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TOPIC PAPER

Stone technology: intracorporeal lithotripters

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Abstract
Purpose Intracorporeal lithotripsy is becoming the most commonly used surgical method of stone treatment in Urology. The five major types of intracorporeal lithotripters are ultrasonic, ballistic, and combination lithotripters as well as laser and electrohydraulic lithotripters. The advantages and disadvantages of choosing each of these treatment modalities are reviewed.
Methods Extensive review of literature was performed to identify the types of intracorporeal lithotripters. An investigation was undertaken of the early development of each modality of intracorporeal lithotripsy and/or the mechanism of action. Challenges of each technique were identified and presented. Finally, a determination was made of how these lithotripters compare on the basis of effectiveness of action and cost based on information provided in primary literature as well as previous reviews of these modalities.
Results Contemporary lithotripters have found widespread use in the management of urinary lithiasis. Holmium laser lithotripsy has become one of the most commonly used tools for intracorporeal lithotripsy.
Conclusion There is a wide variety of intracorporeal lithotripters which can be chosen based on the characteristics of each modality and the requirements of the urologist.

Keywords Nephrolithiasis · Lithotripsy · Lithotrites · Percutaneous nephrolithotomy

Introduction

Intracorporeal lithotripsy provides a minimally invasive means of stone management. Unlike extracorporeal shock wave lithotripsy (ESWL), contemporary intracorporeal lithotripters are used under direct visualization, allowing for real-time confirmation of stone treatment. Use of the various modalities of intracorporeal lithotripters has now all but eclipsed open surgical methods of treating urinary calculi. Indeed, intracorporeal lithotripsy is now recommended by both the AUA and EAU as the preferred treatment option for percutaneous nephrolithotomy and is increasingly used and recommended for the management of ureteral and bladder calculi [1, 2]. This review aims to provide an overview of the various types of intracorporeal lithotripters. This will include a discussion of the mechanics of each instrument and/or a comparison of their uses and effectiveness of action. One way of classifying these lithotripters is by mechanism of action. They can be categorized into mechanical, ultrasonic, combination, electrohydraulic, and laser lithotripters.

Mechanical lithotripters

Mechanical lithotripters include ballistic lithotripters as well as the manually operated bladder calculus fragmenters which were the first lithotripters to be developed. The history of lithotripsy began in the early 1800s with physicians attempting intravesical means of treating stones. Franz von Gruithuisen developed the first model of a functioning lithotrite, the Steinbohrer or stone drill in 1813. It was designed to drill holes into bladder calculi [3]. The term lithotrite was coined by Jean Civiale who developed the

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trilabe, and instruments with an inner and outer tube used to grind and grasp a bladder stone, respectively. In 1821, he officially performed lithotripsy on a living subject for the first time. The first practical device for actual stone crushing was developed by Baron Charles Louis Stanislaus Heurteloup [3]. By 1833, the basic principle for lithotrite functioning had been developed and remained unchanged until the 1900s.

In the 1870s, Henry Bigelow improved on the practice of lithotripsy by developing a dual tube system in which a second catheter was used strictly for the evacuation of calculus fragments, coining the term litholapaxy to describe this new procedure. Decades later in 1908, Hugh Hampton Young introduced the first lithotriptoscope, in which stones could finally be viewed intracorporeally while they were being grasped. This ushered in the contemporary era of lithotripsy under vision [4].

Current lithotripters used in the treatment of bladder lithiasis continue to utilize the classical endourologic approach of fragmentation under vision with fragment removal per urethra. These “stone crushers” include the bladder stone crusher (Karl Storz, Tuttlingen, Germany), which utilizes a turning screw for fragmentation. Other contemporary instruments include stone crushing forceps and the Mauermayer stone punch (Ark Meditech Systems, Gujarat, India).

Ballistic lithotripsy was widely introduced in the 1990s for stone fragmentation. Since their establishment, these lithotripters have been successfully used on many types of stones throughout the collecting system [5]. The mechanism of action is akin to that of a jackhammer, where the energy of contact is transferred to the stone, thus resulting in fragmentation. Ballistic lithotripters include electrokinetic lithotripters which use electromagnetic energy to accelerate the projectile. However, most ballistic lithotripters are of the pneumatic-ballistic type which utilizes compressed air to propel a projectile at the stone of interest. Pneumatic-ballistic lithotripters have multiple firing modes ranging from single pulses to continuous firing. Based on extensive work investigating the efficacy of ultrasonic lithotripters, the single-shot pulsing method has been shown to be the most efficient [6]. Ballistic lithotripters are most successful when placed in direct contact with the stone. As seen with ultrasonic lithotripters, rigid probes have been found to be more effective with this mode of stone fragmentation than flexible probes [7]. However, flexible ballistic lithotripters do exist. For example, flexible ballistic probes are available for use with the Swiss Lithoclast system (Electro Medical Systems, Nyon, Switzerland).

Challenges of ballistic lithotripsy include stone retropulsion during treatment [8]; fixed or large stones have been most suitable for these instruments. Many initial pneumatic-ballistic lithotripters consisted of a solid probe that did not allow for fragment evacuation. This shortcoming was addressed in the formulation of subsequent devices which have incorporated suction channels, improving the efficiency of this treatment modality. Advances in ballistic lithotripters include handheld instruments such as the Stonebreaker which demonstrated more efficient fragmentation compared to the original Swiss Lithoclast [9]. Ballistic lithotripsy is a cost-effective method of calculus fragmentation. Pneumatic-ballistic lithotripters have been shown to cause minimal injury to tissue and have been demonstrated to be safer than other intracorporeal lithotripters [10].

Ultrasonic lithotripters

Ultrasonic lithotripters were originally used experimentally in the early 1950s [11]. Clinical use was first attempted almost 20 years later in the fragmentation of bladder calculi and they have since been applied to the fragmentation of stones during percutaneous nephrolithotomy, which is currently the most important clinical application for contemporary ultrasonic lithotripters [12].

Ultrasonic lithotripters have been shown to work best when used through a rigid endoscope. Thus, contemporary ultrasonic lithotripsy is performed in conjunction with the use of a rigid scope under direct visualization [5]. Calculus fragmentation occurs with the use of the vibrational energy of ultrasound waves, generally at a rate of 20 kHz. Stone particles are formed on contact of the ultrasound probe with the initial calculus. The ultrasound probe tip causes high-frequency resonation of the calculus which in turn results in fragmentation. However, ultrasonic lithotripters do not work equally well on all stone types; they have been demonstrated to be successful with small, less dense stones with a rough surface [13]. The ultrasonic lithotripter core is hollow allowing for suctioning of the resultant stone fragments.

One of the challenges of ultrasonic lithotripters is the requirement for contact with the stone to achieve successful fragmentation. It is important to guard against the application of excessive pressure since this may result in pushing of the calculus into the urothelium. These lithotripters also create larger fragments as manual compression of the stone is increased, thus requiring careful manipulation [5]. Care must also be taken to avoid bending the probe since this may cause heating at the point of flexure. These probes are vulnerable to clogging which can also cause heating particularly in smaller diameter probes. Although rare, there is a small risk of tissue perforation with the use of ultrasonic lithotripters [5]. However, they have generally been shown to cause minimal tissue damage [14].

Combination lithotripters

The most recently developed rigid lithotripters are combination models which join two treatment modes in an attempt to increase the efficiency of stone treatment. There are currently two such models: one combines ultrasonic and pneumatic-ballistic probes; the other combines two ultrasound probes, one of which is fixed and the second movable.

The Lithoclast ultra (Electro Medical Systems, Nyon, Switzerland) was the first of the combination models to be introduced. Its design utilizes a pneumatic-ballistic probe placed through a hollow metallic ultrasound probe with the pneumatic probe tip extending 1 mm beyond the hollow probe. This lithotripter allows for the use of each component singly or in combination. The mechanism of action is identical to that of each component when activated individually. Several studies have now compared this combination device to individual ultrasonic lithotripters as well as pneumatic lithotripters and have demonstrated superior results [27].

The Cyberwand system (Gyrus ACMI, Southborough, A) combines two ultrasound probes. The design incorporates a fixed inner probe and a movable outer probe operating at different frequencies, with the outer probe vibrating in response to the inner probe. Vibration of the inner probe results in the sliding movement of a piston whose motion pushes the outer probe forward. Both the Lithoclast and the Cyberwand have been demonstrated to be effective at fragmenting hard stones. However, the Cyberwand does so with less of a jackhammer effect since the outer probe does not extend past the inner probe in this machine [5].

The safety of combination ultrasonic–pneumatic-ballistic lithotripters has been established and shown to be comparable to that of regular ultrasonic lithotripters. However, investigation of Cyberwand function demonstrated that in comparison to ultrasonic and ultrasonic–pneumatic lithotripters the dual ultrasonic lithotripters did result in a higher rate of perforation [13].

Electrohydraulic lithotripters

Electrohydraulic lithotripsy (EHL) was the first technology specifically developed for intracorporeal lithotripsy in 1955 at the University of Kiev. Subsequent modifications led to the development of the Urat-1 which was first used to fragment bladder calculi in 1960 [14]. The use of EHL was first extended to renal calculi in 1975 during open lithotomy and to the management of ureteral calculi 10 years later with the use of a rigid ureteroscope [14]. EHL probes are flexible lithotripters for the treatment of stones in areas that are difficult to approach. Flexible intracorporeal lithotripters have been proven particularly useful in navigating urinary diversions/reservoirs, ureteral stenosis or stricture, and the inflammatory reaction associated with impacted stone [13]. The EHL modality uses electrohydraulic or spark-gap generated shockwaves to fragment urinary calculi. A high voltage of 3–6 kV is applied across the electrode leads of the lithotripter, creating a spark [14]. The effect of the spark-gap is to create a cavitation bubble (as described in the associated article on ESWL) which in turn produces sound wave energy able to disintegrate a stone. The cavitation bubble size is solely dependent on the energy utilized. Bubble diameter can have a detrimental effect on urothelial tissue, causing distention or disruption even in the absence of direct probe contact [15]. Thus, care must be taken to minimize the quantity of energy used.

Tissue damage may also result from the application of multiple discharges in the same location irrespective of energy level. This damage has been demonstrated to include swelling, hemorrhage, and mucosal denudation [15]. The most significant challenge of EHL use is the ability of these lithotripters to cause tissue perforation on direct contact of the activated probe. Ureteral perforation has been a significant risk with widely documented incidents of ureteral extravasation. This has been mitigated but not removed by the development of a plasma shield which incorporates a hollow spring and a metal end cap [5, 16]. Retropulsion of stone is also a concern with EHL. Hence, the safe use of EHL requires the avoidance of multiple or rapidly repeated shocks in one area and using the least energy necessary to successfully fragment stone. At moderate energy levels and at the appropriate distance to the surface of the calculus, stones can be safely and effectively fragmented.

Improvements to the EHL technology have resulted in smaller probes with 1.6-Fr probes now widely available. The small flexible probes are able to be positioned within the working channel of flexible ureteroscopes and provide little to no hindrance to ureteroscope deflection, thus allowing access to difficult-to-reach stones. EHL has been particularly successful in the management of lower pole calyceal stones with acute infundibulopelvic angles [13]. It is also the least expensive intracorporeal lithotripter and has been shown to be effective in both the kidney and ureter. However, the use of EHL is contraindicated in impacted ureteral calculi and in pregnancy [5].

Laser lithotripters

The word laser is an acronym for light amplification by stimulated emission of radiation. In laser lithotripsy energy is produced by the stimulation of an atom which in turn produces excited electrons. It is these excited electrons that release laser energy in the form of light. Laser lithotripsy is rapidly becoming the most widely used form of intracorporeal lithotripsy [13]. It is now the favored modality for the surgical management of bladder lithiasis [17]. While many lasers have been introduced including the ruby, coumarin green pulsed dye, alexandrite, and neodymium lasers, holmium:yttrium–aluminum–garnet (YAG) is now the most commonly used. Holmium:YAG lasers are solid state and release infrared light at a wavelength of 2140 nm. In these lasers, photothermal energy is primarily used to fragment stones. The stones are disintegrated as a consequence of direct absorption of laser energy. There are several laser fiber diameters currently in use with the 200 µm fiber generally reserved for fragmentation of difficult-to-access lower pole calculi. The 200-µm fiber allows for increased ureteroscope deflection as opposed to larger fibers, hence facilitating access to lower pole calyces. While most holmium laser fibers are sufficiently flexible to be used in flexible ureteroscopes, larger fibers such as those of 550 and 1000 µm are generally used in rigid scopes due to their decreased maneuverability. Holmium laser fibers are used at settings ranging from 0.2 to 1.5 J and 5 to 60 Hz with lower energy/higher frequency settings used specifically for dusting of stones generally at settings of 0.2–0.5 J and 15–60 Hz [18]. Laser energy has been demonstrated to be effective on all stone types and in all regions of the urinary tract [5].

One significant disadvantage of holmium lasers is the expense of this modality. The holmium laser is quite costly as are the individual laser fibers. Additionally, the holmium laser is capable of transecting guidewires and baskets. Other challenges associated with the use of the holmium laser include post-operative ureteral stricture formation, seen at a rate of less than 1% [19].

Holmium laser and flexible ureteroscopy have been effective in the treatment of stones in several, otherwise, challenging patient populations including morbidly obese patients, those on anticoagulation and patients with abnormal anatomy such as pelvic kidneys. Patients with recurrent large stones or a history of cystine stone formation have also benefited from the adoption of this treatment modality. Laser lithotripsy has also proven safe in pregnancy, enabling efficient definitive management in these patients. A further potential use of flexible ureteroscopy with the holmium laser is in the treatment of patients with symptomatic nephrocalcinosis. Laser papillotomy and lithotripsy of the underlying intra-parenchymal calculi have resulted in patient reports of decreased pain and narcotic use [20].

The holmium laser energy is significantly absorbed by water. It has been shown to be safer than EHL since, although it does penetrate tissue, it can safely be used 0.5–1 mm away from the mucosal wall. Holmium laser use has also been shown to result in superior stone-free rates as compared to ESWL [16] and in comparison with pneumatic-ballistic lithotripsy, holmium laser use resulted in better stone-free rates, decreased repeat procedures, and shorter hospitalizations [21].

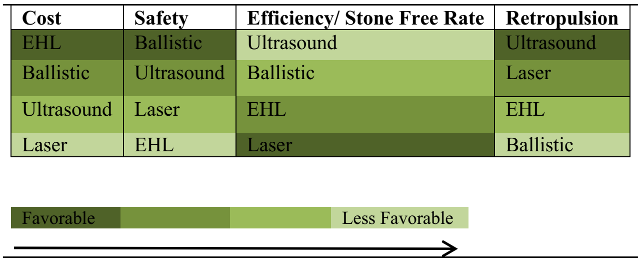
Discussion

The advantages and disadvantages of each type of intracorporeal lithotripter must be taken into consideration when choosing a treatment modality for a given case. Largely flexible lithotripters such as EHL and holmium–YAG are able to access most areas of the collecting system.

With the use of EHL, however, comes the risk of significant damage of urothelial tissue including ureteral perforation. Most lithotripters are associated with retrograde propulsion of urinary system calculi. This effect is worse in EHL as compared to laser lithotripsy [22]. Holmium lasers have been demonstrated to successfully treat all stone types with excellent stone-free rates [22]. It is also safer than EHL and has been demonstrated to result in decreased retropulsion in comparison [23], particularly with smaller fibers [24] and increased pulse duration settings [25]. However, the ongoing cost of laser fibers makes this an expensive modality.

Ballistic lithotripters also demonstrate increased stone retropulsion as compared to laser lithotripsy [23] but they have a better safety profile with regard to perforation of the ureter than ultrasonic lithotripters as well as EHL and laser lithotripsy [10]. Ultrasonic lithotripters allow for simultaneous stone fragmentation and evacuation,

Table 1 Comparison of intracorporeal lithotripters



Cost	Safety	Efficiency/ Stone Free Rate	Retropulsion
EHL	Ballistic	Ultrasound	Ultrasound
Ballistic	Ultrasound	Ballistic	Laser
Ultrasound	Laser	EHL	EHL
Laser	EHL	Laser	Ballistic

Lithotripter modalities compared on a scale of most favorable to least favorable with respect to cost, safety, retropulsion, and stone-free rate thus increasing efficiency. However, they show varying levels of effectiveness dependent on stone type and have been used more successfully in PCNL as compared to the treatment of small ureteral calculi [13]. Combination devices have generally improved on the fragmentation and clearance of large or complex stones managed by PCNL [26]. Table 1 provides a comparison of the different types of lithotripters.

Conclusion

Intracorporeal lithotripsy encompasses the use of a variety of rigid and flexible lithotripters. Advantages and disadvantages of each allow the urologist to choose a modality based on several factors including type and location of stone as well as cost of the procedure. Extensive experimentation with these lithotripters has revealed that ballistic lithotripters are often the safest instruments but are most closely associated with stone retropulsion. EHL is the cheapest modality but also the least safe, whereas holmium laser lithotripsy is the most costly but also the most efficient modality.

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