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Review

Extracorporeal shockwave lithotripsy in the management of urinary stones: New concepts and techniques to improve outcomes

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Abstract *Objective:* Extracorporeal shockwave lithotripsy (SWL) currently plays an important role in the treatment of urinary tract lithiasis. The purpose of this article was to describe new concepts and procedural strategies that would improve results using SWL as a treatment for urolithiasis, thereby achieving better clinical practice.
Methods: A systematic review process was carried in PubMed/PMC from January 2003 to March 2023. A narrative synthesis of the most important aspects has been made.
Results: The important recommendations for the adequate selection of the candidate patient for treatment with SWL are summarized, as well as the new strategies for a better application of the technique. Aspects about intraoperative position, stone localization and monitoring, analgesic control, machine and energy settings, and measures aiming at reduced risk of complications are described.
Conclusion: To achieve the therapeutic goal of efficient stone disintegration without increasing the risk of complications, it is necessary to make an adequate selection of patients and to pay special attention to several important factors in the application of treatment. Technological development in later generation devices will help to improve current SWL results.
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1. Introduction

With the development of extracorporeal shockwave lithotripsy (SWL) as a treatment for urinary lithiasis, there was an important change in the management of this disease. Open surgery, which had been the standard treatment, was displaced by a technique that represented a minimally invasive and effective modality with a low rate of complications [1]. Subsequently, the contraindications for the use of SWL in certain patients, as well as its complications, prompted the appearance of endourological techniques. Due to the development and technological advances achieved, we are witnessing a new change in the management of urolithiasis.

We would like to point out that SWL currently plays an important role in the treatment of urinary tract lithiasis. It is a minimally invasive treatment that, with an adequate technique and patient selection, achieves high effectiveness and continues to be a competitive alternative to other therapeutic modalities. The aim of this article is to describe new concepts and procedural strategies that will improve results using SWL as a treatment for urolithiasis, thereby achieving better clinical practice.

2. Materials and methods

2.1. Evidence acquisition

2.1.1. Search strategy

A bibliographic search was carried out in PubMed/PMC database of articles published from January 2003 to March 2023. The terms were used as search criteria: "extracorporeal shockwave lithotripsy AND urinary lithiasis".

2.1.2. Inclusion criteria

The inclusion criteria for the selection and review of the articles obtained were: i) written in Spanish or English; ii) review studies on technical aspects of SWL application for urinary calculi; and iii) studies on the application of SWL in humans.

2.1.3. Systematic review process

Initially, 699 studies were identified, of which 617 were written in English or Spanish. After an initial screening of their titles and abstracts, 183 studies were identified that addressed technical aspects of the application of extracorporeal lithotripsy. The articles with the best level of evidence on SWL treatment strategies were selected. Regarding the procedural strategies, the selected themes include patient selection, patient position and coupling, control pain, and shockwave delivery.

2.1.4. Data extraction

The data were extracted by Bahilo-Mateu P and reviewed by a second author (Budia-Alba A), to avoid possible errors in obtaining and summarizing them.

2.1.5. Data analysis

A narrative synthesis of the most important aspects of the included studies has been made.

3. Results

3.1. Patient selection

As in any other therapeutic technique, it is important to apply the appropriate indications for it. The clinical history and physical examination will allow the identification of factors that absolutely or relatively contraindicate the procedure. According with the International Alliance of Urolithiasis guideline on SWL, SWL is contraindicated in the following clinical conditions: pregnancy, untreated coagulation abnormality, tumor, aneurysms or other significant pathology in the shockwave path, uncontrolled urinary tract infection, anatomic obstruction distal to the stone, and untreated or severe hypertension [2]. Likewise, we must pay special attention to other factors related to the lithiasis and the anatomy of each patient that will determine the result of the treatment. Nowadays, it is mandatory to make the diagnosis based on CT examination with or without intravenous contrast. Radiological examination allows the identification of important morphological characteristics including stone burden (longest diameter, stone surface area, or volume), stone location, stone density (using Hounsfield unit [HU]), and the distance between the lithiasis and the skin (skin-to-stone distance). The presence and degree of urinary tract dilatation and the morphologic status of the renal parenchyma should be determined. Contrast-enhanced CT can provide detailed information on stone location and renal collecting system anatomy, especially in complex cases such as calyceal diverticula and parenchymal calcification. Such information is important in predicting the response to treatment and the need for repeat sessions or other necessary precautions.

Stone burden is one of the most important risk factors compromising the stone-free rate following SWL. Stones with maximum diameters up to 20 mm (the stone surface area of approximately 200—225 mm^2) are generally considered to be suitable for SWL [3]. That size limit is occasionally extended to 20—30 mm (corresponding to the stone surface areas of about 225—450 mm^2) for stones with low hardness [4], and in such a case, it is advisable to exclude brushite and cystine compounds (compact type) and probably also calcium oxalate monohydrate due to its recognized resistance to SWL [5].

Lithiasis located in the lower calyceal group deserves special attention due to the difficulty in expelling residual fragments in that location. The use of SWL is not recommended for the treatment of stones larger than 15 mm (the stone surface area of approximately 115—180 mm^2). Some authors have even suggested a limit of up to 10 mm (the stone surface area of approximately 50—80 mm^2) [6]. In addition to stone size, using contrast-enhanced CT we can assess for unfavorable inferior calyx anatomical features for SWL including long infundibulum, narrow infundibular neck, and acute infundibulopelvic angle [3].

Stone density measured in HU has been related to stone composition. Approximate limits for lithiasis according to its composition have been published. If a prior analysis and the composition of the lithiasis are available, it is the most accurate information, but otherwise, the determination of this measurement predicts its composition and resistance to fragmentation by shockwaves [7,8]. In general, it is not recommended to use SWL for the treatment of lithiasis with CT measurement value of 1000 HU. It is worth mentioning the importance of skin-to-stone distance. Several studies have reflected the inversely proportional relation between the distance of the shockwave generator and the lithiasis, and the rate of fragmentation [9,10]. Disintegration of stones in obese patients by extracorporeal lithotripsy is difficult due to the limited penetrating ability of the lithotripter. In addition, energy loss occurs through the different tissue during the passage of the shockwave until it reaches the lithiasis. It has been shown that in patients with a skin-to-stone distance of more than 100 mm and a stone density greater than 1000 HU, the probability of stone fragmentation was significantly decreased [11].

3.2. Strategies during treatment

After the proper selection of the candidate patient for lithiasis treatment by SWL, we must pay special attention to the appropriate way to apply the treatment waves. The effectiveness in the disintegration of a lithiasis through the application of SWL depends on the energy applied to the lithiasis exceeding the disintegration threshold. Tight control of a several factors has been shown to influence the efficiency of fragmentation, therefore, being able to improve the effectiveness and minimize the risk of SWL [2].

Broadcast of the shockwave depends on the medium and the interfaces that go through. In current lithotripters, there is a gap between the shockwave source (therapy head) and the body that must be bridged. A perfect coupling between the therapy head and the body avoiding the presence of air bubbles in the acoustic gel applied between the skin and the therapy head is strategies that increase the effectiveness of SWL. Therefore, meticulous care is necessary when the transmission medium is applied to avoid the appearance of bubbles in the gel, which drastically reduces the effectiveness of SWL as demonstrated by Pishchalnikov et al. [12]. It has been determined that the modality of application of the gel that a smaller number of bubbles generated is that which is carried out from a container with a wide mouth, with respect to other modalities such as application by hand or by zig-zag movements from a narrow-mouthed bottle [13].

Regarding the patient position, a stable supine position is preferred regardless of the stone location if an under-table and an over-table shockwave generator are available [2]. Those cases in which the iliac crest blocks the passage of shockwaves require a ventral or ventrolateral position of the shockwave head if the lithotripter head is mobile and can be placed on the table. For lithotripters with a shockwave head located under the table, patients should be treated in the prone position. When the shockwave passes through the intestinal air, it is advisable to increase the pressure of the therapy head to avoid the interposition of intestinal gas in the trajectory of the shockwave.

A more intensive fluoroscopic monitoring during the session, a greater analgesic control, and an effective reduction of respiratory motion, increase the proportion of waves that reach the focal point of the stone, increasing the total energy accumulated [14—16]. The hit rate of shockwave is occasionally low in the kidney or proximal ureter as a result of the patient's respiratory movements. The basic rule is to place the stone in focus during expiratory phase or apply a belt for generating abdominal compression.

Manufacturers have designed two basic stone localization systems: the fluoroscopy system and the ultrasonographic system. When using fluoroscopy, urologists should take all necessary precautions according to the as low as reasonably achievable (ALARA) principles to reduce exposure to ionizing radiation. Fluoroscopy time, distance, mode setting, and shielding should be considered during the treatment to reduce the patient's radiation exposure. Other measures to reduce the radiation dose include intermittent fluoroscopy, use of collimators, decreasing the radiation field as soon as the stone has been identified, holding of the last image, avoiding image magnification, application of dose level settings, pulsed fluoroscopy, and a focus on training operators in awareness of ALARA [17].

Although pain relief during SWL is important, not only to provide patient comfort, but also to facilitate treatment success, no consensus has yet been reached regarding optimal pain management for patients undergoing SWL. The development of newer lithotripters that require lower energy levels and less skin surface contact has led to improvements in pain levels and consequently the need for peri-procedural analgesia. Overall, nonsteroidal anti-inflammatory drugs, opioids, and simple analgesics provide adequate analgesia for the purposes of SWL [18]. Use of general or regional anesthesia reduces the patient's body and respiratory movements, improving effectiveness but increasing its cost. General anesthesia should usually be reserved for infants and young children. For most patients, the entire treatment procedure can be completed with pain relievers and sedatives alone. The combination of morphine and midazolam is sufficient for treatment. In our experience, we were told about the importance of avoiding pain peaks, so periodic administration should be planned based on the patient's weight.

If SWL presents an advantage over other more invasive techniques in the treatment of urinary lithiasis, it is the possibility of performing it on an outpatient basis and using on-demand analgesia-sedation according to patient tolerance. This practice makes it a most cost-effective technique compared to other modalities [19,20]. Complementary therapies including music distraction seem to have acceptable advantages in terms of lowering analgesia requirements and patient anxiety during SWL [21].

The disintegration effect is cumulative and depends on the energy delivered. The number of shockwaves and the energy delivered with each single shockwave determine the total energy dose. It is recommended to adjust the shockwave parameters according to the characteristics of the case. Overtreatment must be avoided since the risk of side effects is also directly related to the total energy dose.

The most recent strategies have focused on improving the safety profile as the first objective, and some of them have also shown an increase in efficiency. The ramping technique is recommended and has several advantages. It is easier for the awaken patient to adapt to the treatment. Ramping facilitates stop at which level stone disintegration starts and overtreatment in terms of energy can be avoided. Therefore, ramping technique results in better disintegration than a power level constantly used during the treatment. Delivering high energy dose results in large fragments of the stone and delivering low energy dose generates small fragments.

A low shockwave frequency is recommended for less renal vascular and tissue injury and better stone fragmentation [2,3]. Ultraslow full-power SWL (30 shockwaves/min) for high attenuation value stones is associated with an improved stone-free rate without affecting safety [22]. In our experience, lithiasis fragmentation depends directly on the energy dose or energy accumulated in the lithiasis. Although the use of a low frequency of shockwaves (60—90 shockwaves/min) can improve stone fragmentation, if enough effective energy is not reached above the stone (totally energy dose), fragmentation probably will not occur (fragmentation threshold).

The precise sequence of shockwave delivery (number of shockwaves at various power settings) in such a step-wise protocol has not yet been standardized and may vary considerably depending on the preference and experience of the urologist. In our department, we evaluated the large volume of practice and experience in SWL delivery. To evaluate the efficacy and safety of increasing the energy dose in treating urinary lithiasis with extracorporeal lithotripsy through an expanded number of shockwaves per session (SWPS), we performed a comparative study with patients with renal or ureteral lithiasis [23]. Two groups were studied: patients treated with 3500 SWPS and the other group subjected to an expanded treatment with 7000 SWPS. In our study, increasing the energy dose applied through an expanded number of SWPS proved to be more effective than standard regimens with a similar safety profile. This was particularly evident when lithiasis was in the kidney, regardless of the size. In ureteral location, the greatest efficiency observed by applying a higher energy did not reach statistical significance. Despite it, when each portion of ureter was analyzed, statistical significance was achieved in the distal ureter.

Finally, it is important to note that patients with a history of hypertension, diabetes mellitus, and generalized vascular calcifications with fragile vasculature may be at increased risk of developing renal hematoma. Subcapsular hematoma is a consequence of rupture of the great vessels of the renal capsule; therefore, it will be also necessary to be aware of this problem when treating proximal ureteral calculi in proximity to the lower pole of the kidney. However, shockwave disintegration of stones in the mid and distal ureteral locations is not a problem in this regard. It is mandatory to monitor blood pressure during treatment and administer antihypertensive treatment if necessary. Besides, the use of strategies of ramping, particularly in the renal location of lithiasis, has shown a decrease in the rate of renal hematomas because of renal vasoconstriction which is produced by the procedure. The utilization of this strategy combined with a pause of 3—4 min after the application of the first 100—500 shockwaves has been shown to reduce damage kidney with increased fragmentation [24,25].

3.3. New lines of research

Currently there are three basic types of lithotripters: electrohydraulic, electromagnetic, and piezoelectric. Stone fragmentation is achieved by subjecting the stone to a series of high-amplitude ultrasonic pulses. These pulses are mechanical waves that produce shear forces inside the calculi and high internal stresses. After being subjected to such mechanical stresses, the stone fractures into smaller fragments that are expelled [26]. These pulses produce a uniform compression on the stone, so for the fragmentation of the solid material to occur, pressure values in the focal zone of the order 60 MPa must be reached. Under this mechanical stress, complications such as bleeding and damage to healthy tissue commonly occur.

Advances in the understanding of stone comminution have resulted in a novel application of focused ultrasound to propel and fragment kidney stones. We know that comminution is a product of direct energy from shockwave produced by high amplitude compressive and indirect energy from collapsing cavitation bubbles produced by low amplitude tensile. With this technology, the best results have been obtained by Dornier HM3 lithotripter (Dornier MedTech, Munich, Germany), because it delivers shockwaves with relatively lower pressure amplitudes to a broader focal zone. It seems to reduce the excessive production of bubbles, which can decrease the energy of following waves from contacting the stone. Burst wave lithotripsy (BWL) is a novel technological modality that delivers focused, sinusoidal ultrasound pulses in short bursts transcutaneously. The use of lower energy amplitudes has less potential for surrounding tissue damage, avoids serial wave attenuation by residual cavitation bubbles, and can be delivered with a modified ultrasound transducer. BWL is highly efficient at stone comminution, and it generates finer fragments with the high frequency of ultrasound and tends to fragment the stone at the working face, which is much like a laser rather than the block fragmentation seen with SWL. This compact handheld probe relies on ultrasound guidance to deliver low peak pressure ($<$12 MPa) at high rate ($<$200 Hz). It tends to fragment the stone at the working face, much like a laser rather than the block fragmentation seen with extracorporeal SWL. Therefore, tissue injury during BWL exposure is detectable in real-time and manifests as increased echogenicity on ultrasound imaging. The threshold duration of echogenicity for more than 20 s has demonstrated to be correlated with injury 100% BWL-related [27].

Our unit is working on technologies for focusing acoustic beams and on the development of new technique that allows the fragmentation and efficient elimination of stones using mechanical waves with reduced amplitudes to minimize the pain suffered by the patient, as well as adverse effects and complications of the usual extracorporeal SWL procedures.

When a high-intensity ultrasonic vortex beam is focused on stones, it produces torques, shear stresses, and high internal stresses that fragment stones much more efficiently than current techniques. Since shear stress generation is more efficient using vortex beams, the ultrasonic field amplitudes required to fragment stones are much smaller than in current extracorporeal SWL techniques, thus minimizing unwanted effects on the stones and soft tissue, such as bleeding into surrounding tissue or cavitation damage. A vortex acoustic beam system is being developed for minimally invasive stone fragmentation. In such a system, vortex beams can be modulated in intensity, phase, repetition rate, topological charge, *etc.*, depending on the size, location, and composition of the mass to be destroyed, as well as the energy that the beam transfers to the mass. In energetic terms, the proposed technique would reduce the energy required for fragmentation up to 100 times less than with current SWL techniques. In this way, the use of acoustic vortices has enormous potential to reduce the risk of cavitation and damage to surrounding healthy tissue, and thus to constitute a new generation of more efficient and safer lithotriptors.

4. Conclusion

Extracorporeal SWL is an effective and minimally invasive treatment, and it plays an important role in the treatment of urolithiasis. To achieve the therapeutic goal of efficient stone disintegration without increasing the risk of complications, it is necessary to make an adequate selection of patients and, in addition, to pay special attention to several important factors in the application of treatment. Technique in lithotripsy is critically important, and it is encouraging that simple and practical steps can be taken to improve the safety and efficacy of SWL. Urologists should be aware that new treatment strategies are being developed to increase the efficacy with a similar safety profile.

On the other hand, the development of new technologies will help to improve the design of later generation devices for the application of extracorporeal lithotripsy with which results comparable to the treatment applied with the original Dornier HM3 equipment can be obtained.

Author contributions

Study concept and design: Pilar Bahilo-Mateu, Alberto Budia-Alba.
Data acquisition: Pilar Bahilo-Mateu.
Data analysis: Pilar Bahilo-Mateu, Alberto Budia-Alba.
Drafting of manuscript: Pilar Bahilo-Mateu, Alberto Budia-Alba.
Critical revision of the manuscript: Alberto Budia-Alba.

Conflicts of interest

The authors declare no conflict of interest.

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