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Recent advances in lithotripsy technology and treatment strategies: A systematic review update

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Abstract

Introduction—Shock wave lithotripsy (SWL) is a well – established treatment option for urolithiasis. The technology of SWL has undergone significant changes in an attempt to better optimize the results while reducing failure rates. There are some important limitations that restrict the use of SWL. In this review, we aim to place these advantages and limitations in perspective, assess the current role of SWL, and discuss recent advances in lithotripsy technology and treatment strategies.

Methods—A comprehensive review was conducted to identify studies reporting outcomes on ESWL. We searched for literature (PubMed, Embase, Medline) that focused on the physics of shock waves, theories of stone disintegration, and studies on optimising shock wave application. Relevant articles in English published since 1980 were selected for inclusion.

Results—Efficacy has been shown to vary between lithotripters. To maximize stone fragmentation and reduce failure rates, many factors can be optimized. Factors to consider in proper patient selection include skin – to – stone distance and stone size. Careful attention to the rate of shock wave administration, proper coupling of the treatment head to the patient have important influences on the success of lithotripsy.

Conclusion—Proper selection of patients who are expected to respond well to SWL, as well as attention to the technical aspects of the procedure are the keys to SWL success. Studies aiming to determine the mechanisms of shock wave action in stone breakage have begun to suggest new treatment strategies to improve success rates and safety.

Keywords

Lithotripsy; Lithotripter; Shock wave generation; Urolithiasis

1. Introduction

The introduction of shock wave lithotripsy (SWL) in 1980 revolutionized the management of kidney stones. Within ten years, it became the most common intervention for patients [1] suffering from renal or ureteral calculi. The changes in SWL technology over the past 3 decades have resulted in varied success rates. Accordingly, researchers have developed a well defined range of uses for SWL to better – optimize results and reduced retreatment rates. Although ureteroscopy is gaining popularity with its recent advances, SWL remains a commonly used treatment option [2].

2. Shock wave generation

The Dornier HM3 was the first lithotripter to be widely utilized in clinical practice. It is a device that features a large water bath for optimum shock wave coupling, fluoroscopic imaging, an ellipsoid reflector with a small aperture and an electrohydraulic shockwave generator [3]. Shock wave sources have evolved over time. There are currently three types of shock wave generators: electrohydraulic, electromagnetic, and piezoelectric.

Electrohydraulic generators are based on spark – gap technology that produces a vaporization bubble. The bubble expands and immediately collapses, producing a high – energy pressure wave. The shock wave then encounters an ellipsoid reflector that focuses the wave [4].

Electromagnetic generators produce a magnetic field. The coil, which is basis of this technology, is located in one of two places: around a cylinder, on the inside plane of a spherical cap, or on a flat exterior with an overlying conductive membrane. A shock wave is produced when the magnetic field causes repulsion of the membrane. It is focused with a parabolic reflector or acoustic lens [5,6]. Unlike electrohydraulic technology, which requires electrode replacement every several thousand shockwaves, electromagnetic generators last for millions of shock waves.

Piezoelectric generators result in the generation of a shockwave by non – linear propagation [7].

A capacitor is fired through a collection of hundreds of piezoceramic elements positioned on a reflector. Each element is focused on the same location (F2) much like a satellite dish.

3. Clinical parameters that may affect outcome of SWL

The outcomes of SWL can be enhanced in many ways. Patient selection plays an important role, and factors to consider include body habitus, stone burden, anatomical location, stone density measured by non – contrast CT, and for renal stone cases, stone to skin distance.

4. Body habitus

Poor outcomes for SWL have been attributed to obesity. Appropriately positioning patients with high body mass index (BMI) to target the stone can be challenging as the focal length of most lithotripters is in the 15 cm range. Furthermore, excess adipose tissue dampens the

energy from the shock wave as it travels to F2 [8]. Ackermann and colleagues' multivariate analysis reported finding that BMI was a significant negative predictor of a stone – free outcome following SWL [9]. Portis et al. have also reported similar findings [10].

Morbid obesity may render SWL impractical or technically impossible for various reasons. Firstly, there are weight limitations on the lithotripter table or gantry. Furthermore, it may be impossible to radio – graphically target the stone. Most often, the skin – to – stone distance (SSD) often exceeds the maximum allowable focal distance of the lithotripter. In such circumstances, a blast path technique that relies on high pressures generated at a point located co – axially beyond second focus (F2) may be considered [11]. The skin – to – stone distance (SSD), as measured by computed tomography, may actually be a more important outcome predictor than BMI.

A recent study combined two parameters: SSD with a measure of stone density (Hounsfield units). The results revealed that patients with both favourable parameters had a 91% stone – free rate, while those with both unfavourable parameters had a 41% stone – free rate (Fig. 1) [12].

5. Stone burden

Stone burden plays a significant role in predicting the outcome of SWL (even for patients with non – staghorn calculi). As stone size increases, the likelihood of a successful outcome decreases. EAU and AUA guidelines do not recommend SWL as primary treatment for stones larger than 2 cm in size [13,14]. These calculi are unlikely to respond well to SWL treatment, and are best managed using an alternative method, such as percutaneous nephrolithotomy (PCNL) [15].

6. Stone composition

Stones of differing composition vary widely with regard to their fragility. Similarly, stones of the same composition may respond differently to shockwaves [16]. For example, when SWL is unselectively used to treat patients with cystine stones, poor results can be expected.

Hockley and collaborators reported on 43 cystinuric patients treated with SWL and PCNL. The stone – free rates with SWL were 70.5% for calculi 20 mm or less; meanwhile, stones greater than 20 mm had stone free rates of 41% [17]. Similarly, Kachel et al. reviewed 18 patients with cystine stones and recommended SWL monotherapy for cystine stones smaller than 15 mm [18]. Chow and Streem also studied SWL treatment outcomes in 31 cystinuric patients and found an overall stone – free rate of 86.9% [19]. Hence, SWL for cystine stones should be reserved for patients with a small stone burden.

Brushite calculi also respond poorly to SWL. Klee et al. reported on 30 patients with a total of 46 brushite stones [20]. Success was defined as fragments less than 4 mm. The overall success rate for patients treated by SWL monotherapy was 65%. Hence, a reasonable treatment paradigm would recommend SWL only for patients with known brushite stones of a small size.

Poor response to SWL is not only limited to stones commonly thought of as exceptionally hard or dense. In fact, very soft matrix calculi, composed of as much as 65% organic matter (in comparison to 2% or 3% organic matter in most non – infected urinary calculi), also respond poorly to SWL [21]. When stone composition is unknown, the density of the calculus (as measured by housefield unit) on preoperative axial imaging can predict stone fragility and response to SWL [22].

Joseph and colleagues reported a significantly reduced stone free rate of 54.5% with SWL for calculi greater than 1000 HU [23]. In contrast, they found a 100% success rate if stones were less than 500 HU. For stones between 500 and 1000 HU, the clearance rate was 85.7%. Gupta and associates found that HU predicted stone clearance by SWL better than stone size alone [24]. The authors reported that patients with stone density over 750 HU needed 3 or more SWL sessions to achieve a 65% clearance rate; whereas, if the stone was less than 750 HU, 80% of patients needed 3 or fewer treatments. Recently, Pareek and colleagues developed CT – based metrics as a scoring system. The Triple D Score incorporates three metrics (stone density, stone volume/dimensions, and skin – to – stone distance (SSD), to augment the prediction of SWL treatment outcome. They established cutoffs of <150 μL for ellipsoid stone volume, <12 cm for SSD, and <600HU for stone density. A Triple D Score of 0,1, 2, and 3 correlated with SWL success rates of 21.4%, 41.3%, 78.7%, and 96.1%, respectively [25].

7. Stone location

Stone location is an influential factor for the outcome of SWL. Attaining a stone – free status with lower pole calculi (even if fragmentation occurs) can be challenging. Albala and collaborators' prospective, multicenter, randomized – controlled trial, Lower Pole I, compared success rates for lower pole calculi treated with SWL in comparison to PCNL [26]. At 3 months postoperatively, they noted an overall stone free rate of 95% for PCNL versus 37% using SWL for lower pole stones. The stone free rate for lower pole calculi less than 1 cm was 63%, meanwhile, stones greater than 2 cm had a stone free rate of only 14% [26].

The follow – up study, Lower Pole II was also a prospective, multicenter, randomized – controlled trial comparing ureteroscopy to SWL for lower pole stones less than 1 cm [27]. The authors reported that although there was a trend favoring ureteroscopy, there was no statistically significant difference between the 2 techniques.

In addition to being contraindicated in young females of childbearing age, SWL of distal ureteral calculi, is associated with lower success rates. The 2007 meta – analysis of EAU/AUA offered guidelines for the management of ureteral calculi and pooled data on SWL outcomes. They noted an 82% stone free rate in the proximal ureter on 41 studies with 6428 patients, 73% stone free rate in the mid – ureter reporting on 31 studies in 1607 patients, and 74% stone free rate in the distal ureter reporting on 50 studies in 6981 patients. (Fig. 2) [28]. When stone size was less than 1 cm, the stone free rates were higher for each location.

Infundibulopelvic angle plus infundibular width and length are anatomical factors that can alter the success rate for treatment of lower pole calculi with SWL. Elbahnasy and associates evaluated intrinsic renal anatomy using intravenous pyelogram features [29]. They found that, regardless of the angle, a wide angle or short length with a broad width was associated with a higher success rate for SWL. When evaluating location, upper pole, renal pelvic, and ureteropelvic junction stones have the highest success rates among calculi treated with SWL [30].

The unique clinical scenario of calyceal diverticula is a controversial topic when discussing appropriateness of SWL. The neck of the diverticulum is classically quite narrow; consequently, it can be quite challenging to fragment the stone enough to get clearance of all or any of the pieces. One study revealed a stone free rate of only 21% [31]. Remarkably, despite the low clearance rate, many patients (60%) were still symptom – free. The duration of follow – up in this study was only 3 months.

Patient selection may play a significant role in this subgroup. If there was adequate visualization of the ostium on pre – operative imaging, with the diverticula filling with contrast, and if stone size was small. Streem and Yost demonstrated stone clearance rates of 58% for calyceal diverticular stones [32]. Caution should be exercised when using SWL as monotherapy for calyceal diverticular stones. SWL may be more beneficial when used following ureteroscopy with dilation of the diverticular neck.

8. Treatment strategies with the potential to improve SWL

Case selection, surgeon technique, and modifiable parameters play a role in enhancing safety and maximizing successful outcomes of SWL.

9. Rate

Improved stone fragmentation and reduced tissue damage can be achieved with an optimal rate of shock wave application. Numerous randomized trials have indicated that decreasing shock wave rate can improve stone fragmentation, especially for stones larger than 1 cm [33–37]. Slowing treatment rate results in longer treatment times.

The optimal treatment rate is not clear. Studies suggest that SWL at 60 to 90 shocks/min results in better fragmentation when compared to 120 shocks/min (particularly for larger stones) [38]. Most studies were performed with renal calculi, however, improved outcomes have been demonstrated for upper ureteric stones as well.

10. Energy ramping

Ramping up the energy voltage of the device (rather than beginning at maximum energy) is one way to minimize the risk of tissue injury and potentially improve stone breakage. Ramping also allows for better patient accommodation to the sensation of treatment [39,40]. One *in vitro* study that had superior fragmentation compared to serially decreasing voltages started with 100 shocks at 12.3 kV, then escalated to 14.8 kV for 400 shocks, followed by 15.8 kV for 1600 shocks [41].

Recently, Lingeman and colleagues discovered that the administration of 300 pretreatment SWs can initiate a protective response in the majority of treated kidneys. Their findings can serve as a guide for minimizing tissue injury while simultaneously decreasing treatment time. This can be attained by selecting 300 or more pretreatment SWs as part of a pause – less treatment protocol; thus, avoiding an extended time pause between initial pretreatment SWs and the main body of treatment shocks [42].

11. Coupling

Maximizing energy delivery to the stone can be achieved by proper coupling of the SWL generator head to the patient in an air – tight manner, with minimization of gas bubbles in the coupling media. Failure to recognize breaks in coupling can result in unsuccessful stone fragmentation [43].

Advances in lithotripter design have led to a shift from water bath coupling (as was seen with the original HM3 design) to the use of a smaller coupling interface. Coupling is influenced by numerous factors: the type of SWL machine, gel used at the patient – generator interface (preferably, a greater volume of lower – viscosity), method of gel application (best to apply to shock head first), and patient factors (i.e. patient movement during treatment, decoupling caused by lifting of the back off the generator and introducing air bubbles into the coupling interface) [44].

12. Targeting

Proper stone targeting is fundamental to SWL success. An ongoing debate exists regarding the superiority of fluoroscopic or ultrasound targeting. Success rates vary based on urologist expertise, SWL machine type, and stone composition [45]. Throughout treatment, targeting should be confirmed at regular intervals. Improved outcomes have been documented with greater use of fluoroscopy time [46].

13. Recent technical innovations

13.1. Wide focal zone shock wave generators

Lithotripters differ based on their acoustic output (i.e. the dimensions and pressures of the focal zone (F2). In cases with multiple renal stones, the efficacy was reduced when compared to the former gold standard, Dornier HM3 [47]. Currently, the evidence indicates that a wide focal zone provides more efficient fragmentation [48,49], while high peak pressures (i.e. high energy flux densities) result in increased tissue injury [50]. Improvements to the design of the acoustic lens of a contemporary Electromagnetic Lithotripter (EML) resulted in the enlargement of the focal zone and significantly less trauma and superior fragmentation (89% stone comminution versus 54%) in a in vivo porcine model [51].

13.2. Dual pulse lithotripter

Distributing the shockwave energy on two applicators is the basis for the dual – EHL system (Direx Duet, Direx Corp, Israel). As shock waves can be delivered along separate paths, the

use of dual shock sources has the potential advantage of reducing treatment time. Twin sources can be operated so that shockwaves are fired simultaneously (synchronous or simultaneous mode) or in sequence (alternating mode). Since this method can manipulate the acoustic field, it also has the potential to improve stone breakage [52]. The limited clinical data available indicates safe application with no advantage over single – source SWL. The main challenge with this approach is creating adequate coupling to the stone [53].

13.3. Future ideas

Recognition of the role of cavitation in stone fragmentation has resulted in increased efforts to enhance the action of cavitation bubbles. One such example is tandem shockwaves generated utilizing a piezoelectric source fitted to an electrohydraulic system with an additional discharge circuit to produce the piezoelectric second pulse [54]. Recently, a similar concept utilizing high – intensity focused ultrasound (histotripsy) with an electrohydraulic lithotripter demonstrated a significant reduction in fragmentation time *in vitro* [55].

On the other hand, cavitation can be detrimental to stone fragmentation. The process results in the production of gas bubbles that last for hundreds of micro seconds, thereby blocking subsequent impulses [56]. Harper and associates developed an innovative technique that utilizes short bursts of focused ultrasonic pulses to transcutaneously reposition stones within the renal collecting system and ureter. Future applications include repositioning stones prior to treatment, expediting the expulsion of residual fragments following ureteroscopy or SWL, and moving obstructing ureteropelvic junction (UPJ) stones into the kidney (to alleviate acute renal colic). The technology is currently being enhanced, and future directions include fusion of the technology with burst wave lithotripsy and stone – specific ultrasound imaging algorithms [57].

Future studies should aim to improve clinical outcomes while simultaneously minimizing complications. The key to achieving better results involves focusing on modifiable factors including shockwave source, focal zone, acoustic output, voltage used, imaging modalities, focusing techniques, and coupling. Lastly, operator or technician experience is critical to success.

14. Conclusion

For the properly selected patients, SWL is a well – tolerated, noninvasive procedure that produces reasonable stone clearance of upper urinary tract calculi while offering low morbidity rates. Recent advances in SWL have produced significant improvements in its safety and efficacy. A drawback to SWL is that retreatments may be necessary.

Ureteroscopy has undergone remarkable advancements in the last 30 years. With the introduction of modern semi – rigid and flexible devices, stones that would have traditionally been considered for SWL, can now be managed via ureteroscopy. In fact, the application of ureteroscopic procedures for upper urinary tract calculi now surpasses that of SWL around the world.

It would be erroneous to conclude that SWL is ineffective or is being replaced. SWL continues to have an important role. Proper selection of patients that are expected to respond well the procedure, as well as consideration of the technical aspects of SWL are key to it success.

Although the features discussed serve as general guidelines for the use of SWL and help predict outcomes, the non – invasive nature of SWL has made it a desirable choice for patients. Many patients that are not ideal candidates for SWL, willingly accept the risk of a failed treatment (and the subsequent need for a secondary procedure) knowing no instrumentation will be necessary with the first attempt.

Acknowledgments

Abbreviations

SWL	Shock wave lithotripsy
CT	Computed Tomography
BMI	Body Mass Index
F2	Second Focus
SSD	Skin to Stone Distance
PCNL	Percutanous nephrolithotomy
HU	Hounsefield Unit
UPJ	Ureteropelvic junction
EML	Electromagnetic lithotripter

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HIGHLIGHTS

- The key to SWL success lies in the proper selection of patients and attention to SWL technique.

- The three modes of SW generation vary in their efficiency.

- New treatment strategies to improve success rates and safety.

- Current evidence indicates that a wide focal zone provides more efficient fragmentation.
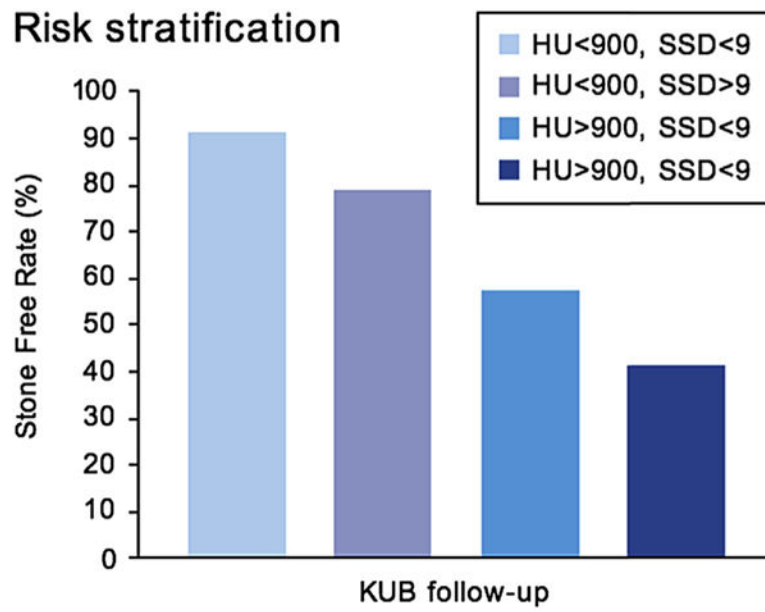
Fig. 1.
Influence of stone density (HU) and SSD. HU, Hounsfield units; SSD, skin-to-stone distance.

Fig. 2.
Stone-free rates for proximal ureteral calculi from the EAU/AUA Guideline.