The role of open and laparoscopic stone surgery in the modern era of endourology

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Abstract | Treatment options for kidney stones and ureteral stones have evolved considerably over the past several decades, to the point where almost any stone can now be considered for treatment with a noninvasive or a minimally invasive approach including shock wave lithotripsy, ureteroscopy or percutaneous nephrolithotomy. The safety and morbidity associated with these techniques are favourable relative to traditional open surgical approaches to stone removal. However, they also require unique skillsets, access to instrumentation and relatively high maintenance costs, potentially limiting their use on a global scale. Coincident with the emergence of endourology have been considerable improvements in laparoscopic surgical techniques to the point that nearly any open surgery can be performed in a minimally invasive laparoscopic fashion. Such approaches, including those with robotic assistance, have potential application for the treatment of upper urinary tract stones, particularly in complex senarios as well as in areas where access to endourological instruments might be limited.

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Introduction

"I will not cut for stone, even for patients in whom the disease is manifest; I will leave this operation to be performed by practitioners, specialists in this art."[1] This classic reference, a part of the Hippocratic oath, is one of the first to detail the inherent challenges of surgical treatment of urolithiasis; however, historical accounts of open lithotomy date back to 276 BC, when the Greek surgeon Ammonius of Alexandria coined the term lithotomy in his description of "cutting for stone" to aid its removal.[2] Fortunately, the modern era of endourology has essentially abolished the need for open stone surgery in areas with adequate technology and resources. Nowadays, the vast majority of stones can be treated with noninvasive or minimally invasive procedures—such as extracorporeal shock wave lithotripsy (ESWL), ureteroscopic lithotripsy and stone removal (URS), or percutaneous nephrolithotomy (PCNL). However, circumstances do exist where these approaches might not be suitable.[3] This Review addresses such instances and assesses the role of open and laparoscopic surgical techniques in treating urolithiasis in the modern era of endourology.

Minimally invasive technique evolution

Open stone surgery (Figure 1), once considered the standard of care for the majority of symptomatic stones, has overwhelmingly been replaced by alternative minimally invasive techniques including ESWL, URS and PCNL. Of these three procedures, ESWL remains the only reliable noninvasive approach (Figure 2). First described in 1980, this technique quickly became one of the most popular alternatives to open stone surgery.[4,5] Although success rates vary depending on stone-specific and patient factors, stone-free rates can exceed 90% in appropriately selected patients.[6] That ESWL has become a mainstay in the treatment of upper urinary tract stones is no surprise considering these success rates; over 1 million patients are now treated with ESWL annually and use of this technique has increased by nearly 55% globally over the past decade.[7] However, not all stones are amenable to ESWL, as success rates are known to vary depending on stone composition and location and patient size, in terms of both weight and BMI.[8]

Ureteroscopy is also being increasingly used to treat stones; in fact, it is the fastest growing endourological method for this purpose.[9] Success using a rigid ureteroscope (Figure 3a) to visualize the distal ureter was first described in the 1970s,[10] and considerable breakthroughs in both instrument and camera design have now made it possible to visualize the entire urinary tract in high definition. Success rates in treating ureteral stones are very high, with reported stone-free rates of >94% when semirigid scopes are used to treat distal ureteral stones, and >95% when flexible scopes (Figure 3b) are used to treat proximal ureteral stones.[11] When used to treat stones located in the kidneys, success rates using flexible ureteroscopes are more variable, especially given the potential for multiple stones. In such cases, stone-free rates after a single stage have been found to be much lower (50–75%).[12] This difference in success rates can be attributed to the fact

Competing interests
J.E.L. has participated in, lectured for and is a consultant and advisor to Lumenis™ and Boston Scientific and has also been involved in a scientific study run by Boston Scientific. He is an owner and medical director of Beck Analytical and an owner of and investor in Midwest Mobile Lithotripsy and Midstate Mobile Lithotripsy. M.S.B. declares no competing interests.

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Key points

- Extracorporeal shock wave lithotripsy, ureteroscopy, and percutaneous nephrolithotomy are first-line treatment options for upper urinary tract calculi
- The role of open stone surgery has essentially been eliminated by noninvasive and minimally invasive alternative treatment options
- Open stone surgery should only be considered for complex cases, as a salvage treatment option, or when access to modern-day technology is limited
- Laparoscopic and robot-assisted techniques are able to replicate the goals of open surgery with reduced potential morbidity and should be offered for indicated cases
- Although overall literature regarding laparoscopic approaches is lacking, favourable evidence exists supporting laparoscopic pyelolithotomy and ureterolithotomy for solitary large stones
- Combining treatment approaches is often the best way to achieve maximal stone clearance and optimal outcomes

that working directly in the kidney is more complicated than working in the ureter, as the anatomy of the kidney is more complex and it is harder to navigate and access in its entirety. Furthermore, stones in the kidney are often larger owing to the increased capacity for stone growth in the larger-diameter system. Historically, 2 cm has been used as the cut-off diameter for the ureteroscopic treatment of renal stones, but with the latest technology and advanced techniques, ureteroscopic treatment of larger sized stones is possible. Cohen *et al.*[13] assessed outcomes of flexible ureteroscopy in 145 patients with renal stones ≥2 cm in diameter and demonstrated stone-free rates of >87% (defined as either complete stone clearance or a solitary fragment ≤4 mm in size at a 3-month follow-up visit). Similar success with the ureteroscopic treatment of large renal stones has also been reported by others,[14,15] but as insufficient evidence exists at present to recommend this approach as a first-line treatment in such instances, PCNL remains the preferred treatment in these scenarios.[16]

PCNL is the minimally invasive technique most appropriate for the largest and most complex stones (Figure 4) and is the recommended treatment for such cases according to the AUA guidelines.[17] Although PCNL is more invasive in nature than either ESWL or URS, the ability to directly access the stone increases the likelihood that the patient will become stone free. Albala *et al.*[18] demonstrated that when PCNL was used to treat lower pole stones with a mean size of 1.5 cm, stone-free status was achieved in >95% of cases. When PCNL is used for larger, more complex stones (such as staghorn calculi) stone-free rates are slightly lower. Soucey and colleagues[18] achieved a 78% stone-free rate immediately after PCNL in >500 patients with complete or partial staghorn calculi, though at the 3 month follow-up point the stone-free rate improved to 91%.[19]

Laparoscopic and robotic approaches

ESWL, URS and PCNL differ dramatically from traditional open surgical methods to remove stones. As these techniques have evolved over the past three decades, so have laparoscopic and robotic approaches. Laparoscopic and robotic procedures are conceptually more similar to open surgical methods than to minimally invasive techniques, but accomplish their goals with smaller incisions, less direct tissue manipulation and a potentially faster recovery time than open surgery. In 2014, Bayar and colleagues[20] highlighted the benefits of a laparoscopic approach over an open approach. The investigators assessed outcomes of the two techniques in patients undergoing ureterolithotomies for large impacted ureteral stones and found that, although surgical outcomes were equivalent, patients in the laparoscopic group had significantly less pain and a >50% reduction in hospital stay (2.9 days versus 6.1 days).

Furthermore, the most recent AUA guidelines on staghorn calculi recommend that open surgery should not be used for most patients, with PCNL being the preferred option as it has comparable outcomes but is associated with a decreased risk of long incisions, hernia and eventration of flank musculature. The AUA guidelines consider indications for open stone surgery to be rare and limited to "extremely large stones, complex collecting system issues, excessive morbid obesity, or extremely

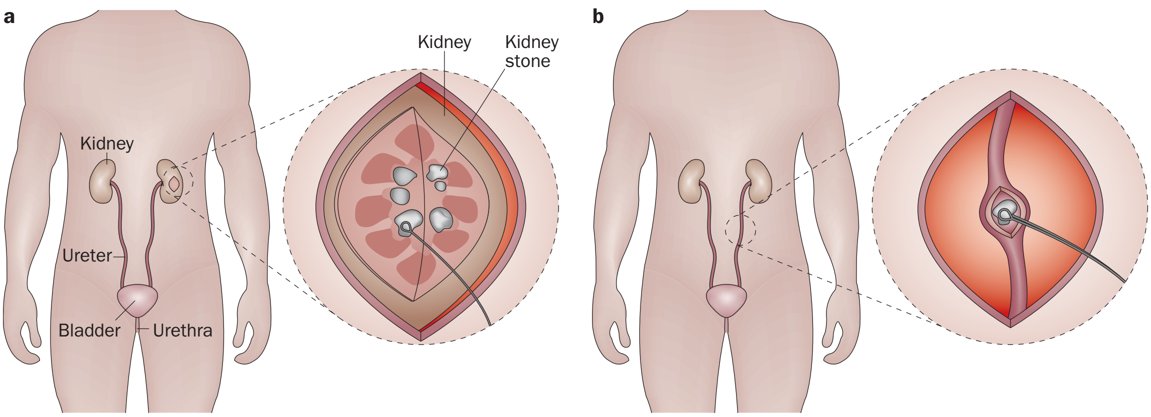

Figure 1 | Open stone surgery. **a** | Open nephrolithotomy, where the renal capsule is incised and the parenchyma split in order to access the area of the collecting system with a large stone. **b** | Open ureterolithotomy, where the ureter is identified and dissected free, then incised over the area of an obstructing stone that can subsequently be removed. Both procedures used to be the standard of care for removing symptomatic stones but have overwhelmingly been replaced by minimally invasive alternative techniques.

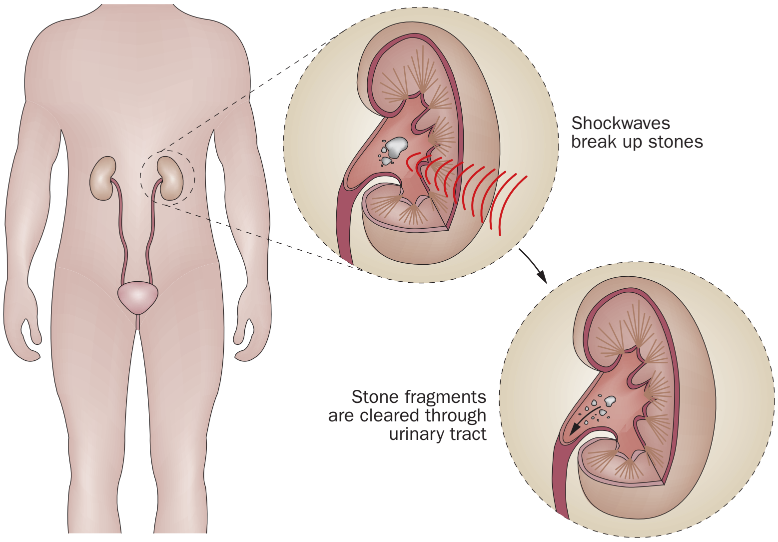

Figure 2 | Extracorporeal shock wave lithotripsy (ESWL). ESWL is the only noninvasive method for fragmenting kidney and ureteral stones. Focused shockwaves are directed towards the stones to fragment them. The pieces are subsequently cleared naturally through the urinary tract. In appropriately selected patients, stone-free rates with this technique exceed 90%.

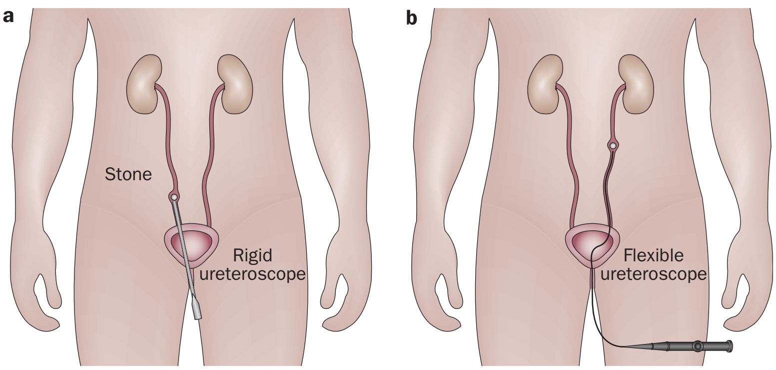

Figure 3 | Endoscopic approaches to stone removal. **a** | Semirigid ureteroscopy, where a long, thin scope with a lens and light source are passed through the urinary tract up to the level of a stone in the ureter. The scope has a working channel within it, which can be used to pass instruments to both fragment and remove the stone. **b** | Flexible ureteroscopy, which is similar in concept to semirigid ureteroscopy but enables increased manoeuvrability within the urinary tract owing to its flexible design. This instrument is also able to access the entirety of the kidney and is the preferred instrument for treatment and removal of small-to-moderate sized renal stones.

poor function of the affected renal unit."[17] However, these guidelines were released in 2005 and predate the widespread diffusion of and increased surgeon comfort level with laparoscopic and robot-assisted approaches.

Over the past decade a tremendous shift has occurred within the field of urology from open surgery to laparoscopic. This move has been facilitated in large part by technological advances. The *da Vinci*® robotic surgical system (Intuitive Surgical Inc., USA) offers several unique advantages over traditional laparoscopic approaches, particularly with regards to manoeuvrability and intracorporeal suturing, which have enabled surgeons to replicate nearly any surgery conducted in an open fashion laparoscopically with the robot.

Despite these advances, the role of open and laparoscopic stone surgery remains limited, predominantly because endoscopic alternatives have demonstrated excellent efficacy with minimal morbidity and can often be performed on an outpatient basis. In 2000, only 2% of patients undergoing surgery for urolithiasis in the USA underwent an open procedure.[21] The numbers of patients undergoing open procedures continue to decline, as evidenced by an 83% reduction in use of such procedures for kidney stones within the UK over the past decade. In fact, during 2009 and 2010 only 47 patients with stones were treated with an open approach compared with >14,000 patients who were treated endoscopically and 22,000 who underwent ESWL.[7] In the UK as familiarity with laparoscopic and robotic techniques continues to grow, it is likely that such techniques will replace open approaches in complex cases. Although clear indications for these alternative approaches for treating large stones remain rare, they are worth discussing. Some of these potential indications include extremely large stone size, unfavourable anatomy (such as infundibular stenosis) and anatomic abnormalities (such as ectopic location or ureteropelvic junction obstruction).[22] This Review will examine the best research assessing outcomes for such cases, although it is important to note that, in general, studies pertaining to these surgical approaches tend to be retrospective in nature and include relatively small numbers of patients. Thus, the widespread applicability of the outcomes of these studies is questionable at this point in time.

Renal stones

In some cases, it is most appropriate to remove renal stones using an open approach, either through the renal pelvis (pyelolithotomy) or parenchyma (nephrolithotomy). Incision of the renal pelvis is preferable when possible, as it minimizes blood loss or loss of renal function compared with a parenchymal incision; however, in many cases, access to the entirety of the collecting system and calyces through the renal pelvis is restricted by the overlying renal hilar vasculature. Laparoscopic pyelolithotomy was first described by Gaur *et al.*[23] in 1994; several studies since have demonstrated acceptable outcomes, with stone-free rates ranging from 71% to 100% and open conversion rates ranging from 0% to 27%.[22,24,25] Although the feasibility of such an approach has been well demonstrated, reasons to use it considering the other endoscopic treatment options that are available remain unclear.

Studies directly comparing laparoscopic pyelolithotomy with PCNL are limited, and the few that have been published show mixed results. In the largest randomized study comparing these techniques, Li and colleagues[26] compared the outcomes of 89 patients who underwent retroperitoneal laparoscopic pyelolithotomy with the outcomes of 89 patients who underwent PCNL. Length of stay, rates of blood transfusion and complications were no different between groups, but the pyelolithotomy group had a shorter mean operative time, a lower likelihood of fever and a smaller mean drop in haemoglobin.

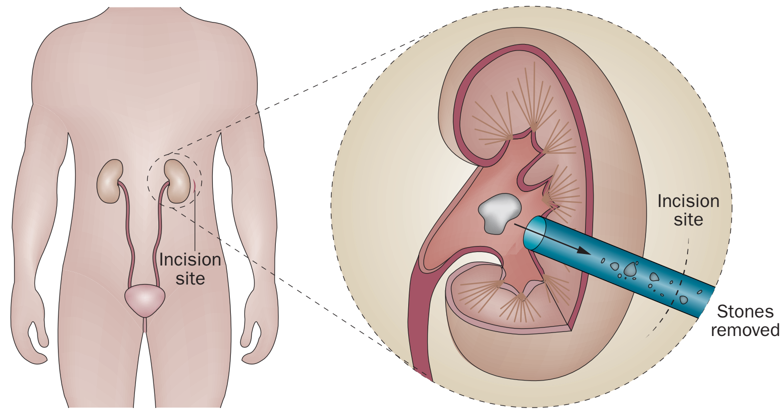

Figure 4 | Percutaneous nephrolithotomy (PCNL). A small incision is made through the skin and a needle is passed percutaneously to the kidney. A tract is then dilated to enable the introduction of larger working instruments that can then be used to rapidly fragment and remove large stones. This is the most appropriate minimally invasive approach for the largest and most complex stones and is recommended for such cases according to the AUA guidelines.

Patients who underwent laparoscopic pyelolithotomy also had a higher stone-free rates (98%) than patients who received PCNL (90%) at 3 months. Conversely, a separate randomized trial of these two techniques found less of a difference in surgical and perioperative outcomes. Al-Hunayan and co-workers[27] randomly assigned 105 patients with solitary large renal pelvic stones to either laparoscopic pyelolithotomy or PCNL and found no significant differences in terms of estimated blood loss, hospital stay, transfusion or stone-free rate. Furthermore, the operative time was significantly longer in the pyelolithotomy group (131 min versus 109 min) and there was also one conversion to open surgery for uncontrolled bleeding. Finally, Basiri and colleagues[28] randomly assigned 60 patients to receive either PCNL or laparoscopic pyelolithotomy and found no significant difference in stone-free rates and complications. The PCNL group had a shorter mean operative time (107 min versus 149 min) and a shorter mean hospital stay (2.2 days versus 3.4 days) than the pyelolithotomy group. However, patients in the laparoscopic pyelolithotomy group had smaller drops in serum haemoglobin than those in the PCNL group (8.5 g/l versus 18.8 g/l, $P = 0.001$) and were less likely to require a transfusion (one patient versus four patients, $P = 0.001$). The investigators also measured postoperative renal function using diethylene triamine pentaacetic acid (DTPA) renal scans 3 months after surgery, and demonstrated improved differential function in the pyelolithotomy group. Notably, glomerular filtration rate improved in both cohorts compared with preoperative baseline rates.

A meta-analysis conducted by Wang *et al.*[29] in 2013 found that outcomes were comparable for both procedures when used in appropriately selected patients. They reported that operative time and hospital stay were shorter in the PCNL group but that decreases in haemoglobin concentration and likelihood of fever were lower in the laparoscopic pyelolithotomy group. Stone-free rates were excellent (>95%) for both procedures and not statistically different between the groups. No difference in transfusion rate between techniques was found. Notably, the majority of studies included in the meta-analysis involved patients with solitary large stones in the renal pelvis; therefore, the results of this study are not applicable to patients with numerous stones or staghorn calculi. Furthermore, the overall number of patients included was small, with fewer than 200 patients in each cohort.[29]

On a technical level, several innovative techniques have been described to help improve stone clearance rates at the time of laparoscopic pyelolithotomy if calyceal calculi are present. Salvado *et al.*[30] described the routine use of a flexible nephroscope inserted laparoscopically during surgery. Borges and colleagues[31] addressed the issue of calyceal stone clearance by creating a stone coagulum using a fibrin and thrombin mixture. Additionally, although experience using laparoscopic pyelolithotomy in the event of staghorn calculi is more limited, Nouralizadeh and co-workers[32] published successful results from 13 such cases. In their study, mean stone size was 5 cm with extension into at least three calices. Despite the complex nature of these stones, 11 out of 13 patients were stone free after the first procedure, with no transfusions, conversions to open surgery or urine leaks noted.

Less controversy exists concerning proceeding with pyelolithotomy in patients with upper urinary tract stones when it is performed concurrently with laparoscopic or robot-assisted reconstructive procedures on the involved renal unit. Advances in laparoscopy, flexible endoscopy and wristed instruments have made it possible to visualize and access the majority of the collecting system through the pyelolithotomy incision at the time of pyeloplasty in order to remove stones. In a review of 117 laparoscopic pyeloplasties, Stein *et al.*[33] noted that >10% of patients required concomitant procedures to remove stones. In the majority of patients (73%), stones were able to be removed with laparoscopic graspers alone, though the authors reported use of flexible nephroscopes and irrigation to clear the stones from the involved kidneys in the remaining patients. They demonstrated a postoperative success rate of 80%, with the remaining patients kept under observation with no further stone events occurring at a mean follow-up duration of 9.7 months.[33] Similar stone-free rates after combined laparoscopic pyeloplasty and pyelolithotomy have been reported by Srivastava *et al.*[34] (75% in 20 patients) and Ramakumar and colleagues[35] (90% in 19 patients). Robotic-assisted laparoscopic pyeloplasties have now found favour owing to the ease of intracorporeal suturing offered by this technology. Atug and co-workers[36] achieved a 100% stone-free rate using flexible nephroscopy at the time of pyeloplasty to remove renal stones in eight patients. Similarly, Mufarrij and colleagues[37] demonstrated 100% stone clearance in 13 patients using such an approach.

When access to an intrarenal stone is not feasible through the renal pelvis, it might be possible to approach it directly through the renal parenchyma via nephrolithotomy. For large, complex intrarenal stones, the kidney can even be split in order to access the entirety of the collecting system via anatrophic nephrolithotomy. In fact, open anatrophic nephrolithotomy or extended pyelolithotomy with multiple radial nephrotomies were the historic interventions of choice for large, branched renal stones. Although stone clearance rates with these approaches are high, they have also been associated with increased morbidity as well with decreased postoperative renal function, high transfusion rates (6%) and need for re-exploration owing to bleeding (2%).[38–40] The introduction of ESWL and advances in percutaneous approaches essentially eliminated use of these open techniques in the 1980s. However, with the advent of laparoscopy and robotics, there has been renewed interest in anatrophic approaches to large renal stones with the goal of duplicating outcomes and minimizing morbidity relative to open procedures.

The first report of successful laparoscopic anatrophic nephrolithotomy was by Kaouk *et al.*[41] in 2003 in a porcine model. Shortly thereafter, Deger and colleagues[42] reported success with a human patient in 2004. Several case series using a laparoscopic technique have since been published, though all of these studies comprised small numbers of patients and there have been no direct comparisons or randomized studies comparing this laparoscopic technique with PCNL. Zhou and co-workers[43] investigated outcomes following a retroperitoneal laparaoscopic approach in 11 patients with a mean stone size of 52 mm. Mean warm ischaemia time was 31 min and all but one patient was stone free on postoperative imaging. Three patients developed urine leaks that resolved with drainage and no patients required a blood transfusion. All patients were maintained on absolute bed-rest for 7 days following the procedure. In 2013, Simforoosh and colleagues[44] published outcomes of 25 laparoscopic transperitoneal anatrophic nephrolithotomies, demonstrating high stone-free rates (88%); however, complication rates were high, with 24% of patients receiving blood transfusions and 20% suffering Clavien grade III or higher complications including one nephrectomy. Despite encouraging stone-free rates, the authors recommended that consideration of this procedure should be limited to expert laparoscopic surgeons. Giedelman and colleagues[45] published results from eight patients who underwent laparoscopic anatrophic nephrolithotomy, reporting mixed success. Although no cases required conversion to an open procedure, three patients were not stone free 15 days after the procedure and one patient developed a vascular fistula requiring embolization. Furthermore, although no changes in serum creatinine levels occurred, of the three patients who underwent DTPA renal functional scans 3 months after the operation, all demonstrated a decrease in function of the treated kidney of between 4% and 12%.

Reports have shown that anatrophic nephrolithotomy seems to be feasible when performed using a robot-assisted laparoscopic approach as well. Ghani *et al.*[46] described the results of this approach in three patients with staghorn calculi using cold ischaemia with a renal ice slush. One of the three patients was rendered completely stone free; the other two patients required second stage percutaneous procedures—one with a residual fragment of 13 mm and the other with two 9 mm stones. Mean cold ischaemia time was 57 min and no changes in renal function at the 1 month follow-up point were observed. King and colleagues[47] performed robot-assisted anatrophic nephrolithotomy on seven patients with staghorn calculi, five of whom had complete staghorn stones. The researchers used renal arterial clamping in all cases, with a mean warm ischaemia time of 35 min; however, only two patients were completely stone free after the procedure (29%), although five patients had >90% reduction in stone burden. Notably, no decrease in renal function was observed at a mean follow-up duration of 5 months.

Ureteral stones

Ureterolithotomy, a procedure that has also essentially been replaced by endoscopic approaches, is another operation that has seen a recent spike in interest owing to advanced laparoscopic and robotic techniques. Although few would advocate such an approach for a straightforward ureteral stone, this procedure has been considered for complex cases as well as instances where access to ureteroscopes is limited. Gaur *et al.*[48] published outcomes of 101 laparoscopic ureterolithotomies performed between 1991 and 2001 with a mean stone size of 1.6 cm. The majority of patients (75) had stones in the upper ureter, with 11 patients having stones in the mid ureter and 15 having stones in the distal ureter. Their success rate (without open conversion) was 92%, with a mean operative time of 79 min. Notably, mean operative time increased from 66 min to 92 min in cases where the ureterotomy was sutured closed rather than being left open. Initial procedures were performed without closure or stenting of the ureter and were associated with a mean period of urinary leakage of 5.5 days. This period of leakage was reduced to just over 3 days when stenting and ureteral closure were added to the procedure. Overall, the complication rate was 31% and the mean hospitalization duration was 3.5 days. Simforoosh and colleagues[49] detailed the results of 123 laparoscopic ureterolithotomies in another large series. Stone size ranged from 1 cm to 5.6 cm, with a proximal ureteral location in 73.2% of cases, a mid location in 16.3% of cases and a distal location in 10.5% of cases. Stone-free rates were excellent, at nearly 97% on postoperative day one. Complications occurred in 11.8% of the cohort, with one open conversion. Procedures were performed both transperitoneally (84.6%) and retroperitoneally (15.4%); a significantly longer operative time was noted with the retroperitoneal approach (171 min versus 137 min).

Several randomized studies have now been published to further determine the utility of laparoscopic ureterolithotomy in modern practice. In 2008, Basiri *et al.*[50] randomly assigned patients with ureteral stones >1.5 cm in size to treatment with retrograde semirigid ureteroscopy, transperitoneal laparoscopic ureterolithotomy or antegrade PCNL. Stone-free rates at discharge were higher with ureterolithotomy (88%) than with ureteroscopy

(56%) or PCNL (64%). However, 3 weeks after the procedure, stone-free rates were more similar in the three groups—90% in the ureterolithotomy cohort, 76% in the ureteroscopy cohort, and 86% in the PCNL cohort. Despite a lower stone-free rate, the ureteroscopy cohort had fewer acute complications, with no conversions, urine leaks or need for immediate re-operation. The ureteroscopy cohort also had the lowest operative time (42.7 min versus 93.6 min for PCNL and 127.8 min for ureterolithotomy). Furthermore, the ureterolithotomy cohort had a 4% rate of conversion to open surgery and a 4% rate of delayed stent placement for ongoing urine leakage. The findings were similar in the PCNL cohort, which had no conversions but a 6% risk of requiring stent placement for ongoing urine leakage ≥1 week after surgery. In 2014, Kumar and colleagues[51] randomly assigned patients with proximal ureteral stones >2 cm in size to treatment with either laparoscopic ureterolithotomy or semirigid ureteroscopy. Their results favoured the laparoscopic approach, with patients in this cohort experiencing a better 3-month stone-free rate than those in the semirigid ureteroscopy group (100% versus 76%), and a corresponding decrease in the risk of retreatment (0% versus 8%) and auxiliary procedures (0% versus 26%). However, there was no difference in operative time or hospital stay between groups. Notably, none of the above studies included flexible ureteroscopy in their technique, which might have improved stone-free rates with the ureteroscopic approach, given the difficulty in accessing the kidney with a semirigid scope in the event of proximal stone migration.

As with nephrolithotomy, the introduction of the surgical robot and the improved ability to perform intracorporeal suturing has generated some enthusiasm towards robot-assisted laparoscopic ureterolithotomies. Although published experiences with this approach are small, the findings are promising. Dogra *et al.*[52] performed 16 robot-assisted laparoscopic ureterolithotomies on obstructing distal ureteral stones that were both large (>2 cm) and impacted. The outcomes of patients were favourable, with a mean operative time of 45 min, only 20 min of which was spent at the surgical console. Mean stone size was 2.2 cm and all patients were deemed stone free after the procedure. Estimated blood loss was 10 ml and mean hospital stay was 2 days. All patients had intra-abdominal drains that were removed 1 day after surgery, Foley catheters that were removed 2 days after surgery and ureteral stents removed after 4 weeks. No incidences of urine leaks were documented and after a mean follow-up period of 13 months, there were no ureteral strictures. Notably, this study excluded any patient with previous abdominal or pelvic surgery, potentially minimizing complications caused by abdominal adhesions and the need for bowel manipulation. Furthermore, the mean age of the cohort was quite young, at 27 years old. Whether these procedures will gain popularity in time is uncertain; presently, they would be best considered as an alternative to open procedures in uniquely complex scenarios where use of ESWL, URS and PCNL might not be possible.

Other renal anomalies

The management of calculi in atypical situations (such as anatomic anomalies, urinary diversions and transplants) remains one of the greatest challenges within the world of endourology and perhaps represents the optimal indication for the application of laparoscopic and robotic techniques. Although the various minimally invasive approaches have been attempted with such cases, these kidneys present a number of inherent challenges that must be considered—including abnormal insertions of the ureters into the renal pelvis, distorted collecting systems and aberrant vasculature.

The most commonly encountered renal anomaly is a horseshoe kidney, whereby the inferior aspects of the kidneys are fused. Such kidneys are prone to stone formation, with approximately 20% of patients affected by nephrolithiasis.[53] They also have a number of anatomical distinctions compared with normal kidneys, with high insertions of the ureter and a lower position within the abdomen owing to tethering at the level of the inferior mesenteric artery. Ectopic kidneys, whereby the kidney or kidneys are located in an abnormal position within the body (most commonly the pelvis), pose unique challenges as well, depending on their variable location.

Of all the available minimally invasive modalities, ESWL is the least effective when used to treat both horseshoe and ectopic kidneys, with stone-free rates ranging from 25% to 92%.[54] First of all, the aberrant location can make stone visualization challenging owing to the increased likelihood of there being overlying structures such as bowel and bone. Drach *et al.*[55] demonstrated that patients with horseshoe kidneys undergoing ESWL not only required more shocks per treatment session, but had a higher retreatment rate of 30%—compared with 10% in anatomically normal patients. Sheir and colleagues[56] reviewed 198 patients with renal anomalies undergoing ESWL; 60% had malrotated kidneys, 25% had horseshoe kidneys and 15% had duplications, with a mean stone length of 13.5 mm for all renal abnormalities. These researchers demonstrated a stone-free rate of 72% 3 months after ESWL treatment and showed that clearance rates were independent of the type of anomaly. Talic[57] described results of ESWL in 14 patients with pelvic kidneys and demonstrated that 82% of patients were ultimately stone free, although four patients required two or more ESWL sessions and steinstrasse—requiring repeat interventions—occurred in two cases.

Data regarding use of flexible ureteroscopy in cases of ectopic and horseshoe kidneys are slightly more limited but have been generally favourable. One important consideration in such kidneys is the potential for an abnormal course and insertion of the ureter, which can often be minimized by placement of an access sheath. Among 20 patients with horseshoe kidneys and a mean stone size of nearly 18 mm treated using flexible ureteroscopy, Atis *et al.*[58] reported a stone-free rate of 70% after a single procedure. Molimard and co-workers[59] reported a slightly higher stone-free rate of 88% in 17 patients with horseshoe kidneys and a mean stone burden of 16 mm, although they did perform a mean of 1.5 procedures

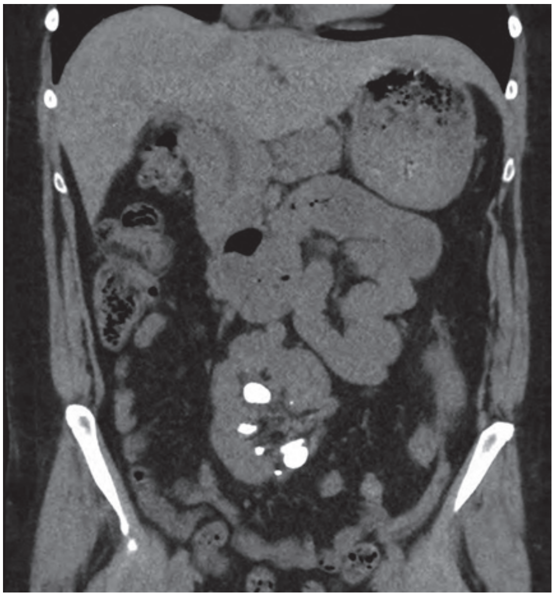

Figure 5 | CT of a stone-containing pelvic kidney. This case was completed in a staged fashion by first using a robotic-assisted laparoscopic approach to open the renal pelvis and clear all accessible stones. The patient underwent retrograde flexible ureteroscopy 4 weeks later to clear the kidney of a small residual fragment that was not accessible at the time of initial surgery.

per patient. In other anomalous and malrotated kidneys, Weizer *et al.*[60] achieved a 75% stone-free rate using flexible ureteroscopy alone for patients with a mean stone size of 11.4 mm.

PCNL is often a suitable consideration for horseshoe and ectopic kidneys. Stone-free rates following PCNL for horseshoe kidneys are comparable to rates achieved in anatomically normal kidneys. Miller and colleagues[61] published the outcomes of PCNL procedures performed on 35 patients with horseshoe kidneys and a mean stone burden of 2.6 cm. The stone-free rate was 84% after primary PCNL, and improved to 93% after accounting for patients undergoing second-look nephroscopy. Stone-free rates after PCNL in ectopic kidneys are more variable as they are affected by the differing location of the kidney relative to its surrounding structures. Skin-to-stone distances in such kidneys can be exaggerated and the atypical location increases the likelihood of bowel or other abdominal structures interfering with a direct line of access between the skin and the kidney. Preoperative cross-sectional imaging is essential in such cases for this purpose. Despite the inherent challenges, a variety of approaches for removing stones from ectopic kidneys have been described. Watterson *et al.*[62] successfully treated a 12 mm stone in a left-sided pelvic kidney after obtaining access via the greater sciatic foramen; however, they cautioned that such an approach might not be feasible in all cases, given the potentially increased distance to the kidney when a transgluteal approach is used. Furthermore, if alternative routes to the stone are not feasible, there is the option of puncturing through an otherwise suboptimal structure, as has been described with transhepatic and transileac PCNL, both of which have been successfully performed without complications.[63]

The myriad of different possible anatomical orientations of ectopic kidneys makes generalization of any one treatment plan for these scenarios unrealistic. As such, we believe that a unique treatment plan must be developed for such kidneys on a case-by-case basis. We recommend preoperative cross-sectional CT imaging, not only to better characterize the stone, but to map the surrounding structures, vasculature, collecting system and ureteral anatomy. Cases for which ESWL, URS and PCNL are extremely complex represent ideal scenarios for laparoscopic assistance, which can be used either to assist in obtaining access to the kidney or for the entire lithotomy. When laparoscopy is used to facilitate renal access in PCNL, the patient is placed in the Trendelenburg position to move the bowel cephalad and a needle is used to puncture the kidney under direct visualization to ensure that no injury to any adjacent structure occurs.[64] Alternatively, depending on the anatomy of the kidney and the surgeon's experience with laparoscopic techniques, removing the stone from the ectopic kidney entirely through use of a laparoscopic approach, as described earlier, could be considered (Figure 5). Although there is a paucity of literature examining the outcomes of these different approaches in kidneys with anatomic abnormalities, several case series have been published. In one of the largest studies of its kind, El-Kappany *et al.*[65] reported the outcomes of five patients undergoing laparoscopic-assisted PCNL and six patients undergoing laparoscopic pyelolithotomy for stones in pelvic kidneys. All of the cases were completed without conversion to open surgery and no intraoperative or postoperative complications were reported. Of these 11 patients, 10 achieved complete stone-free status, with the remaining patient's residual stone successfully treated with subsequent ESWL. Elbahnasy and co-workers[66] published results of 11 cases of laparoscopic pyelolithotomy for stones in pelvic ectopic kidneys and similarly reported favourable outcomes. Complete stone clearance was achieved in 10 of 11 patients and the patient with a residual fragment underwent successful second-stage ESWL. Similarly, no intraoperative complications or conversions to open procedures occurred, although two patients did have prolonged urine leakage that required procedures to replace and/or manipulate drainage catheters.

Several other case studies have also reported successful outcomes using laparoscopic and even robotic approaches for stones in ectopic kidneys.[67,68] In summary, although the rare overall incidence of stones in ectopic kidneys limits the ability to study and compare treatment options, a variety of minimally invasive approaches are available that can successfully treat the stones. The ideal approach should be determined on a case-by-case basis, taking surgeon comfort level with the various treatment options into consideration. Finally, considering the inherent challenges of such cases, combined techniques should be considered where indicated, in order to avoid the morbidity associated with an open approach.

Future perspectives

With ever-improving laparoscopic and robotic technologies, techniques and experience, it comes as no surprise that there is some enthusiasm surrounding the expansion of these applications into stone disease. One consideration that is often underappreciated in the medical literature is access to surgical equipment. In particular, flexible ureteroscopes, which are commonplace in the USA, remain relatively uncommon in other parts of the world, owing to quite high costs and need for maintenance and repair.[69] Laparoscopy, on the other hand, is a rapidly evolving technique across the whole globe and might be more familiar to surgeons working in areas without immediate access to a full armamentarium of endoscopic instruments.[3] In some instances, familiarity with laparoscopic techniques might even be of greater importance than surgeon comfort in achieving percutaneous access to the kidney. Obtaining percutaneous access can be quite challenging and has high potential morbidity. This challenge has been postulated as a reason why as few as 11% of urologists performing PCNL routinely obtain percutaneous access by themselves.[70] In the majority of PCNL cases, therefore, co-ordination with a radiologist is necessary and causes an additional logistical concern in treatment that does not occur with a laparoscopic approach, in which the urologist is self-sufficient.

However, several disadvantages to both the patient and provider are present when considering laparoscopic methods compared with noninvasive and endoscopic alternatives. First, the use of a robot potentially increases the cost of surgery, which inevitably must be scrutinized as attempts are being made to make medicine more cost efficient. Heated debates over increased expenditures as a result of use of the surgical robot without clear improvements in outcomes are a central theme in prostate surgery and have recently extended to hysterectomies as well.[71,72] Adding stone disease to the discussion would seem impractical, especially in the absence of outcomes demonstrating superiority as a result of use of this technique. Another concern is the limitation that robotic surgery places on the use of fluoroscopy. The surgical robot requires a stationary position outside the body that would essentially eliminate the use of intraoperative fluoroscopy. As such, the surgeon must rely either on direct visualization of the stone or on an alternative means of visualizing the stone, such as ultrasonography, which is suboptimal and not an established a method for identifying stones in an intraoperative setting. Concerns also exist regarding laparoscopic techniques. For example, the majority of laparoscopic nephrolithotomies have been performed with the assistance of renal arterial clamping, which is not necessary during PCNL. Although short-term changes in renal function have been unremarkable with laparoscopic techniques, the potential long-term risk of renal insufficiency resulting from prolonged renal ischaemia remains a concern.[73] Furthermore, all cases of laparoscopic techniques for treating urinary stones in the literature have been reported from tertiary care referral centres with master laparoscopic and robotic surgeons, potentially leading to biased results and limited applicability to the field as a whole.

Conclusions

In summary, dramatic advances in both endourologic and laparoscopic technologies have given providers more tools and techniques for treating urinary stones than at any time in the past. The next critical step in the evolution of care is to determine the optimal use of each technique for any given patient, such that the stones can be removed with maximal efficiency and minimal morbidity.

For the time being, the vast majority of stones can and should be treated with ESWL, ureteroscopy or PCNL. Each of these modalities has been extensively studied and demonstrated to be safe and effective when appropriately used. As a result, they are all supported as first-line treatments by guidelines such as those from the American Urological Association (AUA) and the European Association of Urology (EAU).[15,16] However, as the field continues to evolve it is likely that increasing consideration will be given to laparoscopic approaches. To date, the strongest evidence for consideration of a primary laparoscopic approach to stone disease is in the case of a large renal pelvis or a proximal ureteral stone. In these cases, stone-free rates have been found to be high with comparable morbidity to current standard-of-care treatments.[26,27,29,50,51]

Evidence supporting laparoscopic anatrophic nephrolithotomy is less favourable as it has poorer safety and efficacy profiles than ESWL, URS and PCNL, and surgical experience in this area seems to be limited. Based on the evidence and experience in the field, it is the authors' opinion and recommendation that, for the time being, laparoscopic and robotic approaches should be reserved for use as a second-line treatment modalities in particularly complex cases.

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Author contributions

Both authors made substantial contributions to discussion of content, wrote the article and reviewed and edited the manuscript before submission. M.S.B. researched data for the article.