Shock Wave Lithotripsy for Urolithiasis : Where do we Stand Today?

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***Abstract**: Extracorporeal shock wave lithotripsy provided a non-invasive option of treating urolithiasis. Since its inception, various improvisations in energy source, targeting method, and administration have been made to improve its efficacy. Advances in technology, specially the development of holmium laser have further evolved our approach to treating urinary stone disease. This article revisits the current status of SWL in treating urolithiasis. It highlights the latest technological advances, best practice guidelines and contraindications of SWL.*

INTRODUCTION

Extracorporeal shock wave lithotripsy (SWL), first introduced in 1980, rapidly revolutionized the treatment of stone disease. It allowed renal and ureteral stones to be treated in a non-invasive, outpatient fashion, avoiding invasive surgical procedures. The resultant paradigm shift in stone treatment has stood the test of time with reports in early 21st century showing that SWL accounted for as many as 69% of all stone treatment procedures[1]. Over the years we have better understood the limitations to SWL technology. Safety of performing SWL has shown lack of unanimity. On a larger background of successful medium to long-term safety profile[2], some reports of new-onset hypertension and diabetes mellitus have raised concerns regarding long term consequences of SWL[3]. Increasing experience with SWL found that shock waves may cause renal parenchymal damage, with potential long-term consequences, especially in a subset of patients with renal insufficiency, hypertension, children and the elderly[4,5]. The more recent introduction of miniaturized instrumentation, durable flexible technology and efficacious holmium laser lithotripsy has further evolved the treatment paradigm of nephrolithiasis favouring flexible ureteroscopy and retrograde intra-renal surgery (RIRS) to SWL in a variety of situations.

This article aims to highlight the advances in the technology and methodologies in administering SWL and its current status in treating nephrolithiasis.

PRINCIPLES OF SWL

SWL is based on the principle of acoustic physics, wherein a shock wave generated extracorporeally, and passed through the body experiences acoustic impedance due to change in density, resulting in stone fragmentation[6]. Lithotripters have four main features; an energy source for shockwave generation, a focussing device, a coupling medium and a stone localization system.

Mechanism of stone fragmentation

Stone comminution involves compressive and shear induced fracture, spallation, and cavitation. The first two mechanisms occur due to the positive-pressure wave front. As the shock wave passes through fluid, it has a trailing negative pressure wave which creates microbubbles at the fluid-stone interface which coalesce and burst, releasing energy producing compressive forces which causes stone fragmentation. This phenomenon likely produces fine passable fragments, while the positive pressure component produces larger fragments.

Mechanism of tissue injury

Initially, mechanical trauma to blood vessels caused by cavitation was believed to be the cause of tissue injury. More recently, SWL-induced renal vasoconstriction is additionally considered a major contributory factor, which potentiates tissue free-radical formation[7]. Damage to the kidney in a single session is dose-dependent for pulse amplitude and shock wave number, and an increased risk of long-term adverse effects is associated with multiple lithotripsy sessions[3, 8-11] session.

INDICATIONS AND RESULTS OF SWL

SWL is efficacious in fragmenting and clearing most **'simple' renal stones** up to 2.5 cm in size[12]. However some factors are associated with poorer stone clearance rates- larger stone burden (mean stone size 22.2 mm), stones in dependant (inferior pole) or obstructed collecting systems (uretero-pelvic junction obstruction, calyceal diverticulae, horse-shoe kidneys), harder stone compositions (calcium oxalate monohydrate, cystine) and obesity (larger skin-to-stone distance) or body habitus which limits stone targeting[13].

The success of SWL for treating non-lower-pole stones varies from 62–92% when treating small stones and 33–84% for larger stones[14]. Larger stone burdens require higher retreatment rates and are associated with additional ancillary procedures (stenting, ureteroscopy, even mini-percutaneous nephrolithotomy) to treat complications ('steinstrasse'-impacted ureteral fragments) and residual stones. Larger stone burden, staghorn calculi, infective calculi, stones associated with complex renal anatomy, and those associated with obstruction are better treated with percutaneous nephrolithotomy (PCNL) [15].

Management of the **lower pole stone (LPS)** is more controversial. A randomized control trial of SWL and PCNL for treating LPS revealed poorer outcomes of SWL with increasing stone burden[16]. The reported stone free rate for stone ≤1cm was 63% and 100% for SWL and PCNL, respectively. For stones >1 cm, the stone-free rates were only 21% for SWL and 91% for PCNL. The low success rates achieved with stones in the lower pole are attributable to the effects of renal anatomy and gravity on the retention of fragments, and probably have little to do with the efficiency of stone breakage. Although PCNL resulted in a higher stone-free rate and less need for re-treatment compared with SWL, the complication rate was higher and hospital stay was longer.

Ease of administration, short hospital stay, low complication rates, low morbidity, high safety profile, easier retreatment and acceptable success rates have established SWL as the first line of treatment for most **pediatric renal stones**[17, 18]. Younger children achieve better stone-free rates[19, 20]. This has been linked to the better fragility characteristics of the more recently formed stones in younger children, decreased loss of shock wave impacted due to lower body

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resistance and a more rapid evacuation of the fragments by the ureter[18, 19]. However, stone size remains the most important factor determining stone clearance following SWL even in the pediatric population[21, 22]. Shockwave lithotripsy is an effective modality to treat pediatric upper urinary tract calculi, especially with stone burden ≤ 200 mm[2, 22]. Increasing stone burden necessitates more ancillary procedures and portends lower stone-free rates with a higher complication rate. Endourological options may be more appropriate in such cases.

The two main surgical options for **ureteral stones** are SWL and URS. Alternative procedures include antegrade percutaneous ureteroscopy and laparoscopic uretero-lithotomy[23]. Improvements in ureteroscopic technology has enabled retrograde ureteroscopy to become a first-line option for most ureteral stones. The 2007 AUA–European Association of Urology (EAU) Ureteral Stone Guidelines Panel highlighted the advances in URS in the previous decade and reported that the stone-free rates with SWL and URS for small (<1 cm) proximal ureteral stones were 90% and 80%, respectively[24]. Generally, for small ureteral stones, URS is preferred in the distal ureter and either SWL or URS is acceptable in the proximal ureter[23]. For larger stones, URS seems to result in a higher stone-free rate and less need for re-treatment compared with SWL, but has a slightly higher complication rate and longer hospital stay[24].

LIMITATIONS OF ESWL

SWL was introduced as the 'Holy Grail' of urinary stone treatment with the promise of eliminating virtually any stone without injury to the kidney or urinary tract. Enthusiastic promotion of this new technology led to use of SWL even in complex cases such as multiple stones, bilateral stones, stones in solitary kidneys and staghorn calculi[25-26]. However, increasing experience with lithotripsy highlighted its limitations. Certain stone types (brushite, calcium oxalate monohydrate, and cysteine stones) could be resistant to SWL[13]. Among stones that could be readily broken, fragmentation was not always complete, and the presence of residual fragments often necessitated re-treatment. There is a justifiable concern regarding the retained/ residual stone fragments which despite being asymptomatic could provide a nidus for recurrent stone formation. Variable renal anatomy (lower pole calyx, acute infundibulopelvic angle, calyceal diverticula) also influences clearance of stone debris[13]. Most importantly the relatively limited capacity of the ureter to evacuate stone fragments restricted SWL treatment to a stone burden of less than about 2.5 cm[13, 22].

Reports of sometimes serious adverse effects of SWL in the form of severe hematuria, intraparenchymal hemorrhage and massive renal hematomas requiring transfusion, or even nephrectomy revealed the potential of shock waves to cause rupture of blood vessels [8] Extrarenal damage such as intra-abdominal bleeding, splenic rupture and hematomas of the liver and pancreas were also reported.

Current **absolute contraindications** to use of SWL include uncorrected coagulation disorders, presence of infection, associated urinary tract obstruction and during pregnancy. **Relative contraindications** include large burden stone disease, complex renal anatomy, abnormal body habitus (obese, spinal deformities precluding stone targeting), cardiac arrhythmias, and patients with pacemakers.

ADVANCES IN LITHOTRIPSY

In the last three decades SWL has undergone further evolution, with newer generation devices making SWL a more convenient and effective intervention. Technical changes such as the shock wave source, coupling mechanisms, machine size, imaging and targeting capabilities, and focal zone parameters were made in an effort to improve stone fragmentation and reduce tissue injury.

Shock wave sources

The original Dornier device was an electrohydraulic lithotripter, whereby the shock wave was generated by a spark gap electrode seated in the lithotripter water bath. Explosion at the electrode (spark plug) vaporizes the water between the electrode tips producing a burst of plasma, or energy, which produces a focusable shock wave. Over a period of time the electrode tips progressively erode causing variable and less predictable shock waves[27]. Advancement in electrode technology has made the present day electrodes as encapsulated or self-advancing, which results in greater shock wave consistency and electrode lifespan. Piezoelectric shock wave sources have also been used in SWL as an alternative energy source however it achieved inferior fragmentation rates to those achieved with electrohydraulic versions. Electromagnetic shock wave generators were designed to overcome the shortcomings associated with electrohydraulic lithotripters. They create a magnetic field which moves a membrane, resulting in a shockwave which is then focussed using an acoustic lens. Electromagnetic sources are more consistent, reproducible and durable than electrohydraulic generators, with reported life spans of one to two million shock waves[12].

Treatment heads

All modern lithotripters utilize a 'dry treatment head' as it allows smaller and more portable machines. The important aspect of this is to adequately apply jelly (coupling medium) without any air bubbles/pockets which reduce efficacy of stone fragmentation by 20-40% with even a 2% air pocket in the coupling interface[28]. Recent innovations include a **dual-head machine** which has two sources of shock waves firing along different pathways; these may fire alternately or simultaneously. These are reported to reduce time for treatment as well as improve fragmentation[29-31].

Tandem-pulse therapy is another innovation wherein two shock waves are fired in rapid succession. The second generator is a piezoelectric shock head as an auxillary unit[32].

Focal zone width

In an effort to minimize tissue trauma, newer lithotripter have narrower focal zones. However, there is loss of stone fragmentation efficacy despite achieving higher focal pressures because accurate targeting of the moving stone (due to respiration) is reduced. The optimal setting for efficient fragmentation and reduced organ damage require a wider focal zone and lower pressure[33]. Currently two such newer lithotripters are only recently available, the data for which is yet to mature.

MODIFICATION OF TREATMENT STRATEGY

Newer data has demonstrated that stone fragmentation outcomes are improved at **lower shock wave rate** (60 shock waves per min) compared to a higher rate (120 shock waves per min)[34]. The slower rate is also associated with reduction in tissue damage in the porcine model.

The method of administering SWL also has an impact upon the fragmentation rate. Although no definite protocol exists, the practice of **'power-ramping' (voltage stepping)** is found to be beneficial not only in improved fragmentation rate, but even reduced renal injury. Further studies concluded that rather than the power-ramping, the effect of including 'the pause' to the protocol was the actual protecting effect[35,36]. The initial low-voltage shock waves induce a global renal vasoconstriction, which protected the kidney from hemorrhagic injury. Animal studies have demonstrated superior cavitational effects at a point 2cm proximal to F2, therefore better fragmentation is reported if the F2 is placed 2 cm beyond the stone during targeting **(pre-focal alignment)**[37].

Most modern machines have fluoroscopic and ultrasound imaging modalities for stone localization, yet the precise determination of the treatment end point remains unreliable. Softening of stone margins, loss of density and movement of particles are signs of fragmentation, but such features are hard to judge and difficult to qualify[12]. This leads to over-treatment with shock waves. Recent progress includes the development of an **acoustic feedback system** to monitor stone comminution and determine the breakage end point[38]. This allows limiting the number of shock waves during therapy.

Due to respiratory excursions, stones can move upto 5 cm or more in and out of the focal zone of the lithotripter with each breath. Depending on the respiratory rate, the length of excursion, and the focal width and shock wave rate of the lithotripter, the stone can be outside the focal zone during 50% or more of the shots fired, leading to missed shots[39]. Several **acoustic tracking systems for stone targeting** have been developed to track stones during treatment to trigger the lithotripter only when the stone is on target and thus shorten treatment time and reduce exposure to shock waves.

These include use of ultrasound imagers and tracking algorithms, and a system built into a piezoelectric lithotripter to actively steer the beam to hit the moving stone[40,41]. None of these systems have translated into clinical use, but they have demonstrated that tracking can improve the hit rate by about 50%.

ADJUNCTS TO IMPROVING SWL SAFETY AND EFFICACY

Methods of improving **clearance of residual /stone fragments** post SWL include **mechanical intervention** in the form of percussion, diuresis, or inversion of the patient. Transcutaneous focused ultrasound producing acoustic radiation forces and acoustic streaming has been used to move stone fragments in a desired direction in the renal pelvis[42]. The **pharmacological assistance** has included addition of **alphablockers** to improve stone expulsion[43]. Pre-treatment of patients at high risk for acute/ chronic SWL-mediated injury may be protected from free-radical injury by administering **anti-oxidants** (allopurinol, mannitol, vitamin E and even citrate)[44].

BEST PRACTICE GUIDELINES

The current standard is treatment at low-to-moderate acoustic pressures with as few shock waves as possible, to minimize acute and lasting tissue injury, and at a slow shock wave rate (60 shock waves per min or slower), to enhance stone breakage and reduce tissue damage[30]. Damage to the kidney in a single session is dose-dependent for pulse amplitude and shock wave number, and an increased risk of long-term adverse effects is associated with multiple lithotripsies[30].

CONCLUSION

SWL remains the only entirely noninvasive surgical treatment to remove urinary stones. SWL has certain limitations and a spectrum of potentially serious adverse effects. However, significant advances have been made in SWL technology and technique that have begun to improve success rates and reduce the potential for adverse effects. Following 'best practice guidelines' and attention to shock wave parameters and treatment protocols will improve success rates and help to enhance safety.

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