Minimally Invasive Surgical Treatment for Kidney Stone Disease

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Minimally invasive interventions for stone disease in the United States are mainly founded on 3 surgical procedures: extracorporeal shock wave lithotripsy, ureteroscopic lithotripsy, and percutaneous nephrolithotomy. With the advancement of technology, treatment has shifted toward less invasive strategies and away from open or laparoscopic surgery. The treatment chosen for a patient with stones is based on the stone and patient characteristics. Each of the minimally invasive techniques uses an imaging source, either fluoroscopy or ultrasound, to localize the stone and an energy source to fragment the stone. Extracorporeal shock wave lithotripsy uses a shock wave energy source generated outside the body to fragment the stone. In contrast, with ureteroscopy, laser energy is placed directly on the stone using a ureteroscope that visualizes the stone. Percutaneous nephrolithotomy requires dilation of a tract through the back into the renal pelvis so that instruments can be inserted directly onto the stone to fragment or pulverize it. The success of the surgical intervention relies on performing the least invasive technique with the highest success of stone removal.

Key Words: Nephrolithiasis, Ureteroscopy, Extracorporeal shock wave lithotripsy, Percutaneous nephrolithotomy

Kidney stone disease is estimated to affect 1 in 11 people in the United States, and the incidence is rising.[1] Individuals requiring intervention are offered mainly 1 of 3 interventions: ureteroscopic lithotripsy (URS), extracorporeal shock wave lithotripsy (ESWL), or percutaneous nephrolithotomy (PCNL). These surgical techniques have been refined over time as surgery has focused on noninvasive techniques. To appreciate the advancement of these techniques, it is important to briefly review the history of surgical intervention for stones.

The first documented stone surgery was open surgery for bladder stones which dates back to the ancient Indian, Chinese, and Greek civilizations. The next main advancement was the emergence of anesthesia and aseptic techniques toward the end of the 19th century. Improvements in diagnostic capabilities for stone disease followed, prompted by the discovery of the X-ray by Roentgen in 1895. In fact, the first kidney stone was seen on an X-ray of the abdomen in 1897. Most kidney stones and ureteral stones were localized by X-ray and surgically removed by open techniques. Over time, advances in equipment, energy sources, and imaging have led to a range of options. Indeed, by the 1980s, treatment options for urinary stones included extracorporeal shock wave lithotripsy, ureteroscopy, and PCNL. Today, open surgery in the United States for renal calculi is rapidly disappearing, comprising 0.3% to 4% of all stone surgery cases.[2] With the advancements of technology, minimally invasive surgery for stone disease has been refined with less morbidity and increased rates of stone clearance.

EXTRACORPOREAL SHOCK WAVE LITHOTRIPSY

The first human treatment of a stone by ESWL was on February 20, 1980, by Dr Chaussy who used an HM1 lithotripter by the German aerospace firm Dornier (Lindau, Germany). In 1984, the first commercially available lithotripter (HM3) was introduced.[3] The technology was derived as a spinoff from military research. The aerospace firm Dornier noted unusual patterns of metal fatigue in aircrafts and theorized that shock waves created by raindrops striking an aircraft in supersonic flight could cause metal fatigue. Lithotripters generate a "shock wave," which is a short acoustic pulse that lasts approximately 5 microseconds. To focus the shock wave on the stone, the lithotripter uses a reflector around the tip of the electrode. The "shock" is generated at the focal point of the reflector. The shock wave produced spreads and bounces off the reflector moving in a manner so that they converge simultaneously at a second focal point, which is the point of greatest force. The stone is positioned at this second focal point for maximum stone fragmentation.

Lithotripters are classified based on the energy source used to generate shock waves: piezoelectric, electrohydraulic, and electromagnetic. All share some basic characteristics: an energy source, a shock wave-focusing mechanism, a coupling medium, and a system for localizing the target. During propagation and transmission of a shock wave, energy is lost at interfaces with differing densities. Therefore, a coupling medium is necessary to minimize the dissipation of energy of a shock wave as it traverses the skin surface. The combination of several events during shock wave lithotripsy are thought to cause stone fragmentation: spallation, tear and shear forces, cavitation, quasi-static squeezing, dynamic squeezing, and stone fatigue.[4] In summary, the successive shock wave pressure pulses result in direct forces that fragment the stones into smaller pieces.

ESWL is the one truly noninvasive treatment for stones. The American Urological Association guidelines on the management of renal calculi support the use of ESWL for kidney stones.[5] It is recommended for patients with normal anatomy who have a kidney stone that is less

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than 2 cm^2. This treatment is contraindicated in patients who are pregnant, morbidly obese, have a kidney artery or abdominal aortic aneurysm, coagulopathy, skeletal malformations, urinary tract infection, or have an uncorrected obstruction distal to the stone.

The widespread use of this technology is due to its noninvasiveness nature, low morbidity, and excellent initial success rates. ESWL has revolutionized the approach to patients with kidney stones. In fact, in almost 3 decades after its introduction, ESWL has become the most commonly used urinary stone treatment for patients with upper urinary tract stone disease.[5]

A number of factors affect ESWL success rates, including stone size, composition, and location as well as patient characteristics.[6-8] Anatomic features, including ureteropelvic obstruction, calyceal diverticuli, and fusion anomalies, such as horseshoe kidney, can also negatively affect the outcome.[9] Increasing stone size has been inversely correlated with stone-free rates.[7] Success rates are highest (80% to 90%) with calculi in the renal pelvis and ureteropelvic junction.[10] Stone-free rates are also dependent on stone location in the renal pelvis: upper (81%), middle (70%), and lower (56%) pole calyces.[11] To evaluate the discrepancy of ESWL for lower pole stones, a multicenter Lower Pole Study Group was organized to determine the optimal treatment of lower pole calculi in a prospective, randomized trial comparing ESWL and PCNL.[12] The authors concluded that ESWL constitutes reasonable first-line treatment only for lower pole stones smaller than 1 cm. PCNL should be the recommended therapy for stones larger than 1 cm. Stone composition also affects the effectiveness of ESWL. Cystine, brushite (calcium phosphate), and calcium oxalate monohydrate stones are less prone to fracture with shock wave lithotripsy.[13-15] At this time, computed tomography (CT) is the most effective means for identifying the composition of in vivo stones. Along with stone-related factors, patient characteristics contribute to the effectiveness of ESWL. In 1994, Ackermann and colleagues[6] first described body mass index as an independent predictor of ESWL failure, finding that regardless of the positioning and technical concerns, patients with body mass index greater than 28 (kg/m^2) had a suboptimal outcome after ESWL. Furthermore, it has been shown that a skin-to-stone distance of greater than 10 cm on CT scan will decrease the efficacy of the treatment.[16] When choosing ESWL, these factors must be considered to ensure that the correct treatment is being used to optimize stone-free success rates.

CLINICAL SUMMARY

- The 3 main surgical treatments used to remove kidney stones are extracorporeal shock wave lithotripsy, ureteroscopy, and percutaneous nephrolithotomy.
- Ureteroscopy and shock wave lithotripsy are the 2 most commonly used procedures for treating stones.
- The decision on which technique to use is based on patient and stone characteristics.

The development of dual-energy multidetector CT, which provides a low- and high-energy scanning during a single acquisition, provided the ability to differentiate materials that have similar electron densities but varying photon absorption.[17,18] This technology allows for the in vivo determination of the composition of urinary stones.[17,18] This in addition to the measurement of Hounsfield units (HUs) has contributed information used to determine stone fragility and success with ESWL. Gupta and coworkers[19] found a HU value of 750 to be predictive of ESWL success for kidney stones. Patients with dense calculi (>750 HU) required more treatment sessions and were less likely to achieve complete stone clearance than calculi with lower HU. Therefore, dual-energy CT examination may contribute to not only the identification but also the chemical characterization of urinary stones, which may impact surgical and medical treatment decisions.

Improvements in the lithotripter have been matched by both an improvement in the patient experience and the success rate. With early lithotripters, patients had to be immersed in a large water bath with degassed and deionized water for acoustic coupling. In contrast, the newer and smaller lithotripters free the patient from a water tank by using a dry treatment cushion head with ultrasound gel or oil placed against the patient's abdomen. As extracorporeal shock wave lithotripsy technology evolved, newer generation lithotripters provided decreased cost, better portability, and increased convenience for the medical team and patient. Newer generation lithotripters also reduce the need for anesthesia because the power has been reduced. With these improvements, ESWL has become a much less intimidating experience for the patient. However, it should be noted that the technical improvements in these newer models have been largely based on practical concerns for the user and the patient's convenience rather than a rigorous understanding of the underlying mechanisms in ESWL.

Although newer machines have proved to be more convenient, an increasing number of problems have been identified. These newer dry head lithotripters can have air bubbles in the gel applied at the treatment head. This diminishes the efficient transfer of shock wave energy. As a result, more shock waves may be needed for fragmentation, which can lead to increased trauma to the kidney parenchyma and potential blood vessel damage. Furthermore, efforts to achieve high peak pressures on the stone and narrow focal zones to reduce the field of transmission of energy have been found to produce greater tissue trauma and lower success rates.[5]

Recent research efforts have focused on different techniques to use during ESWL that improve shock wave efficiency maximizing stone fragmentation while simultaneously minimizing tissue trauma. One area of research has been the optimization of shock wave coupling, in which shock waves are gated to fire during the patient's myocardial refractory period through an electrocardiogram. This strategy has helped avoid shock wave delivery