Published in final edited form as:

Adv Chronic Kidney Dis. 2009 January ; 16(1): 60–64. doi:10.1053/j.ackd.2008.10.008.

Surgical Management of Stones: New Technology

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Abstract

In recent years, the surgical treatment of kidney stone disease has undergone tremendous advances, many of which were possible only as a result of improvements in surgical technology. Rigid intracorporeal lithotrites, the mainstay of percutaneous nephrolithotomy, are now available as combination ultrasonic and ballistic devices. These combination devices have been reported to clear a stone burden with much greater efficiency than devices that operate by either ultrasonic or ballistic energy alone. The laser is the most commonly used flexible lithotrite; advances in laser lithotripsy have led to improvements in the currently utilized Holmium laser platform, as well as the development of novel laser platforms such as Thulium and Erbium devices. Our understanding of shock wave lithotripsy (SWL) has been improved over recent years as a consequence of basic science investigations. It is now recognized that there are certain maneuvers with SWL that the treating physician can do that will increase the likelihood of a successful outcome while minimizing the likelihood of adverse treatment-related events.

Index Words

Shockwave lithotripsy; Lithotrite; Laser; Holmium; Thulium; Erbium

Introduction

The surgical treatment of patients with kidney stone disease is greatly dependent on surgical technology, and as technology advances, procedures and techniques that were at one time inconceivable become possible and even commonplace. No case shows this progression better than shockwave lithotripsy (SWL); patients who once required open surgical stone removal could, after the introduction of SWL, be treated in a completely noninvasive fashion. Just over 2 decades after its introduction, SWL has become the most commonly applied treatment for patients with upper urinary tract stone disease.¹

Although in recent years we have not witnessed the introduction of a paradigm-shifting technology such as SWL, more subtle advances have, nonetheless, occurred. Herein, we review recent advances in surgical technology used in the treatment of patients suffering from stone disease.

Intracorporeal Lithotripsy

Ultrasonic and Ballistic

Intracorporeal lithotripsy is one of the integral elements of percutaneous stone treatment. In general, the majority of commercially available intracorporeal lithotripters are ultrasonic devices, which can efficiently fragment and remove the majority of stone types. However, there are certain stones, such as those composed of cystine or calcium oxalate monohydrate, that are less efficiently fragmented and removed with ultrasonic technology. For such stones, pneumatic lithotripters are often used for fragmentation because these devices readily break stones of any composition. However, the chief disadvantage of pneumatic lithotripters is their inability to concurrently evacuate stone debris while fragmenting the stone. Rather, manual fragment removal is necessary when using a pneumatic lithotrite, an often time-consuming process.

Several manufacturers have introduced combined ultrasonic and pneumatic devices that aim to combine the superior fragmentation ability of the pneumatic component with the ability of the ultrasonic modality to simultaneously evacuate stone fragments. The first combination device brought to the clinical market was the Lithoclast Ultra (Boston Scientific, Natick, MA), which relied on a combination hand piece (actually, 2 separate hand pieces connected together) to join the ultrasonic and pneumatic components. The first portion of the combination hand piece was a traditionally designed pneumatic handle, with a smaller diameter solid probe. The ultrasonic handle, driven by a standard piezoelectric mechanism, was modified to allow the coaxial insertion of the pneumatic probe. Each modality could be activated separately or in unison; when operated in unison, the ballistic fragmentation of the stone is accomplished with the pneumatic component, and the ultrasonic component then removes the resulting debris.

A rigorous and impartial evaluation of intracorporeal lithotripters is a subject of importance to urologists because each device may have certain unique properties that make it more suitable for particular applications. Manufacturer's claims may contain elements of bias, making it difficult for the urologist to ascertain which device may be most suitable for their practice. Therefore, a number of investigators have devised testing methods to compare intracorporeal lithotrites. Liatsikos^{et al}² first reported an in vitro testing system designed to measure the efficiency of ultrasonic lithotrites in which stone phantoms were fragmented in a nephroscope-guided manner. The inherent weakness in this study design was that stone fragmentation was directed by hand, which could introduce significant operator bias. Haupt and Haupt³ subsequently reported an in vitro system that relied on an elaborate weight and fulcrum to bring a stone phantom into contact with the probe tip at a constant force. Although operator bias was no longer present, this system was complex and cumbersome, making replication challenging. Kuo *et al*⁴ have presented a novel and simple hands-free testing system in which the ultrasonic hand pieces were secured upright and the stone phantom placed into contact with the probe by a weight mechanism (Fig 1). This design system was first used to test the efficiency of pure ultrasonic lithotrites and measured the time it took for the probe to penetrate the stone phantom. In this study, the Olympus LUS-2 (Olympus, Melville, NY) produced the fastest overall stone penetration time.

After the introduction of the combination ultrasonic and pneumatic devices, the same testing apparatus previously used by Kuo *et al*⁵ to evaluate the ultrasonic devices was used to evaluate the Lithoclast Ultra. Because of the wide variety of ultrasonic power and pneumatic frequency settings available, the testing apparatus was used to assess the efficiency of various setting combinations. The endpoint was stone penetration time, and the fastest stone penetration times were achieved at settings of 100% ultrasonic power and 12-Hz pneumatic frequency. Pietrow *et al*⁶ have evaluated the efficiency of the Lithoclast Ultra combination

device in a clinical setting, performing a prospective, randomized trial comparing the combination device to standard ultrasonic lithotrites in patients undergoing percutaneous nephrolithotomy. The stone clearance times were significantly better for the combination device than for the convention alultrasonic lithotripters.

The Cyber wand (Gyrus ACMI, Southborough, MA) is an intracorporeal lithotripter that relies on a dual ultrasonic probe design that incorporates coaxial high-frequency and low-frequency probes. The dual-probe design creates a synergistic effect that enables efficient stone fragmentation while still allowing the suction evacuation of small fragments just as other ultrasonic devices do. Kim et al⁷ used the aforementioned hands-free testing design previously described by Kuo et al and found that the stone penetration time for the Cyberwand was almost twice as rapid as it was for the Lithoclast Ultra.

Laser

Any stone within the urinary tract may be treated with the holmium: yttrium aluminum garnet. Laser lithotripsy is sensitive to stone size, and for large stone burdens, the procedure's efficacy can be markedly reduced. When the stone burden increases beyond 1.5 cm, the likelihood of achieving a stone-free outcome is reduced, and such patients maybe best approached in a percutaneous fashion using a rigid lithotrite. The only true contraindication to holmium laser lithotripsy of urinary calculi is the presence of untreated infection because life-threatening sepsis may result. Otherwise, there are no other specific contraindications to holmium laser lithotripsy. Indeed, even patients receiving anticoagulation therapy have been reported to have successfully undergone holmium laser treatment of urinary calculi.

The holmium laser is one of the safest intracorporeal lithotrites available for stone fragmentation. The most significant adverse event is injury of the urothelial tissue adjacent to the treated stone. The depth of tissue penetration of the holmium laser is 0.5 to 1.0 mm, so in most cases such injuries may be managed conservatively, although a ureteral stricture may be a long-term consequence of such an event. The holmium laser does produce a weak shockwave, so in some cases stone fragments can be retro pulsed and migrate away from the endoscope, which may increase the complexity of the procedure. Eye protection is required for operators of the holmium laser, although at the energy levels used for the fragmentation of calculi, the operator's cornea would be damaged only if it was positioned at less than 10 cm from the laser fiber.

The field of laser lithotripsy is advancing in 2 different directions: improvements to the existing holmium laser platform and the development of novel laser platforms. The most significant improvement in holmium laser lithotripsy will likely come from improved delivery fibers. At present, the smallest fiber in wide spread use, the 200- μ fiber, impedes the deflection of a flexible ureteroscope by up to 20°. As smaller laser fibers, such as those of 150- μ m diameter and smaller, are produced, it is likely that this effect on endoscope deflection will be further reduced. The fracture of a laser fiber inside of an endoscope can result in a catastrophic failure of the scope because when this occurs the fiber optic bundles that transmit images and light are generally destroyed. Future efforts toward maximizing fiber durability may reduce these events.

The erbium: yttrium aluminum garnet laser has recently been tested for the fragmentation of urinary calculi; the high-temperature water absorption coefficient at the erbium laser wavelength of 2.94 μ is about 30 times higher than that of the holmium laser wavelength at 2.12 μ , which has translated to a 2-to 3-fold increase in efficiency for fragmenting urinary stones in an in vitro setting.⁸ There are several limitations of the erbium laser that prevent its immediate use for clinical applications in urology. The erbium wavelength cannot be

transmitted through standard available silica fibers; specialty mid-infrared fibers are needed, and these fibers are typically less flexible, more expensive, and less biocompatible than silica fibers.

Recent advances in fiber laser technology have resulted in the commercial availability of the thulium laser, which has several potential advantages over other solid-state lasers such as the holmium. The thulium fiber laser wavelength is tunable, and, when operated in the pulsed mode, it is capable of fragmenting urinary calculi.⁹ In addition, the thulium fiber laser-beam diameter is only 18 μ , allowing easy coupling of the laser radiation into small-core optical fibers. Such diminutive fibers have a great potential use when coupled with flexible endoscopes in demanding applications, such as access to the lower pole of the kidney for lithotripsy.

SWL

SWL revolutionized the field of stone disease. Although it was initially thought that shock wave energy would pass harmlessly through the kidney, it is now well documented that renal injury occurs as a side effect of SWL; detailed morphologic analyses of porcine kidneys treated with a clinical dose of shock waves have shown that shockwave energy induces a hemorrhagic lesion in the renal vasculature. The volume of the hemorrhagic lesion is dose dependent, and, as the number of shocks and the power settings of the lithotripter are increased, the lesion size will similarly increase.^{10,11}

Although efforts are underway to develop new lithotripter technologies that will ultimately make SWL safer and more effective, at present, a fundamental question remains open; how can we maximize stone fragmentation while simultaneously minimizing tissue trauma? The answer to this question, at the present time, may be fairly straight forward; the technique with which SWL is applied can be critical to achieving optimal treatment outcomes.

A recent literature review and meta-analysis have reported that slowing the rate of SWL delivery to 60 shockwaves per minute breaks stones more effectively than treatment at a rate of 120 shockwaves per minute.¹² The disadvantage of slowing the treatment rate is that overall treatment time is increased. Although the reason why a slower treatment rate increases stone fragmentation is not understood with certainty, hypotheses have been suggested. Cavitation, the formation and subsequent dynamic behavior of bubbles, may be induced by a lithotripter-generated pressure field. The bubbles that are initiated by 1 shockwave may persist long after the shockwave has passed and serve as nuclei, or promoters, of cavitation. As subsequent shockwaves are delivered, the growth of additional cavitation bubbles seeded by these nuclei may draw energy from the negative-pressure phase of the shockwave. The ultimate effect of this energy sink may be reduced stone breakage. The process of cavitation and “bubble shielding” of a targeted stone has been reported to be enhanced at fast shockwave rates.¹³

The process by which the patient is coupled to the lithotripter can also affect treatment outcome. The first-generation SWL devices were of a water bath design; patients were coupled to the shockwave source by the water bath itself. However, most modern lithotripters use a dry treatment head that is coupled to the patient with a medium of high-acoustic transmission such as gel or oil. The great advantage of a dry treatment head when compared with the water bath design of the Dornier HM3 is its transportable nature. Unfortunately, it is difficult to achieve good coupling of the treatment head to the patient because typical protocols often create air pockets at the coupling interface. Such defects can be a significant barrier to shockwave transmission. In vitro studies have shown that coverage by air pockets of just 2% of the coupling interface reduced stone breakage by 20% to 40%.^{14,15} When

coupling is poor and energy transfer is attenuated, more shockwaves are therefore required to fragment a stone, which may also have a traumatic effect on the kidney.

The injury associated with SWL may be attenuated by a priming dose of low-amplitude shockwaves; initiating treatment at a low power setting before shifting to a higher-power setting has been reported to result in a significant reduction in lesion size.¹⁶ These findings are clinically meaningful because they suggest a potential treatment strategy to reduce the adverse effects of SWL. The physiologic mechanism responsible for this protective effect has yet to be fully characterized, but assessment of renal hemo dynamics suggests that shock waves induce transient vasoconstriction in the treated kidney.^{17,18} Increased vasculature may make the treated vessels less susceptible to cavitation or shear stress.

Conclusions

As surgical technology advances, the manner in which we treat patients suffering from stone disease has become more efficient and less morbid. Intracorporeal lithotrites have the ability to rapidly fragment and evacuate renal with flexible endoscopes in demanding applications, such as access to the lower pole of the kidney for lithotripsy.

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Figure 1.

An in vitro testing apparatus for a “hands-free” testing approach to the evaluation of intracorporeal lithotrites. Reprinted with permission from Kuo RL, Paterson RF, Siqueira TM Jr, et al: In vitro assessment of ultrasonic lithotriptors. *J Urol* 170:1101–1104, 2003.