Chapter

Renal Tract Stones - Diagnosis and Management

Ivan Thia and Matthew Chau

Abstract

This chapter explores the diagnosis as well as various methods for stone clearance and recent advancements in each of the avenues, so as to provide the avid reader an understanding of the basis of each intervention and new exciting technology that lay on the horizon. Each section is further subdivided such that it would be easy for readers to search and look up relevant information at a glance without having to read through the entirety of the chapter. Firstly, diagnosis of renal calculi is explored, as renal tract pain can mimic a variety of abdomino-pelvic conditions and cause the same constellation of symptoms. Evidence based investigation modalities are discussed. Subsequently, management of renal tract calculi are divided into conservative management with analgesia and medical expulsion therapy, extracorporeal shock wave lithotripsy, ureteropyeloscopy and laser lithotripsy, as well as percutaneous nephrolithotomy. The different stone size, composition, location and patient factors have all contributed to the different surgical options as detailed above. Each section end with a discussion of new and exciting innovations in each of the areas that may lead to even more efficient and safer interventions for the Urology of the future.

Keywords: urolithiasis, extracorporeal shockwave lithotripsy, Ureteropyeloscopy, percutaneous Nephrolithotomy

1. Introduction

Renal tract calculi is a common presentation to an emergency department, and accounts for approximately 75% of presentations due to disorders of the genito-urinary system [1–2]. One in ten people will have kidney stones in their lifetime. Recurrence of renal stones within five years approaches 50% [3]. However, not all renal tract calculi require surgical intervention, with 75–90% of these passing spontaneously with conservative management [3]. Despite this, the large volume of work in this area had prompted medical professionals, pharmaceutical companies and researchers alike to explore different avenues of approach to tackle this problem.

2. Diagnosis

2.1 History taking and examination

Haematuria is a common feature of ureteric calculi and is associated with approximately 82% of renal colic presentations [4]. Nausea and vomiting as well as lower urinary tract symptoms such as urinary urgency, frequency, dysuria or hesitancy are also often present. Associated fevers might be indicative of another inflammatory or infective processes or signal the presence of an infected obstructed kidney, which is a urological emergency.

A comprehensive examination of all abdominopelvic organ systems is essential to rule out other important or life-threatening conditions. It is important to remember that a diagnosis of renal colic does not exclude other concomitant medical conditions that may require more urgent attention.

2.2 Bedside tests

Patients who are thought to have renal stones should have the following tests: [5].

- urine dipstick analysis/urine culture
- full blood examination
- C-reactive protein
- serum urea, electrolyte, creatinine
- serum calcium and uric acid
- serum parathyroid hormone
- 24-hr urine metabolic screen

In conjunction with individual patient (eg age, comorbidities, renal function) and disease (stone, duration) factors, these investigations are important in helping to identify a subset of patients who are not suitable for conservative management, especially if there are markedly raised inflammatory markers or severe renal failure in the absence of other infections/inflammatory conditions.

2.3 Diagnostic imaging

Expedient imaging should not be delayed in patient populations suspected of suffering from renal tract calculi. Low-dose, non-contrast computed tomography (CT) of the kidneys, ureters and bladder (KUB) is the current gold-standard imaging of choice. CT KUB accurately determines stone location, size and density, aiding in surgical planning. Mimickers of renal colic such as appendicitis, cholecystitis, bowel obstruction, diverticulitis or adnexal pathology can also be reliably excluded. A meta-analysis by Worster et al. has demonstrated that CT KUB has a pooled sensitivity of 93.1% and specificity of 96.6% in detecting renal tract calculi [6]. Especially when patients are not obese with BMI <30 kg/m2, sensitivity for detection of stones >3 mm in size approaches 100% [7].

KUB ultrasonography (USS) is a useful alternative first-line imaging tool to pick up renal tract calculi, especially in patients who are more vulnerable to radiation exposure. USS KUB can also identify hydroureter and hydronephrosis secondary to post-renal obstruction. Unfortunately, sensitivity of USS is compromised due to its poor penetration of air, and is also highly dependent on factors such as operator skill and patient body habitus. Overall, KUB ultrasonography is safe, reproducible and inexpensive, with acceptable calculi detection rates for both renal (sensitivity 45%, specificity 88%) and ureteric (sensitivity 45%, specificity 94%) calculi [8].

X-Ray KUB readily picks up calcium containing calculi but are often inhibited by lack of sensitivity in picking up small renal tract calculi due to obscuring overlying bowel gas and presence of phleboliths. Brisbane et al. argues that XR KUB has value in monitoring of growth in cases of known renal calculi under surveillance and is less useful in the acute setting. This modality is not widely used anymore in tertiary centres to diagnose renal tract calculi where ultrasound and CT services are widely available.

3. Management of renal stones

The management of renal stones depend on many different factors and has to be individualised to patient needs and availability of resources. The table below lists some of the important factors to consider when determining the best therapeutic approach in a given scenario (**Table 1**).

There are various therapeutic options available to tackle renal and ureteral calculi, and one or more of these can be utilised in conjunction in the management of more complex cases. It is important to remember that not all calculi need surgical intervention, at least not at initial presentation, and that the above factors mentioned are dynamic and so should the therapeutic option selected.

The average diameter of a ureter measures 3-4 mm and a plethora of studies have been performed to determine factors that would predict spontaneous stone passage. The size of a stone is a known independent factor, with stone size <7 mm being the usual cutoff for trial of conservative management with analgesia. In a meta analysis by Pearce et al., likelihood of passage is 60% for stones smaller than 7 mm in a cohort of 1093 patients [9]. Another important factor studied was the location of the stone, with proximal ureteric stones generally having a lower spontaneous passage rate as compared to distal ureteric stones, although this finding was not universal. This is likely due to patients electing to undergo elective surgery for symptom control as well as lack of consistency in time period allowed for spontaneous passage before surgical intervention is organised. Medical expulsion therapy (MET) is frequently used in conjunction with analgesia to quicken passage of stone and reduce opioid use, thereby reducing risk of complications and providing symptomatic relief. Various medical therapies have been studied, and this will be discussed later in the chapter.

Extracorporeal shock wave lithotripsy (ESWL), first invented in 1980 in Germany, is still widely used to treat renal and ureteric calculi in healthy individuals with low stone burden. This approach to stone management is enticing as it allows for a minimally invasive method to fragment certain types of calculi in favourable locations, circumventing the need for more invasive options. ESWL is highly effective when applied to the appropriate patient population and should be incorporated into the repertoire of urological centres where available.

Factors Impacting Treatment of Renal Stones
Disease Factors: • Size • Location • Composition
Patient Factors: • Renal anatomy - ptosis, horseshoe, pelvic, cross-fused, single functioning • Intrarenal anatomy - infundibulo-pelvic angle, infundibular length, infundibular width • Ureteric anatomy - strictures, pelvi-ureteric junction obstruction, duplication, ectopic • Medical comorbidities - including but not limited to coagulation status, pregnancy, cardiac/renal/respiratory function, immunosuppression, inflammatory or malignant conditions* • Surgical history - previous intervention for urological and non-urological pathologies, cardiothoracic and vascular procedures along retroperitoneum • Fitness for surgery • Superimposed infection • Preference • Compliance with follow up • Socioeconomic considerations - length of stay, morbidity, cost, legal • Geographic consideration - rural/urban/suburban
Service Provision Factors: • Infrastructure/equipment availability • Technical expertise • Perioperative support availability • Imaging and radiology expertise availability

**Many medical factors are implicated in decision making, as they impact on the general fitness of an individual. The list stated is not exhaustive and a patient's comprehensive medical and medication history need to be taken into consideration when deciding on interventional therapies.*

Table 1.
Factors that impact the management of renal tract calculi.

Calculi fragmentation with laser lithotripsy is now the mainstay of nephrolithiasis management, and is widely employed for this purpose, with many urologists favouring its use due to its easy availability, flexibility, and ability to deal with almost any situation. Recent advancements in this field have allowed for greater and more accurate energy delivery, reduced retropulsion of stone fragments, and more customisable options to achieve better stone clearance with shorter operating times.

As for larger calculi >2 cm in size, percutaneous nephrolithotomy (PCNL) remains the gold standard surgical approach when attempting to achieve stone clearance. Patients do need to be counselled carefully as this procedure have higher preoperative complication rates as compared to the other interventions described. Open nephrolithotomy is now rarely used given its high morbidity rate and exclusive indications and is not within the scope of discussion in this chapter.

4. Conservative management

4.1 Analgesia

Non-obstructing renal calculi are generally asymptomatic and are frequently discovered incidentally in patients who have undergone either ultrasound or computed tomography (CT) imaging for other causes. The classic renal colic is triggered by an acute ureteric or calyceal obstruction leading to stretching of the corresponding proximal calyx, ureter, renal pelvis and/or peripelvic renal capsule [10–11]. This pain cycle occurs in a predictable pattern and can be categorised into phases:

- acute - insidious, constant with intermittent exacerbation leading to severe pain, crescendo picture that lasts up to 6 hours

- constant - sustained, maximal pain intensity, lasts up to 4 hours

- relief - gradual diminishment of pain intensity, lasts up to 6 hours

- This cycle can and often does repeat till offending stone is removed or passed.

Renal colic is unique in its migratory nature and pattern of referred pain. Sensory innervation of the ureter is fed back via the sympathetic autonomic nervous system of levels T10-L2 [12]. Depending on the level of obstruction, the distribution of referred somatic pain varies. Intrarenal or proximal ureteric obstructing calculi tend to cause renal angle tenderness and flank pain. As the stone migrates into the middle and distal third of the ureter, patients with lower abdominal or groin pain that radiate to or from the scrotal/labial region [13]. Distal ureteric obstruction is also associated with storage lower urinary tract symptoms (LUTS) such as urinary urgency, frequency, dysuria and oliguria. However, it must be noted that renal colic is highly variable, and no one symptom or painful region can reliably predict the location of the offending stone.

4.2 Non-steroidal anti-inflammatory drugs (NSAIDs)

Renal colic is mediated by the secretion of prostaglandins secondary to local stimulation of the obstructing calculus. In turn, these prostagladins stimulate vasodilatation with greater permeability of glomerular afferent arterioles, increasing urine production and renal pelvic pressure in the acute phase [14]. The tight fibrous renal capsule does not allow room for expansion to accommodate this increased urine volume, with the increased intrarenal pressure manifesting as pain.

NSAIDs have been included in various guidelines and protocols across general practitioner and emergency department services as a first line analgesia drug for management of renal colic. Paracetamol and NSAIDs are non-selective or selective COX inhibitors and they inhibit the production of prostaglandins. Depending on formulation, this class of medication takes 3–7 days to reach maximal effect, causing a reduction in prostaglandin production, reducing glomerular filtration by up to 35%, thereby relieving renal pelvic pressure [15]. They also have local effects in reducing ureteric oedema and peristalsis, further reducing local stimulation of pain receptors [16–18]. This is evident with per-rectal (PR) administration of indomethacin for distal ureteric stones resulting in much better symptomatic pain relief as compared to other forms of analgesia.

Studies have shown that patients receiving NSAIDs as part of routine analgesia regimen for renal colic experience greater reduction in pain scores, require lower amounts of rescue analgesia for breakthrough pain and lower doses of opioids and therefore experience less opioid related side effects such as nausea and vomiting (5.8% vs. 19.5%) [19–20]. Also, both oral PR NSAIDs reduce colic episodes when used as a regular medication, and reduce hospital admission rates by 28–57% [21]. However, it is worth noting that despite its benefits, NSAID administration does not reduce time to stone passage, nor does it increase the likelihood of spontaneous stone passage [22].

NSAIDs are versatile and come in different preparations including oral, intravenous, and PR formulations with analgesic effect seen from 30mins of administration. As only short courses of NSAIDs are required for symptomatic pain relief for renal colic, the potential side effects of exacerbating gastric irritation, renal and cardiac failure are rare even in patients with pre-existing disease if used with caution.

4.3 Opioids

Opioids are medications that work via binding to opioid receptors found predominantly in the nervous system and gastrointestinal tract, thereby producing its analgesic and anaesthetic effects [23]. There are many different opioids, binding to various receptors to varying degrees, either as agonists or antagonists, and these have found widespread application in the management of both acute and chronic pain. In the setting of renal colic, opioids mediate a quicker analgesic effect, although there is no significant difference found between opioid and NSAID for pain relief by 30mins. Also, opioids are ineffective in treating the underlying cause of renal colic, unlike NSAIDs, and require frequent, repeated dosing to achieve the desired pain relief, resulting in higher risk of gastrointestinal and neurodepression side effects.

4.4 Medical expulsive therapy (MET)

MET has been extensively studied as there is evidence that it reduces the time for passage of stones that would otherwise not have required surgical intervention, thereby achieving earlier symptomatic relief, reducing need for prolonged analgesia and risk of side effects, as well as reducing emergency department presentations and number of surgeries performed [24]. It was discovered that the distal ureters are rich with alpha-adrenergic receptors and that alpha blockers could possibly relax ureteral smooth muscle without impeding ureteral peristalsis as well as reduce ureteral oedema [25].

Alpha-blockers prove efficacious in increasing the rate of expulsion (RR 1.54, 95% CI: 1.29, 1.85; $p < 0.01$), reducing time to expulsion ($p < 0.01$), reducing analgesia use and providing relieve from renal colic ($p < 0.01$) [26]. The most well studied alpha-blocker is tamsulosin. The effect of this class of medication is most evident in larger stones (>5 mm) within the distal ureter. Newer, more selective medications of the same class such as silodosin (α1A) and naftopidil (α1D) show great promise, at the same time reducing the risk of experiencing the most common reported side effect of postural hypotension [27–30]. Alpha-blockers have also found a place as adjunct to surgical intervention, for example laser lithotripsy or external shockwave lithotripsy (ESWL), in aiding in the passage of residual stone fragments [31].

The use of calcium channel blockers, steroids and phosphodiesterase type 5 (PDE5) inhibitors are historic, and they have been shown to be inferior to alpha-blockers in several small studies. Therefore, the use of these medications should not be first line in MET.

4.5 Advancements

A multidisciplinary team approach to management of renal calculi has been shown to improve patient outcomes. The team should consist of a urologist, general practitioner, nurse practitioner. A radiologist, pharmacist and dietician should also be part of the team for the management and prevention of renal calculi. Conservative management of renal colic requires active monitoring, as stones that do not pass within 4 weeks require surgical removal to reduce risk of chronic renal scarring and atrophy.

5. Extracorporeal shockwave lithotripsy (ESWL)

ESWL was first invented in the 1970s and introduced as a novel method for management of renal tract stones in the 1980s, gaining widespread recognition and utility as a first-line treatment option [32]. Over the last 40 years, better technology and more advanced equipment have been developed, yet there has been little modification to the way the shock waves are generated or delivered to its intended target. The acoustic shockwave, a pressure pulse, produced by a lithotripter is responsible for both the fragmentation of renal tract calculi. Newer lithotripters have been built to focus on the efficient and safe delivery of these acoustic waves through body tissue to the intended target.

5.1 Basis of ESWL

A typical shockwave is short (~5 μs duration), with its energy spread over a large frequency range. Regardless of the type of lithotripter, the waveform of the shockwave produced is similar, consisting of a near instantaneous shock front, followed by a compressive phase, then a slowly diminishing tensile phase [33–35]. The difference in energy generated and magnitude of focal area determines the performance of the lithotripter.

An acoustic wave is created when an object moving through an air or fluid medium causes local compression and excitation of the medium surrounding it [36–38]. These molecules in turn excite their neighbours, leading to the successive propagation of the wave of energy. The speed at which the wave propagates depends on the medium in which it is travelling. When the object moves away from a medium, there is an opposite resultant disturbance called rarefaction, with its ensuing propagation leading to a tensile phase [39–41]. Shock waves generated by a lithotripter have compression and tensile phases travelling at different amplitude and speed, as the generation of a shockwave is nonlinear in nature [42–44].

The amount of energy delivered to the renal tract calculi is dependant on the wave intensity and its transmission or reflection. In relation to the above, acoustic impedance, the effective resistance of a medium to the propagation of an acoustic wave, is an important property [45–47]. The acoustic impedance of tissue, renal tract calculi, bone and air relative to water increases in orders of magnitude respectively, therefore it is important to minimise any air medium separating the lithotripter and the patient [48–49]. As a comparison, up to 95% of energy would be transferred from water-to-stone via a shockwave, but only 0.1% of the same energy would be delivered water-to-air. Naturally, a flank approach through a predominantly tissue medium is favoured for an effective ESWL procedure.

Similar to the theory behind delivering radiotherapy, focusing and minimising diffraction of an energy source would ideally maximise damage to a particular area or object in question whilst minimising collateral injury as much as possible [50–51]. Due to the nature of shockwave propagation, a focal area of high acoustic pressure is unavoidable. The size of the focal area is depending on how the lithotripter focuses the shockwave as well as the shape of the waveform it generates. A safe design feature would aim to deliver as large an acoustic pressure over as small a focal area as possible.

Shockwave generation can be created via a spark source (electrohydrolic lithotripter), magnetic repulsion (electromagnetic lithotripter) or crystal deformation (piezoelectric lithotripter) [52–55]. All of the above lithotripters would require a means of focusing shockwaves, whether it be an ellipsoid reflector, an acoustic lens or a spherical cap respectively. Once the shockwave is generated, coupling between the lithotripter and body is required for good transference of energy. Most modern lithotripters utilise an ellipsoid rubber couplant filled with water placed against a patient's body with a coupling gel in between to reduce any air pockets present, so as to deliver as much energy to the calculus as possible [56–57].

5.2 Mechanism of action

The surface of a renal tract calculus is generally complex and irregular, meaning that the angle of incidence between a shockwave to stone is different at different regions. This results in a longitudinal compression wave as previously discussed, but also a perpendicular transverse shear wave that cause oscillation of molecules it passes through. These two waves travel at different speeds, reflect and refract again at different angles, and this interference causes high tensile stress within the calculus itself. Proposed mechanisms of stone fragmentation with ESWL include:

Spall fracture [58] - reflection of shockwave from posterior wall of calculus into incoming tensile phase pressure tail causes focal large tensile stress leading to material failure.

Shear stress [59] - interference between shear waves and compression waves exploit layered nature of calculus, leading to fracture along weakness of organic binding material between each layer of crystalline stone.

Superfocusing [60] - the amplification of stresses within a calculus due to its inherent geometry and elastic properties with initial shockwave reflected via diffraction and refraction to varying degrees.

Squeezing [60] - difference in property between calculus and surrounding urine/fluid medium results in circumferential hoop stress from shockwave travelling outside the calculus, leading to maximal axial tensile stress and material failure.

Cavitation [60] - collapsing bubbles predominantly on the proximal surface of the calculus created from the negative pressure tail of the acoustic pulse lead to generation of secondary shockwaves that are equally powerful.

Fatigue [60] - imperfections in stone material, coupled with repeated high stress insults lead to formation of cracks and eventual material breakdown.

5.3 Discussion

Due to the physical properties of wave formation and propagation, ESWL should be utilised selectively for management of renal calculi to achieve optimum success rates. Careful selection of patients should take into account of multiple factors, including:

- size of stone (renal calculi <20 mm, proximal or distal ureter calculi <10 mm)
- location (ureter, renal pelvis, renal calyx)
- stone composition
- patient habitus
- lithotripter availability

Snicorius et al. demonstrated that stone size or volume is the greatest prognostic factor in determining ESWL success, with an 80–85% stone clearance rate for stones <20 mm in size, down to 33–65% for stones >20 mm [61]. Stone clearance rates in the renal pelvis (86–89%), upper pole calyx (71–83%), inter polar calyx (73–84%) and lower pole calyx (37–68%) also differ significantly [61]. Stone composition determines material tensile and shear strength and therefore susceptibility to stress. For example, cystine and calcium oxalate monohydrate stones are difficult to comminute, and frequently fractures into larger fragments that are difficult to expulse, requiring further medical and surgical therapy [62]. Obesity translating into increased skin-to-stone distance is another independent predictive factor for stone failure [63]. Therefore, the importance of proper patient selection cannot be understated in improving treatment success rates.

Complications from ESWL is not uncommon and can result in devastating outcomes. As previously discussed, the mechanisms causing stone fragmentation also result in the same stress damage to body tissue. Due to the need to adjust the length of the focal area to penetrate deep into tissue onto stone, as well as patient movement or potential misalignment, many of the shockwaves pass directly onto surrounding tissue, which over prolonged and repeated insult will suffer collateral damage in spite of inherent tissue protective factors [64–66]. Mechanical stress from direct compression of tissue, variation in tissue impedance, expansion and collapsing cavitation bubbles all contribute to tissue damage [67]. Also, stone clearance may not be achieved satisfactorily, leading to secondary complications from residual stone fragments. Commonly cited complications and risk of individual events is described (**Table 2**).

ESWL complications	
Steinstrasse	4–7%
Renal colic	2–4%
Urinary tract infection	7–23%
Haematoma	4–19%
Cardiac dysrhythmia	11–59%
Bowel perforation, other solid organ haematoma	rare

Table 2.
ESWL complications and rates [68].

There is no general consensus regarding maximum number of shock waves that can be delivered per session, although small case series demonstrate >4000 shocks delivered, in an effort to reduce complication rates [69–70]. Each session usually lasts 45-60mins, and repeated sessions can be performed to improve stone clearance rates. Insertion of a ureteric stent prior to commencement of ESWL therapy has not been shown to improve stone clearance. Another potential beneficial measure with weak evidence include commencing treatment at a low-power, low-frequency setting and subsequent stepwise power ramping may increase stone clearance rates and reduce tissue damage by inducing vasoconstriction and therefore renal bleeding [71–73].

Absolute contraindications of ESWL include: [74].

• pregnancy

• untreated urinary tract infection

• decompensated coagulopathy

• uncontrolled arrhythmia

• abdominal aortic aneurysm greater than 4 cm

5.4 Advancements

Greater understanding of shock wave generation and its mechanism of stone fragmentation have allowed for devices with producing waves with wider focal zones and lower peak pressures to reduce risk of injury yet at the same time improve stone fragmentation efficiency [75]. Secondly, experimental devices with twin sources firing in tandem or sequentially have been shown to improve stone fragmentation by increasing the number and amplitude of cavitation bubbles via a second pulse [76–78]. Combinations of piezoelectric with an electrohydraulic or piezoelectric with electromagnetic lithotripter have been experimented with.

Raskolnikov et al. describes a new ultrasound technique that takes this even further, with promising results in vitro. The new technology, utilising ultrasound technology and named burst wave lithotripsy (BWL), utilises a prolonged burst of consecutive, low amplitude ultrasound pulses rather than a single high amplitude shock wave produced in ESWL [79–81]. ESWL pulses lead to a focused fracture point, with resulting unsatisfactory stone fragmentation into large fragments that are then subsequently more difficult to break up with successive pulse waves. BWL, on the other hand, causes multiple fracture points to develop along the stone surface, with smaller fragments breaking off the main stone body, theoretically achieving better fragmentation. Fragment sizes are also more controlled depending on frequency of the ultrasound waves as compared to erratic fragment sizes produced by ESWL. Finally, BWL devices are more portable, less cumbersome and have the potential to be incorporated into pre-existing ultrasound devices, culminating in an exciting avenue of research for the future.

6. Ureteropyeloscopy with laser lithotripsy

Light amplification by stimulated emission of radiation, or laser for short, has found various applications in medicine since its inception in 1951, with dermatologist

Dr. Leon Goldman utilising a ruby laser to remove skin tattoos, while Dr. McGuff made use of one to ablate atherosclerotic plaques [82]. More recently, lasers are used extensively in the field of dentistry, cosmetic surgery, opthalmology, plastics surgery, and of course urology. In 1968, Mulvany first attempted to use a rubidium laser to fragment bladder stones, and has been a hallmark in the management of calculi in the urinary tract from the 80s [83].

6.1 Mechanism of action

All laser generators compose of an energy source, an active medium from which electromagnetic radiation is produced, and finally a resonant cavity with two mirrors (reflective and partially reflective) at each end [83]. The active semi-conductive, solid state medium (e.g Yttrium Aluminium Garnet, also known as YAG) is doped with excitable ions of neodynium, erbium, holmium or thulium [83]. An electric current is passed through the active medium, exciting atoms within its molecules, leading to the subsequent discharge of this energy as photons. Once the number of excited photons outnumbers the non-excited photons, a laser beam is produced. These laser beams have the same wavelength, travels in a single direction, and can be directed to travel in collimation with little divergence, with energy being delivered to a finite space with minimal dispersal [83]. Laser production is delivered in pulses, which can be controlled either with phase lock or a shutter mechanism, thereby reducing the potential for collateral tissue damage due to sustained exposure during procedures [83].

Laser-tissue interactions consist of photomechanical and photothermal processes [82]. Photomechanical processes induced by laser directed at calculi is akin to the mechanisms discussed for ESWL in previous sections. The deposition of energy from the laser beam around a calculi causes a transient, unstable stress wave leading to spallation or mechanical disruption, as well as formation and collapse of cavitation bubbles, both of which cause stress fractures to occur along the stone matrix and the ejection of ablated material through recoil [82]. Photothermal processes are a result of direct absorption of energy by the calculi and depending on the temperature induced, results in ablation, fragmentation and eventual vaporisation of material [82]. This energy transfer occurs via direct photon absorption by the calculi or indirect transfer from surrounding water through explosive vaporisation [82].

6.2 Laser fibre construct

There are certain requirements to be met for a laser fibre to be able to deliver photons from its energy source to its intended target: [84–86].

- light travelling without impediment
- minimal energy loss or dissipation
- low back-burn
- easy insertion and travel within ureteroscopes (semi-rigid and flexible) or nephroscopes
- lightweight with ease of transport and storage

- able to sustain prolonged use
- flexible, able to bend and maintain use

To that end, a laser fibre is usually constructed from a fused silica-glass compound at its core, with multiple layers of cladding around it to reduce risk of fibre failure due to bending and heat absorption [87].

Fibre tip design is vital in determining ease of use of the fibre as well as minimising back-burning, whereby the tip of the fibre with its covering jacket might be damaged due to overheating or contact with calculi [88]. A variety of tips are in use today, namely the flat tip and the ball tip. Other advancements including usage of a hollow steel tip (increased durability), tapered fibre (increased flexibility) and inverse tapered fibre (reduced overheating) have also been experimented with success [88].

6.3 Laser parameters

As discussed, photothermal processes induce dehydration, vaporisation and carbonisation of the stone surface when a critical thermal threshold is reached, and is effective in all stone types [89–90]. As this process is going on, the photomechanical processes then exploit this weakness, leading to material failure, fragmentation, and retropulsion through cavitation bubble disruption. Ease of calculus fragmentation is dependent on both stone and laser properties. There are multiple parameters that determine or influence the laser beam, with the following three described being the most commonly calibrated by urologists during a procedure: [91].

- frequency: number of pulses emitted per second (Hz)
- pulse energy: total energy power of the laser pulse (J)
- pulse duration: time during which the laser pulse energy remains above half its maximum value

Generally, to fragment and basket a calculus in the ureter, typical settings used would be one of high pulse energy and low frequency [92]. To dust a stone, on the contrary, a low pulse energy and high frequency is employed [92]. Pulse duration is another important parameter gaining more scrutiny as it influences efficiency of calculus fragmentation. Long-pulse mode reduces stone fibre back-burn without sacrificing stone retropulsion. Newer energy sources allow for the Moses effect, whereby a shorter, lower energy pulse is first projected to create a cavitation bubble followed by a longer, higher energy pulse which improves fragmentation efficiency [93–95].

Also it must be noted that increasing fibre size does not correlate with increased energy delivery. Conversely, larger fibre sizes are associated with increased energy dispersion and poorer fragmentation rates [96].

6.4 Dusting versus fragmentation

Dusting of calculi refer to the use of low energy, high frequency laser pulses to break them down to dust or minute fragments, after which the larger residual fragments can be broken down further with the “whirlpool” and “popcorning” method [97]. The fragmentation technique aims to break down calculi into larger, bite-sized fragments measuring ~3 mm or so and retrieving them with a basket, thereby leaving the patient stone free [98]. Both methods are widely used, and although Chatloff et al. demonstrated that re-presentations to the emergency department was more frequent with the dusting group (30–3%), Humphreys et al. found no difference in re-presentations or complication rates between the two groups, with the fragmentation group requiring a longer operative time [98–99].

The method of choice should depend on the stone composition, size, location and patient preference. Dusting would arguably reduce the need for use of a ureteric access sheath and stent, with a shorter operating time whilst increasing risk of subsequent renal colic. Fragmentation, on the other hand, necessitates the use of a ureteric access sheath with increased risk of ureteric trauma, as well as requiring stent placement post-operatively.

6.5 Safety and complications

Safety principles when operating laser equipment include: [100].

deploying laser fibre at a safe distance away from the tip of ureteroscope and not close to or within it

- directing laser fibre tip away from tissue surfaces
- maintaining irrigation throughout procedure
- minimise prolonged, continuous laser activation
- Injury to human tissue could be due to direct contact or indirect thermal damage. Complications from laser lithotripsy are rare, but can include operator eye injuries, ureteral injuries/perforations, bladder injuries/perforations, air emboli, bleeding and skin burns [100].

6.6 Future directions

The Holmium:YAG laser has been the dominant system utilised globally over the last 20 years, with the newer Thulium fibre laser (TFL) system showing major improvements over its predecessor. Apart from offering the most comprehensive modifiable laser parameters to improve stone ablation efficiency, it also has greater water absorption peak, meaning risk of optical or tissue damage is reduced to a quarter as compared to the Holmium:YAG system [101]. The TFL also uses nine times less energy, is more flexible and breaks calculi into smaller fragment by virtue of its smaller fibre. It also boasts a more manoeuvrable energy system that is seven times smaller and eight times lighter than a conventional Holmium:YAG model [102, 103]. Future improvements with the TFL include being able to use different endoscopic instruments simultaneously as well as miniaturisation of instruments with important applications.

6.7 Conclusion

Laser lithotripsy is an extremely flexible procedure that could be used in most situations to break up stones of any composition. Indeed, it is the most widely used technique for stone fragmentation at present, quickly overtaking ESWL and percutaneous nephrolithotomy (PCNL) with most guidelines recommending it as first-line therapy in various situations.

The only absolute contraindication to the use of laser lithotripsy is untreated urinary tract infections that may lead to severe urosepsis.

7. Percutaneous nephrolithotomy (PCNL)

7.1 Introduction

PCNL is a minimally-invasive surgical technique that allows removal of stones through a percutaneous access, typically through the back and into the kidney. The first nephroscopy was described by Rupel and Brown in 1941 in which a rigid cystoscope was passed into the kidney during open surgery [104]. Shortly after, Goodwin placed the first nephrostomy tube after performing the first antegrade nephrostogram. This lead to Fernström and Johansson to describe the first technique of stone extraction through percutaneous access under radiological guidance in 1976. With ongoing advancement of technology starting from the Godfathers of endourology such as Kurt Amplatz and Arthur Smith, the PCNL technique has developed into a reliable and effective technique for stone extraction.

PCNL monotherapy, or in combination with ESWL, is currently the most effective treatment option for patients with large stone burden. Stone free rate is seen up to 80–90% after PCNL for renal calculi and 86% for proximal ureteric stones. Multiple tracts allow for the successful treatment with a single surgical session in almost all stone burden.

PCNL is reserved for patients with large stone burden in the kidney and upper ureter, as seen in patients with complete or partial staghorn calculi, renal stones larger than 2 cm, proximal ureteric stones larger than 1 cm and multiple stones between 1 and 2 cm [105–107]. Patients with large (>1 cm) lower pole stones where retrograde access is difficult, may also benefit from PCNL. Additionally, patients who have failed conservative options such as retrograde lithotripsy or shockwave lithotripsy may also be considered for PCNL. Given the more invasive nature of PCNL, patients with uncorrected coagulopathies are excluded from PCNL due to the high risk of bleeding. Untreated urinary tract infections are another absolute contraindication for performing PCNL. Careful consideration should be made for patients with single kidneys.

Pre-operative assessment of patient prior to PCNL should include a complete medical history and physical examination. Assessment of the before mentioned contraindications should be addressed. Antiplatelet and anticoagulation therapy should be assessed and individualised to each patient in order to balance the bleeding risk with the thromboembolic risk. The underlying pathology for each patient necessitating anticoagulation/antiplatelet therapy differs and should be taken into account when deciding on the cessation period and reinitiating timing [109, 110, 112]. Bridging therapy may be required in patients with high thromboembolic risks such as mechanical prosthetic heart valves. If medically suitable, antiplatelet and anticoagulation therapy should be withheld according to local protocols. Current literature recommends cessation of antiplatelet therapy 7 days prior to surgery. Anticoagulation therapy cessation depends on the type of therapy and patient ability to excrete medication. Preoperative urine culture should be performed to exclude UTI and appropriate antibiotic therapy given. Broad-spectrum antibiotics can also be given prophylactic to assist with the bacteria colonised on calculi [105]. Anaesthesia review should also be obtained.

Preoperative planning with computed tomography (CT) scans is essential for planning of percutaneous access. CT allows identification of stone burden, location and puncture trajectory. The kidney typically lies within the retroperitoneum on the psoas and quadratus lumborum muscles. Significant structures surround the kidney includes the ribs, liver, duodenum and colon on the right, and the ribs, pancreas (tail), spleen and colon on the left. Bilaterally, the diaphragm and pleura lie in close relation with the upper pole of the kidney. Planning of puncture site and trajectory should consider these surrounding structures as well assessment of complex anatomy such as hepatomegaly or retrorenal colon. It is also particularly useful in cases of anatomical variations such as horseshoe kidneys, congenital renal anomalies, transplanted kidney, morbid obesity and evaluation of adjacent visceral structures [105].

7.2 Approaches

Patients are typically positioned in prone, prone-flexed, supine, supine oblique or split-leg modified lateral positions. The ideal position for optimal access is still controversial and is usually determined in a case-by-case method. Complex anatomy, patient characteristics (such as body habitus) and surgeon training are all factors to be considered.

PCNL is performed with percutaneous access into the renal collecting system. There are multiple modalities of imaging that can be used to assist with access. Common modalities include fluoroscopy, ultrasound, CT or MRI guidance and endoscopic guidance. Often, the surgeon urologist prefers to obtain their own access over interventional radiology as it allows targeting of calyces that maximise calculi access.

Most urologists are familiar with fluoroscopy guided percutaneous access, clarity of visibility of their needle and guide wire and the ability to visualise the calculi [114, 116]. During fluoroscopic puncture of the calyx, radiation exposure should be considered as the fluoroscopic screening time during PCNL is higher than most other urological procedures. At the beginning of a procedure, cystoscopy and retrograde placement of a ureteral catheter or access sheath assists with injection on contrast. The renal collecting system is initially opacified with contrast to assist with localising the target calyx.

Ultrasonographic guidance uses real-time diagnostic ultrasonography (US) to identify a renal collecting system to target calyces. Agarwal et al. have identified the overall success rate of this technique to be 88–99%. US utilises no radiation, minimising the radiation exposure for patients and staff, making it safe for pregnant and paediatric patients. USS allows visualisation of soft tissues including surrounding structures, which assists with avoiding iatrogenic injury to the surrounding structures. US can be more difficult in patients without a dilated system, as visualisation of the calyces will be more difficult. Instruments such as wires and needles are harder to identify on US.

Once access into the collecting system is gained, a nephroscope is introduced to identify the stone. Stone extraction can be performed by different methods.

7.2.1 Manual

If calculi are smaller than 1 cm in size, they may be manually extracted through the access sheath with a grasper. Graspers can be toothed or non-toothed. Other devices such as stone baskets, made of soft, pliable material, can be used as well.

7.2.2 Laser lithotripsy

As previously described, laser can be used to fragment stones for extraction.

7.2.3 Ultrasonic lithotripsy

The use of ultrasonic lithotripter is the author's preferred method of stone extraction. The setup typically includes a handheld device, a metal rod containing the working channel and master control unit [115–117]. A handheld device is used to convert electrical current into vibration waves by utilising a piezoelectric crystal. The ultrasonic waves are translated down a metal rod, which fragments the stone when brought into direct contact. Variable suction is also applied through the working channel to allow stone removal, post-fragmentation. Heat energy is produced as a byproduct though, a risk of thermal injury to both the patient and surgeon needs to be considered when being used. Current technology combines the use of ultrasonic energy with ballistic energy to increase the rate of stone clearance. Ballistic devices repeatedly drive a solid probe into the target to drill and fragment stones. Similar to a jackhammer, it is particularly useful in hard stones resistant to ultrasonic lithotripsy. The lack of heat production and dissipation mitigates the thermal injury risk that is associated with ultrasonic lithotripsy.

Calyceal stone clearance is confirmed with a combination of careful inspection of the collecting system and ensuring all shadows on fluoroscopy have been removed. Following completion of lithotripsy, depending on surgeon preference, a ureteral stent, nephrostomy tubes or nothing may be inserted. Nephrostomy tube, usually a foley catheter, insertion may assist with a second access (relook PCNL or emergency access) and provide low intrarenal pressure to assist with haemostasis. Ureteral stents may assist with residual stone fragments or dust passage. In very select patients who are deemed to have total clearance and without pelvi-ureteric junction oedema, stent and nephrostomy tubes may be omitted.

7.2.4 Endoscopic combined intrarenal surgery (ECIRS)

In recent years, the popularisation of ECIRS has been experienced with studies supporting the efficacy and efficiency of stone clearance during PCNL. Initially described in 2008 by Scoffone et al., it describes a technique that combines retrograde and antegrade access to large and complex renal stones using both rigid and flexible endoscopes [119]. Cracco et al. published a systematic review in 2020 that updated the results and outcomes of ECIRS since its popularisation [120]. Studies have shown ECIRS demonstrates better stone clearance rates in a single surgical procedure (61–97% with ECIRS vs. 57–78% with standard PCNL) with reduced number of percutaneous punctures. ECIRS has reported similar complications rates when compared to standard PCNL techniques, with the majority of complications reported being low grade. However, ECIRS is associated with lower risk of bleeding complications, which is likely related to the single puncture site compared to multiple punctures by standard techniques. The reduced need for multiple access is an important factor that reduces the adherent risk of haemorrhage, infection and operative time.

7.3 Complications

Common complications from PCNL include mild bleeding immediately post-operative, residual stone burden requiring a second operation, recurrent (new) stone

PCNL complications	
Haematuria	4–7%
Haemorrhage	
Requiring Transfusion	0.6–11.2%
Requiring Intervention	0.3–2.0%
Fever	11–32%
Sepsis	0.8–1.8%
Recurrent stone formation	50%
Residual stone requiring another surgery	4.8–20%
Bowel or surrounding organ injury	0.3–2%

Table 3.
PCNL complications [121].

formation and urinary tract infections [105, 118]. Less common complications include haemorrhage, sepsis requiring intensive care admission, pneumothorax/hydrothorax. Moderately severe bleeding from the kidney or pseudoaneurysms requiring interventional radiological intervention for embolisation, failure of access to the kidney, infection of the nephrostomy puncture site and anaesthetic or cardiovascular related complications. Extremely rare, major damage to major renal vessels may result in emergency nephrectomy to control bleeding. Urine leak, bowel, spleen or liver injury is rare, but may also occur. Complications are outlined in **Table 3**. Both clinical and biochemical assessment is required in order to identify complications early for management.

During a PCNL, haemorrhagic complications may occur from the puncture, tract dilatation and stone fragmentation, thus careful pre-operative planning is required to prevent these from occurring. Lee et al. described body mass index (BMI) as a contributing factor to bleeding in PCNL [112]. Conversely, Said et al. and Gok et al. found no significant correlation with this [108–109]. Yesil et al. had identified previous open abdominal surgery, stone treatment (ESWL) and those with previous PCNL all held a higher risk of haemorrhagic complications [113]. This was backed by Said et al. and Arora et al. A more significant risk factor for haemorrhagic complications is diabetes mellitus. It has been hypothesised that the arteriosclerosis can be the source of bleeding post-PCNL in diabetic patients. The other identified risk factor is the presence of pre-operative urinary tract infections. An urinary tract infection can cause inflammation of renal parenchyma that makes it more friable and impairs coagulation, which results in haemorrhagic complications. Interestingly, current literature shows no convincing evidence of correlation between bleeding post PCNL with age, stone position and anticoagulation use [108–111]. Despite no correlation, the authors still recommend careful pre-operative planning with anticoagulants and anti-platelet therapy cessation.

8. Summary

There are many approaches to managing renal and ureteric stones as mentioned, and careful patient selection is required for optimal outcomes. **Tables 4** and **5** detail current guideline recommendations regarding treatment modality of choice listed by

Renal calculus	
Larger than 20 mm	1. PCNL 2. URS or ESWL
10-20 mm	1. URS or ESWL 2. PCNL
Lower pole 10-20 mm (unfavourable)	1. URS 2. PCNL 3. ESWL
Lower pole 10-20 mm (favourable)	1. URS or ESWL 2. PCNL
Smaller than 10 mm	1. URS or ESWL

Table 4.
Current guideline recommendations for the management of renal calculi.

Proximal ureteric calculi	
Larger than 10 mm	1. URS or ESWL
Smaller than 10 mm	1. ESWL 2. URS
Distal ureteric calculi	
Larger than 10 mm	1. URS 2. ESWL
Smaller than 10 mm	1. URS or ESWL

Table 5.
Current guideline recommendations for management of ureteric calculi.

the European Association of Urology according to stone size and location. These are meant to help guide clinician decision making, bearing in mind each patients' individual unique circumstance and requirements.

Author details

Ivan Thia* and Matthew Chau
Fiona Stanley Hospital, Western Australia, Australia

*Address all correspondence to: ivan.thia@health.wa.gov.au

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