve SWL outcomes and be implemented into clinical practice.

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Coupling Techniques

Numerous studies have documented that second- and third-generation lithotripters may not be as effective as compared with the first-generation Dornier HM3.[53] Several of these reports attribute this discrepancy to the fact that first-generation lithotripters functioned by immersing both the patient and the head of the lithotripter in a water bath, providing an excellent medium for the transmission of acoustic energy.

Comparatively, although the newer lithotripters are smaller, more transportable devices, they utilize a dry shock wave delivery head that is not immersed in water. There is conclusive evidence, however, that lithotripter shock waves essentially do not propagate through air. In fact, greater than 99% of a shock wave is reflected by an air pocket.[54] This necessitates the use of a coupling agent to eliminate air between the head of the lithotripter and the patient, ultimately providing a medium for shock wave transmission to the targeted calculus.[55,56]

In light of these facts, when the second- and third-generation lithotripters were first used, a wide variety of coupling mediums were utilized, including creams, castor oil, petroleum jelly, ultrasonography gel, and other water-soluble lubricating jellies. Studies in the late 1990s advocated the use of several types of media as both coupling agents and topical anesthetics.[57-59] Cartledge and coworkers[60] performed an in vitro study comparing five different contact media to determine if coupling agents affected the number of shock waves required for stone fragmentation. Their results showed that a commercial water-soluble lubricating jelly required the least number of shock waves to achieve fragmentation to particles < 2 mm. EMLA (eutectic mixture of local anesthetics) cream and petroleum jelly necessitated a significantly greater number of shock waves compared with the other media utilized.

Subsequent studies on SWL coupling demonstrated that air pockets trapped within the coupling media can substantially reduce the transmission of acoustic energy, thus providing a mechanism for the divergence in outcomes between coupling agents. Pishchalnikov and coworkers[53] illustrated this effect when they observed and photographed air pockets trapped at the coupling interface between a Dornier Doli U50 electromagnetic lithotripter and a test tank covered by a polyester membrane. Throughout the experiment, a commercial coupling gel (LithoClear; NEXT Medical Products, Bellingham, WA) was used. The authors demonstrated that the process of coupling produced air pockets ranging from 1.5% to 19% of the coupling surface area, causing a 20% mean reduction in shock wave amplitude. In fact, air pockets covering 2% of the coupling area diminished stone fragmentation by 20% to 40%. The process of decoupling and recoupling, simulating patient repositioning, reduced transmission of acoustic energy by 57%. Similarly, Jain and Shah[61] utilized high-resolution photographs to show that decreased bubble contents of gel significantly increased depth and volume of stone craters in vitro ($P < .001$). The implications of these studies are noteworthy in that inferior acoustic coupling results in ineffective stone fragmentation, which could place succeeding patients at increased risk for renal injury if they received higher shock wave dosages.

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In light of the aforementioned conclusions, it is possible that the technique of applying coupling gel may impact fragmentation. Neucks and associates[62] used digital imaging for detection of coupling defects in an effort to determine the best methods for gel application. They found that the best technique was to dispense a large volume of gel directly from a stock jug onto the lithotripter water cushion, as opposed to gel application by hand. The gel was then allowed to spread during stepwise inflation of the lithotripter water cushion. These techniques resulted in significantly fewer coupling defects compared with application of gel by hand, although clinical application of these techniques could prove difficult. This same group has found that the coupling interactions at the central portion of the water cushion are the most important.[63]

A surveillance mechanism could aid in the discovery and subsequent elimination of air pockets, thereby optimizing coupling during SWL treatment. Bohris and associates[64] demonstrated the potential benefits of this strategy. They used a video camera integrated into a Dornier Doli SII lithotripter to detect air pockets in coupling gels during SWL. Three different coupling gels were used, including LithoClear, Sonogel (Sonogel Vertriebs GmbH, Bad Camberg, Germany), and a low viscosity custom-made gel. Air ratios in the coupling area were measured and lithotripter fragmentation was assessed at varying air ratios. Their results showed that the mean number of shock waves needed for effective stone fragmentation increases with greater air ratios. Furthermore, less air was produced within the coupling medium when the custom-made low viscosity gel was used. These findings suggest that utilization of surveillance mechanisms monitoring for defects in coupling gels and refinements of such products may improve SWL results.

Facilitating Fragment Passage

α_1-*Antagonists*

Medical expulsive therapy with α_1-blockers may facilitate clearance of fragments after SWL. Küpeli and colleagues[65] performed a trial in

48 patients with stones in the distal ureter 5- to 16-mm in size who were randomized to undergo SWL without or with adjuvant tamsulosin for 15 days after treatment. The stone-free rate was significantly higher in those receiving tamsulosin—70.8% versus 33.3%, respectively.[64] Gravina and colleagues[66] studied a 130-patient cohort with renal stones 4- to 20-mm in diameter who underwent a single SWL session. Patients were randomized to receive methylprednisolone, 75 mg, and diclofenac or the same agents combined with tamsulosin for a maximum of 12 weeks. The success rate (stone-free or fragments < 3 mm) was significantly higher in the tamsulosin group (78.5% vs 60%). In a prospective, randomized trial of 60 patients with renal or ureteral calculi treated by SWL, Bhagat and associates[67] compared tamsulosin and placebo administered for a maximum of 30 days. There were no differences in success (stone-free or < 3 mm fragments) at 1 month in those with stones 6- to 10-mm in size, whereas tamsulosin was demonstrated to significantly improve success in those with stones 11- to 24-mm in size. Georgiev and colleagues[68] studied a cohort of 248 patients with ureteral or renal stones treated with SWL who were randomized to receive either steroids alone or steroids combined with tamsulosin for 1 month. The success rate (stone-free and < 3 mm fragments) was higher in the tamsulosin group—91.3% versus 74.6% at 12 weeks. In addition, time to fragment clearance, rate of rehospitalization, and episodes of severe renal colic were significantly lower in the tamsulosin group. Kobayashi and associates[69] randomized a group of 102 patients with ureteral stones undergoing SWL to receive tamsulosin, an herbal preparation, or no adjunctive treatment. The stone-free rates were similar in all three groups, but the tamsulosin group experienced a significantly shorter mean expulsion time. Gravas and colleagues[70] performed a randomized trial in 61 SWL patients with distal ureteral stones > 6 mm who were either given tamsulosin or no adjunctive therapy. Stone-free rates were similar but time to expulsion and analgesic requirements were less in those receiving tamsulosin. Resim and associates[71] reported a study of 67 patients with steinstrasse in the lower ureter following SWL in which subjects were randomized to either tamsulosin or no adjunctive measures. There were no differences in spontaneous resolution rates but the tamsulosin-treated group had less pain.

... studies suggest that α-blocker therapy may be a useful adjunct for patients undergoing SWL.

The aforementioned studies suggest that α-blocker therapy may be a useful adjunct for patients undergoing SWL. Potential benefits include bolstering stone-free rates, quicker expulsion, and lowering of analgesic requirements.

Percussion, Diuresis, and Inversion

Lower pole stone fragments are thought to clear less effectively after SWL. The technique of percussion, diuresis, and inversion (PDI) has been utilized for the clearance of lower pole stone fragments following SWL. D'a Honey and colleagues[72] performed a study of 12 patients with residual lower pole stone fragments ≤ 2 mm at a mean of 37 days following SWL. PDI was executed with the following methods: patients were given 20 mg of furosemide, placed in the prone Trendelenburg position on a pivoting stretcher, and given 10 minutes of percussion over the flank using a mechanical chest physiotherapy device. Five patients were rendered stone free after a single PDI treatment. The authors subsequently performed an expanded trial employing a crossover design. Their cohort consisted of 69 patients with lower calyceal fragments ≤ 4 mm at 3 months following SWL. Patients were randomized to receive PDI using the aforementioned technique weekly for 1 month or until rendered stone free versus observation. Results demonstrated a significantly higher stone-free rate in the PDI group (40% stone-free vs 3%). The control patients with remaining stones were then subjected to the same regimen, which resulted in a similar stone fragment clearance rate.[73] Chiong and colleagues[74] performed a prospective, randomized study in which 108 patients harboring lower pole stones < 2 cm were subjected to SWL. The patients were randomized to either observation or to receive PDI therapy starting 1 to 2 weeks after SWL if they had residual fragments. Approximately one-third of each group was subjected to multiple SWL sessions and the distribution of multiple SWL treatments was similar in both groups. The PDI method differed in that diuresis was induced with oral consumption of 500 mL of water, after which the patients were inverted at a 45° prone angle, and percussion was performed by a registered nurse or trained assistant for 10 minutes. A maximum of four PDI sessions was administered after each SWL treatment. The stone-free rate for the PDI group was significantly higher than that of the control cohort (62.5% vs 35.4%).

The aforementioned results suggest that PDI may facilitate clearance of stone fragments remaining in the lower pole after SWL. Therefore, it may be proposed to such patients and theoretically could be supplemented with α-blocker therapy.

Shock Wave Delivery

Focal Zone Width

One of the many differences between the second- and third-generation lithotripters and the Dornier HM3 is that many of the newer devices have a narrower acoustic energy focal zone, resulting in more focused and often higher pressure shock waves. A number of experimental studies, including mechanistic assessments in vivo and randomized controlled trials, have been performed to evaluate the potential effects of focal zone variation on stone comminution and renal injury.

The generation of shear waves external to the stone from the shock wave as it passes through fluid is thought to play an important role in stone comminution. Cleveland and Sapozhnikov[75] and Sapozhnikov and colleagues[76] used mathematical modeling to demonstrate this phenomenon. They demonstrated that these shear waves were significantly more powerful than the spall effect. As the focal zone of the lithotripter gets smaller, the intensity of these shear waves decreases. Subsequent investigations by this group using a Dornier HM3 lithotripter and artificial stones showed that these shear waves generate the greatest stress on the stone.

Animal experiments have demonstrated that renal injury is more prominent with narrow focal zone devices. Connors and associates assessed renal parenchymal hemorrhage following the delivery of shock waves to the porcine kidney using either a Dornier HM3 or Modulith SLX device (Karl Storz Lithotripsy-America, Kennesaw, GA). The latter lithotripter produced areas of more intense renal injury mainly focused in the cortex and medullary areas.[77] Evan and colleagues[78] compared a new device, the XX-Es lithotripter (Suzhou XiXin Medical Instruments, Jiangsu, China) (wide-focus, low-pressure, electromagnetic), with the Dornier HM3 in a porcine model in which gypsum stones were implanted into the lower pole. The results were similar between both groups with regard to renal injury and hemodynamic function. Fewer shock waves were needed to comminute the stone using the XX-Es device. This illustrates that this new device may yield similar results to those achieved with the gold standard wide focal zone lithotripter, the Dornier HM3.

Animal experiments have demonstrated that renal injury is more prominent with narrow focal zone devices.

Clinical studies of wide and narrow focal zone lithotripters demonstrate that the former devices appear to yield better results. Eisenmenger and associates[79] performed a study assessing the effectiveness of a novel wide-focus, low-pressure lithotripter. A total of 297 patients were treated with this device and 86% were stone free at 3 months; no auxiliary procedures for stone clearance were performed. In addition, the patients did not require general or regional anesthesia and only three were administered IV sedation or analgesia. Gerber and associates[80] performed a study in which patients with renal stones were either treated with a Dornier HM3 device (largest focal zone), Siemens Lithostar Plus (intermediate focal zone), or Modulith SLX (smallest focal zone). Although there were no differences in ultimate stone-free rates between devices at 3 months, the HM3 device was associated with the lowest retreatment rate and the Modulith SLX with the highest. The study of Dhar and associates,[81] in which 4.1% of patients treated with a narrow focal zone lithotripter, Modulith SLX, developed a subcapsular or perinephric hematoma, suggests that these devices may generate more renal injury than the wider focal zone devices where significantly lower rates have been reported.

The aforementioned findings suggest that wider focal zone lithotripters may be more effective and produce less tissue injury than narrow focal zone/high energy devices. Prospective randomized studies are needed to determine if this is truly the case.

Dual-Heal Lithotripters

Dual-pulse lithotripters have been developed in an effort to improve shock wave stone comminution and to reduce renal damage. The majority of work has been done in vitro and in vivo and a limited number of clinical studies have been reported.

In 2001, Sokolov and colleagues[82] designed a dual-pulse lithotripter that was compared with a conventional single-head lithotripter in an attempt to localize and intensify cavitation damage in vitro using twin lithotripter pulses. They used a high-speed digital video camera to record the cavitation fields produced in water on aluminum foil. The dual-pulse lithotripter was set up such that the two shock wave sources faced each other and were triggered simultaneously to create a confocal 4 cm × 5 cm cylindrical cloud of cavitation bubbles. A focused hydrophone was used to measure bubble growth and collapse. The authors observed that synchronous arrival of twin pulses increased bubble growth and increased foil pit depth (a measure of cavitation) compared with the conventional lithotripter. Subsequently, Sheir and associates[83] designed a similar lithotripter with two identical shock wave generators and identical twin heads. This lithotripter was used to target aluminum foil or 10-mm dental bone cement stone phantoms placed within an acrylic water tank. Targets were treated using synchronous dual-head shocks versus shocks from a single lithotripter head. Results showed a more localized cavitation field with the use of two reflectors. Furthermore, the use of two reflectors improved fragmentation. Sokolov and associates[84] assessed the impact of a dual-pulse lithotripter (modified after the Dornier HM3) on gypsum stones and human erythrocytes. Both were treated with 100 dual pulses at a charging voltage of 15 kV or 200 single pulses at 18 kV. The dual-pulse shock waves significantly increased stone fragmentation, whereas there was no significant difference in hemolysis between groups. A commercially developed dual-headed, Duet lithotripter (Direx Medical Systems, Petach Tikva, Israel), was developed. Greenstein and colleagues[85] assessed the ability of this device to fragment gypsum stones using single-pulse and dual-pulse modes. They demonstrated a decreased number of shocks required for complete fragmentation in the dual-pulse mode.

In vivo porcine studies have been performed to assess the impact of tissue damage with these devices. Sheir and associates[86] utilized a Twinheads dual-pulse lithotripter (FMD, Lorton, VA) to treat 20 porcine kidneys operating in single- or dual-pulse modes and found that the kidneys receiving dual-pulse treatments had minimal histologic damage, whereas injury was substantial with the single-pulse group. Handa and colleagues[87] assessed renal injury generated by the Duet and Dornier HM3 devices in a porcine model. Histologic injury and renal functional responses were similar. The same group then employed the Duet lithotripter to treat U30 gypsum stones implanted into porcine kidneys using a synchronous or asynchronous mode and found that fragmentation and renal functional responses were similar.[88]

Sheir and associates[89] presented the results of the first clinical study on synchronous dual pulse SWL utilizing the Twinheads lithotripter in a group of 50 patients with renal or upper ureteral stones (mean stone size = 12.3 mm); 14 days after treatment, 74% of patients were stone free or had residual stones of ≤ 5 mm. A total of 26% of subjects underwent a repeat treatment; the stone-free rate, including patients receiving another treatment, was 100% at 1 month. The same group then compared the Twinheads lithotripter with the Dornier Lithotripter S (single generator) in a group of 240 patients with single renal stones ≤ 25 mm. Patients were evaluated with magnetic resonance imaging and urinary enzyme studies before and after treatment. Stone-free rates were similar whereas renal hematomas were only present in the single-generator group. Urinary enzyme (markers of renal injury) levels increased in both groups but normalized sooner in those treated with the Twinheads device.[90] Thus, although some of the aforementioned studies suggest that twin-pulse lithotripsy may have some benefits, more studies are needed to demonstrate the efficacy of this technology.

Conclusions

There are many ways to improve results with SWL. Patient selection is very important and factors to consider include stone size, BMI, stone attenuation measured by NCCT, and SSD for renal stone cases. Modifying lithotripsy technique can also facilitate success. There is strong evidence that performing SWL at a low delivery rate improves results, whereas the benefits of a ramping-up strategy are less clear. Anesthetic technique may impact results; utilization of general anesthesia may result in better targeting and fragmentation. Real-time monitoring of stone position is technically feasible and it is hoped that it will be improved. If this technology is introduced as a component in future devices, targeting and fragmentation should be enhanced. Measures to assure proper coupling may also be beneficial. A technical modification that should be considered for rebirth is the utilization of lithotripters with wide shock wave focal zones. Although there may be some theoretical benefits to dual-head lithotripsy, more clinical trials are needed to assess their real utility. Finally, adjunctive measures should be considered, such as α-blocker therapy, to promote expulsion of renal and ureteral stone fragments, and physiotherapy to assist passage of lower pole stone fragments. The implementation of these strategies in appropriate patients should facilitate more effective stone comminution and fragment expulsion, thereby optimizing shock wave therapy. ■

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MAIN POINTS

- Stone size, skin-to-stone distance (SSD), and body mass index all have an impact on patients' stone-free status after shock wave lithotripsy (SWL). Patients with stones $>$ 2 cm are less apt to be rendered stone free. Results also illustrated that an SSD $>$ 10 cm was a strong predictor of SWL treatment failure.
- There is in vitro, in vivo, and clinical evidence that reducing the rate of shock wave delivery enhances fragmentation and thus stone clearance. A reduction in the shock wave delivery rate may also limit renal damage that can occur when this energy is delivered to the renal parenchyma. A practical approach is to use rates of 60 to 90 SW/min.
- Utilization of general anesthesia during SWL may promote better targeting and efficient fragmentation when a third-generation lithotripter is used; increased respiratory motion compromises shock wave delivery.
- α-Blocker therapy may be a useful adjunct for patients undergoing SWL; potential benefits include bolstering stone-free rates, quicker expulsion, and lowering of analgesic requirements.
- Animal experiments have demonstrated that renal injury is more prominent with narrow focal zone devices. Wider focal zone lithotripters may be more effective and produce less tissue injury than narrow focal zone/high-energy devices.

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