**NEPHROLITHIASIS**

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**ABSTRACT**

Kidney stones are concretions of different mineral salts mixed with an organic matrix that form in the upper urinary tract. As a stone moves from the kidney to the ureter, it can present with renal colic symptoms, and may cause urinary tract obstruction and/or infection. In fact, acute passage of a kidney stone is one of the leading reasons for visits to an emergency room. Over the past four decades, the lifetime prevalence of nephrolithiasis has more than doubled in the United States (and several developed countries), afflicting around 11% of men and 7% of women. Unless the underlying etiology of stone formation is adequately addressed, kidney stones can recur at a rate of around 50% ten years after initial presentation. The evaluation of a kidney stone former requires an extensive medical history (to identify environmental, metabolic, and/or genetic factors contributing to stone formation), imaging studies to evaluate and track stone burden, and laboratory studies (serum and urinary chemistries, stone composition analysis) to guide lifestyle and pharmacological therapy. The majority of kidney stones are composed of calcium (calcium oxalate and/or calcium phosphate), either pure or in combination with uric acid. Calcium oxalate stones can be caused by hypercalciuria, hyperoxaluria, hyperuricosuria, hypocitraturia, and/or low urine volume. Calcium phosphate stones occur in patients with hypercalciuria, hypocitraturia, an elevated urine pH, and/or low urine volume. In addition to lifestyle changes (increasing fluid intake, reduction in salt intake, moderation of calcium and animal protein intake), pharmacological therapy directed at the underlying metabolic abnormality (thiazides for hypercalciuria, potassium citrate for hypocitraturia, xanthine oxidase inhibitors for hyperuricosuria) can significantly reduce calcium stone recurrence rate. Pure uric acid stones account for 8-10% of all stones, although their prevalence is significantly greater in stone formers with type 2 diabetes and/or the metabolic syndrome. Uric acid stones are primarily caused by an excessively acidic urine, and urinary alkalinization with medications such as potassium citrate can dissolve uric acid stones and prevent recurrent uric acid nephrolithiasis. Cystine stones result from inactivating mutations in genes that encode renal tubular transporters that reabsorb the amino acid cysteine, typically present in childhood, are highly recurrent, and require aggressive control of cystinuria with specific pharmacological therapy. Infection (struvite) stones often present as staghorn, and require careful surgical removal of all of the stone material.

**OVERVIEW**

Urinary stone disease is a common clinical condition that afflicts 1 in 11 individuals in the United States, and is increasing in incidence. It typically presents with renal colic symptoms following the passage of a calculus from the kidney to the ureter. The pathophysiology of kidney stone formation is diverse, and includes a combination of genetic and environmental factors. In fact, kidney stone formation should not be viewed as a diagnosis but rather a symptom of an underlying abnormality. Evaluation of a kidney stone former with a detailed history, and appropriate laboratory and imaging studies helps to identify risk factors for stone formation and provides an opportunity to institute therapy that reduces the risk of stone recurrence. This chapter reviews the epidemiology of kidney stone disease, discusses the pathophysiology underlying the most commonly encountered stone types, and details the evaluation and management of patients with nephrolithiasis.

**EPIDEMIOLOGY AND NATURAL HISTORY**

**Epidemiology**

Nephrolithiasis is a common clinical condition encountered in both developed and developing countries. Its prevalence in the United States has more than doubled over the past 4 decades from 3.8% in 1976-1980 to 5.2% in 1988-1994 to 8.8% in 2007-2010 (1, 2). Similar increases in the prevalence of nephrolithiasis have been reported in other developed countries (3). Factors underlying this rising prevalence include changes in diet and fluid intake, greater use of medications and procedures that predispose to stone formation, the association of stone disease with the rampant epidemics of obesity and type 2 diabetes, climate change, and increased use of abdominal imaging (2). In the United States, stone disease afflicts Caucasians at a greater frequency than Hispanics (Odds Ratio: 0.60 vs. Caucasians) and African Americans (Odds Ratio: 0.37 vs. Caucasians) (2). It is also more prevalent in men than women, although recent reports suggest a narrowing in this gender gap, with the greatest increase in stone incidence in recent years occurring in younger women (4). A marked geographic variability in the prevalence of nephrolithiasis is also reported, with 20-50% higher prevalence of stone disease in the U.S. Southeast (“stone belt”) than the Northwest, primarily due to differences in exposure to temperature, humidity, and sunlight (5). Recent predictions suggest a likely northward expansion of the present-day U.S. “stone belt” as an unanticipated result of global warming (6). In 2000, the total cumulative costs for caring for patients with urolithiasis were estimated at US $2.1 billion (7). The rising prevalence of obesity and diabetes, together with population growth, is projected to contribute to dramatic increases in the cost of urolithiasis by an additional $1.24 billion/year estimated by 2030(8).

**Natural History**

RECURRENCE

The natural history of stone disease was studied in detail in all validated cases presenting with incident kidney stones in Olmsted County, Minnesota between 1984 to 2003 and followed for stone recurrence through 2012 (9). For the first episode, 48% of patients passed their stone spontaneously with confirmation, 33% required surgery for stone removal, 8% presumably spontaneously passed their stone (without confirmation), and 12% had no documentation of passage (9). This cohort was followed for a median of 11.2 years with recurrence occurring in 11%, 20%, 31%, and 39% at 2, 5, 10, and 15 years, respectively. The stone recurrence rates per 100 person-years were 3.4 after the first stone episode, 7.1 after the second episode, 12.1 after the third episode, and 17.6 after the fourth or higher episode (10). Independent risk factors for incident stone recurrence include younger age; male sex; higher body mass index; family history of stones; pregnancy; history of a brushite, struvite, or uric acid stone; number of kidney stones on imaging; and diameter of the largest kidney stone on imaging (10). These studies have led to the development and refinement of the Recurrence Of Kidney Stone (ROKS) tool to predict the risk of symptomatic recurrence by using readily available clinical characteristics of patients with kidney stones (9, 10).

POTENTIAL COMPLICATIONS

*Urinary Tract Infection*

There is a bi-directional relationship between urinary tract infections (UTI) and nephrolithiasis, as chronic UTIs lead to the formation of struvite stones, and stone disease increases the risk of UTI. Struvite stones typically occur in patients infected with urea-splitting organisms, and their pathogenesis and management are described in more detail in a later section. Gram-negative bacilli are the most common pathogen in UTI in patients with urolithiasis. Independent risk factors for UTI among patients with kidney stones include female gender, older age, presence of obstruction, and higher number of kidney stones (11). Low fluid intake is a reversible risk factor for both UTI and nephrolithiasis (12). Infectious (13) as well as non-infectious stones (14) can harbor bacteria inside, making the bacteria resistant to antimicrobial therapy. In patients with recurrent UTIs, removal of non-struvite non-obstructing stones is associated with elimination of further UTI recurrence in nearly 90% of cases (15).

*Chronic Kidney Disease and End-Stage Renal Disease*

Loss of renal function in patients with kidney stones may occur as a complication of obstruction by a stone lodged in the ureter, a complication of the urological procedure to remove a stone, or from the disordered pathophysiology underlying some stones. Staghorn stones caused by uric acid nephrolithiasis, cystinuria, renal tubular acidosis (RTA), or chronic infection are well-recognized causes of decreased renal function. Additional risk factors for the development of chronic kidney disease in stone formers include a solitary kidney, ileal conduit, neurogenic bladder, and development of hydronephrosis (16). In the Olmsted County cohort, end-stage renal disease incidence in patients with recurrent symptomatic kidney stones was twice that of the general non-stone forming population even after adjusting for baseline hypertension, diabetes mellitus, dyslipidemia, gout, obesity, and chronic kidney disease (17). Still, the absolute risk of ESRD from kidney stone disease was low.

*Stone Disease in Pregnancy*

Pregnancy-related mechanical and physiological changes alter risk factors for kidney stone formation, and management of acute nephrolithiasis in pregnancy is significantly more complicated than in non-pregnant women, at least in part due to imaging limitations and treatment restrictions (18). In an observational study, stones in pregnancy were associated with recurrent abortions, mild preeclampsia, chronic hypertension, gestational diabetes mellitus, and cesarean deliveries (19). Urinary tract infections and pyelonephritis and signs of ureteral obstruction including hydroureter and hydronephrosis were common, while premature rupture of membranes and preterm delivery were not more frequent. The newborns also were affected by perinatal complications including low birth weight, lower Apgar scores, and perinatal mortality. The majority of stones during pregnancy are calcium phosphate with a lesser number of calcium oxalate, in contrast to non-pregnant women in whom calcium oxalate stones are most common (20).

ASSOCIATION WITH OTHER CONDITIONS

Traditionally, nephrolithiasis was thought of as a condition caused by poor diet and abnormal renal handling of electrolytes, with complications limited to the kidneys and the urinary tract. However, recent investigations suggest that kidney stones may in fact be a systemic disorder associated with serious disorders including osteoporosis and greater fracture risk (21), metabolic syndrome features including diabetes, hypertension, and dyslipidemia (22), and greater incidence of cardiovascular disease (23).

**CLINICAL MANIFESTATIONS**

**Symptoms and Signs**

A classical episode of renal colic has a sudden onset, with fluctuation and intensification over 15 to 45 minutes. The pain then becomes steady and unbearable and often is accompanied by nausea and emesis. As the stone passes down the ureter toward the bladder, flank pain changes in a downward direction toward the groin. As the stone lodges at the ureterovesical junction, urinary frequency and dysuria appear. The pain may clear as the stone moves into the bladder or from the calyceal system into the ureter. Hematuria, generally microscopic but occasionally frank, frequently accompanies stone passage. The presence of bleeding alone does not predict a more severe outcome. Episodes of rapid onset of pain, bleeding, and then rapid clearing, often called ‘passing gravel’, is the result of passing a large amount of crystals of calcium oxalate, uric acid, or cystine. “Non-classical” presentations of kidney stones include dull low back pain, gastrointestinal symptoms such as diarrhea, isolated microscopic hematuria, asymptomatic urinary obstruction with renal insufficiency, recurrent urinary tract obstruction, or incidental discovery on abdominal imaging.

**Likelihood of Passage**

The size, number, and metabolic composition of new stones strongly influence the natural history and complication rates. Smaller stone size and more distal location in the ureter at presentation predict greater likelihood of spontaneous stone passage. Furthermore, the clinical presentation can be in part classified by metabolic type (Table 1). Spontaneous stone passage may occur with calcium oxalate, calcium phosphate, uric acid, and cystine stones. Rarely does a struvite stone or a staghorn stone of other composition (cystine, uric acid) pass spontaneously.

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| **Table 1. Clinical Manifestations of Stones by Composition** | | | | |
| **Clinical feature** | **Calcium** | **Uric acid** | **Struvite** | **Cystine** |
| Crystalluria | **+** | **+** | **-** | **+** |
| Stone passage | **+** | **+** | **-** | **+** |
| Small discrete stones | **+** | **+** | **-** | **+** |
| Sludge and obstruction | **-** | **+** | **-** | **+** |
| Radiodense | **+** | **-** | **+** | **+** |
| Staghorn | **-** | **+** | **+** | **+** |
| Nephrocalcinosis | **+** | **-** | **-** | **-** |

**EVALUATION**

**History**

Evaluation of kidney stones starts with a detailed history focusing on medical conditions associated with higher risk of kidney stones (*e.g.* primary hyperparathyroidism, gastrointestinal disorders or surgeries, frequent urinary tract infections, gout, metabolic syndrome, *etc*.), family history suggestive of genetic causes of kidney stones (*e.g.* cystinuria, idiopathic hypercalciuria, young age at onset, *etc*.), dietary history (*e.g.* intake of fluid, salt, protein, dairy products, oxalate-rich foods (Table 2) (24), *etc.*), medications associated with increased risk of kidney stones (*e.g.* topiramate, zonisamide, excessive vitamin C, *etc.*) (25, 26), and medications that directly precipitate and form stones (*e.g.* indinavir, triamterene, *etc.*) (Table 3). This history can provide guidance on the biochemical evaluation and management of kidney stones.

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| **Table 2. Oxalate content of foods** (24) | | |
| **Food category** | **High in oxalate** | **Low in oxalate** |
| Fruits | Figs, raspberries, dates | Apples, oranges, peaches, raisins, mango |
| Vegetables | Spinach, okra, beans, beets | Lettuce, asparagus, carrots, avocado, corn |
| Grains | Whole grain products | White rice, pasta, white bread |
| Nuts | All nuts (peanuts, almonds...) |  |
| Other | Chocolate, cocoa, black tea | Coffee, milk products, meat products |

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| **Table 3. Drugs associated with kidney stones (25, 26)** | |
| **Drugs associated with increased risk of stones** | **Drugs that precipitate and form stones** |
| Hypercalciuria (predispose to calcium stones):  Excessive calcium and vitamin D supplement  Loop diuretics  Glucocorticoids  Hypocitraturia and high urine pH (predispose to calcium phosphate stones):  Carbonic anhydrase inhibitors (acetazolamide, topiramate, zonisamide)  Hyperoxaluria (predispose to calcium oxalate stones):  Frequent use of antibacterial agents  Excessive vitamin C supplement  Hyperuricosuria (predispose to uric acid stones and calcium oxalate stones):  Uricosuric drugs (probenecid, losartan)  High urine ammonium (predispose to ammonium urate stones):  Laxative abuse | Anti-viral:  Indinavir  Atazanavir  Nelfinavir  Tenofovir disoproxil fumarate  Raltegravir  Efavirenz  Antibiotics:  Sulfadiazine  Sulfamethoxazole  Ciprofloxacin  Amoxicillin  Ampicillin  Ceftriaxone  Others:  Triamterene  Sulfasalazine  Allopurinol  Guaifenesin / Ephedrine  Magnesium trisilicate |

**Laboratory Testing**

The extent of biochemical evaluation depends on the risk of stone recurrence and patients’ interest. For first-time stone formers, a basic evaluation including urinalysis, urine culture, and basic metabolic panel should be obtained. For high risk stone formers (Table 4) and interested first-time stone formers, a thorough evaluation (Table 5) is warranted which includes 24-hour urine stone risk profile (27-29).

BLOOD

The recommended blood testing of kidney stone formers includes assessment of renal function, serum electrolytes (including potassium, calcium, phosphorus, and magnesium), and serum uric acid. Assessment of serum PTH may be needed in patients with suspected primary hyperparathyroidism.

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| **Table 4. High Risk Stone Formers** (27-29) |
| **Recurrent stone formers:**   * Recurrent kidney stones * Bilateral or multiple kidney stones   **History suggestive of genetic causes of kidney stones:**   * Early onset of kidney stones (age < 18 years) * Family history of kidney stones   **Stone types that are more commonly associated with metabolic abnormalities:**   * Pure calcium phosphate stones * Non-calcium stones (uric acid, cystine, struvite, and magnesium ammonium phosphate stones) * Any stone requiring percutaneous nephrolithotomy   **History of medical conditions associated with increased recurrence risk:**   * Hyperparathyroidism * Sarcoidosis * Bowel disease (*e.g.* inflammatory bowel disease, chronic pancreatitis, chronic diarrhea) * Bowel resection (*e.g.* colon resection, ileostomy, small bowel resection, Roux-en-Y gastric bypass) * Cystic fibrosis * Metabolic syndrome (*e.g.* obesity, type 2 diabetes mellitus, dyslipidemia, hypertension) * Gout * Spinal cord injury * Neurogenic bladder * Recurrent urinary tract infection * Osteoporosis * Renal tubular acidosis * Polycystic kidney disease * Cystinuria * Primary hyperoxaluria * Anatomical abnormalities that result in impaired urine flow (*e.g.* medullary sponge kidney, ureteral stricture, horseshoe kidney, *etc.*)   **At high risk for complications of kidney stones:**   * Solitary kidney (functional or anatomical) * Chronic kidney disease * Complicated stone episodes that resulted in severe acute kidney injury, sepsis, or complicated hospitalization   **At high risk occupations** (*e.g.* pregnancy, pilots, police officer, military personnel, firemen, *etc.*) |

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| **Table 5. Biochemical Evaluation for High Risk Stone Formers and Interested First Time Stone Formers (27-29)** |
| **Serum:** Basic metabolic panel, albumin, phosphate, magnesium, uric acid, PTH  **Urinalysis and urine culture**  **24-hour urine:** Volume, creatinine, pH, calcium, citrate, oxalate, uric acid, sodium, potassium, magnesium, chloride, sulfate, phosphate, ammonium and cystine (if cystine stone is confirmed or suspected)  **Stone analysis** |

URINE

The initial 24-hour urine sample should be collected on the patient’s typical random diet. It is controversial whether one or two 24-hour urine collections should be obtained (30-34). At least one collection is needed, but two collections are preferred (27-29) . It is important to provide detailed instructions to patients to ensure an adequate collection and proper storage of urine sample. Patients start urine collection after their first morning void and end collection with the first morning void the next day. Storage of urine sample varies according to the instructions of the urine collection kits. Urine sample should be sent to a reliable lab for 24-hour urine stone risk profile analysis. 24-hour urine stone risk profile should be repeated at 8-16 weeks after dietary changes or if pharmacotherapy is initiated to monitor response to therapy and allow dose adjustment as needed (28). Once the therapeutic target is achieved, 24-hour urine stone risk profile is repeated annually (28).

24-hour urine stone risk profile typically provides information on 24-hour urine volume, creatinine, pH, calcium, citrate, oxalate, uric acid, sodium, potassium, magnesium, sulfate, phosphate, ammonium and cystine (if requested). In addition, relative supersaturations with respect to calcium oxalate, calcium phosphate and uric acid are reported. Relative supersaturations are calculated accounting for multiple factors including promotors and inhibitors associated with crystallization (35). Higher relative supersaturation is associated with higher likelihood of being stone formers and correlate with stone composition (36, 37).

STONE ANALYSIS

Knowledge of stone composition may help direct the appropriate choice of urological procedures, evaluation of potential underlying metabolic abnormalities, and medical interventions to prevent stone recurrence (27-29, 38, 39). Current guidelines recommend obtaining stone analysis when feasible for all first-time stone formers (27-29). Stone composition may change in the same individual over time (40, 41) Discordant stone compositions may also coexist in the same individual with bilateral kidney stones (42, 43). Therefore, repeat stone analysis should be obtained in recurrence under pharmacological treatment, early recurrence after urological intervention and late recurrence after a prolonged stone-free period (28).

Multiple analytical techniques are available for stone analysis. The currently preferred methods are X-ray diffraction and Fourier transform infrared spectroscopy (44). X-ray diffraction uses monochromic X-rays to create a unique diffraction pattern of the crystalline structure of the stone (45). Fourier transform infrared spectroscopy uses infrared radiation to create a unique energy absorption band pattern of the molecular structure of the stone (45). These patterns can then be matched to a reference database to determine the stone composition. Both X-ray diffraction and Fourier transform infrared spectroscopy are very accurate in identifying pure stones; however, the majority of kidney stones in clinical practice are mixed stones (44, 45). Both methods have limitations in identification of certain mixed stone compositions. X-ray diffraction cannot identify non-crystalline structures thus is prone to high rates of error in the detection of apatite component in mixed stones which is mostly pseudo-amorphous (44). It is also time-consuming and expensive which limit its broad use in clinical practice (45). Fourier transform infrared spectroscopy is quick and less expensive, but it cannot reliably detect small amounts of components in certain mixed stones (e.g. whewellite (hydrated calcium oxalate) in whewellite/uric acid stones and struvite in struvite/apatite stones) (44-47). The accuracy of stone analysis by Fourier transform infrared spectroscopy depends on the quality of the reference database and trained personnel (46, 47). While pure stones are reliably identified, there is variability in reporting the components of mixed stones in commercial laboratories which needs to be kept in mind when interpreting stone analysis results (47, 48).

**Imaging**

A number of imaging modalities are available to evaluate stone number, size, and location in patients with nephrolithiasis (Table 6). Abdominal computed tomography (CT) without contrast is the initial imaging test of choice for suspected stone disease due to its high sensitivity and specificity, along with its widespread availability and the rapidity of scan time. One downside to CT scan use is exposure to ionizing radiation, which may increase long-term cancer risk. Lower radiation doses are effective in the diagnosis of nephrolithiasis in most patients, leading to greater recent adoption of “low-dose” and “ultra-low dose” CT scan protocols for evaluation of stone disease (49, 50). Use of ultrasonography as the initial test in patients with suspected nephrolithiasis in the emergency department (ED) may reduce cumulative radiation exposure without significantly increasing subsequent serious adverse events, pain scores, return visits to the ED, or hospitalizations (51). Abdominal X-rays (KUB) may be used as an alternative to CT scan and ultrasonography for follow-up of stone burden, although this modality misses radiolucent stones such as uric acid stones. Magnetic resonance imaging is capable of identifying kidney stones, but cost and limited availability make it a less attractive imaging modality for nephrolithiasis.

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| **Table 6. Comparison of Different Imaging Modalities in the Assessment of Nephrolithiasis** | | | | | |
|  | **Availability** | **Cost** | **Ionizing Radiation** | **Other Advantages** | **Other Drawbacks** |
| **CT Scan** | Wide | Moderate | Highest | -Detects extra-renal pathology  -Useful in identifying uric acid stone composition | -Major drawback is radiation |
| **Ultrasound** | Wide | Moderate | None | -Portable US available  -Use in children, pregnancy | -Does not visualize ureteral stones  -Large body habitus limits visualization |
| **X-ray** | Wide | Low | Low | -Useful in follow-up of known radiopaque stones  -Visualizes kidneys, ureters, and bladder | -Misses radiolucent and/or small stones  -Overlying bowel gas, and extra-renal calcification impact stone visualization |
| **MRI** | Limited | High | None | -Use in children, pregnancy | -Contrast risk in CKD patients  -Cannot distinguish stone from blood clot |
| **IVP** | Limited | Moderate | High | -Occasional use in  preoperative planning | -Contrast use |

**SURGICAL MANAGEMENT**

An obstructive stone in the setting of urinary infection is a urological emergency and requires urgent decompression with a ureteral stent or nephrostomy tube (28, 38). Patients should have urine and, if appropriate, blood cultures obtained and be started on broad spectrum intravenous antibiotics until culture results are available. These patients often require fluid resuscitation and monitoring in an intensive care setting. Definitive stone treatment is delayed until infection resolves.

Patients who present with a ureteral stone up to 10mm can be offered a trial of passage if they have no signs or symptoms of urinary tract infection, their renal function is at their baseline, and their pain is well controlled. The likelihood of ureteral stone passage is influenced by stone size and location with smaller, more distal stones having the highest chance of passage (52). Furthermore, smaller stones tend to pass quicker than larger stones (53). For those patients attempting spontaneous passage, a trial of medical expulsive therapy with pain control and α-blocker for 4-6 weeks can be offered in uncomplicated cases (*i.e.* in the absence of infection, uncontrolled pain, obstruction, renal insufficiency, or renal anatomy associated with low likelihood of spontaneous stone passage) (28, 38, 54-56). Nonsteroidal anti-inflammatory drugs (NSAIDs) including intravenous ketorolac are the treatment of choice for pain control. (57) Opioids are used as rescue therapy for pain refractory to NSAIDs. (58) In emergency room setting, IV lidocaine is a useful non-opioid option for pain control with close cardiac monitoring if there are no contraindications. (59, 60) Alpha-blockers inhibit basal tone and decrease peristaltic frequency and amplitude in the lower ureters, decrease intraureteral pressure and increase fluid transport, thus they are proposed to be useful in stone expulsion. (61) However, the effectiveness of α-blockers as medical expulsive therapy remains controversial. A recent meta-analysis showed the use of α-blockers is associated with increased stone clearance and decreased time to stone passage with little major adverse events compared to standard therapy without α-blockers, but the quality of evidence is low. (62) The benefit of α-blockers was mainly demonstrated in individuals with ureteral stones with sizes 6-10mm. Little effect was found in stones measuring 5mm or smaller likely because these stones frequently pass spontaneously even without medical expulsive therapy. (62) Potential side effects of α-blockers include orthostatic hypotension, dizziness, tachycardia, palpitations, headache, and abnormal ejaculation in males. In large clinical trials, these were not found to be more frequent in individuals treated with α-blockers than placebo with the exception of ejaculatory dysfunction in males. (62, 63)

Outpatient referral to urology is indicated for stones larger than 10mm, stones smaller than 10mm that fail to pass with medical expulsive therapy, and stones causing obstruction at the ureteropelvic junction, renal pelvis, or renal calyces especially in symptomatic patients and those at high risk for potential complications. Urological referral should also be considered for high risk stone formers (Table 4). Surgical intervention for stone treatment depends on symptoms, stone composition, size, and location (Table 7) (28, 38, 64).

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| **Table 7. Surgical Management of Kidney Stones** (28, 38, 64) | | |
| **Stone** | **Surgical procedure** | |
| **Urological emergency:** | |
| Obstructive stone with infected urine | * Obtain urinalysis, urine culture and start empiric antibiotics and IV fluid resuscitation * May need ICU care * Urgent decompression (ureteral stent or percutaneous nephrostomy tube) * Delay definitive stone treatment until infection resolves | |
| **Ureteral stones:** | |
| Uncomplicated ureteral stone ≤ 10mm | * Trial of medical expulsive therapy with pain control (NSAIDS with narcotics if needed) and α-blocker for up to 4-6 weeks with reassessment of pain control, renal function and stone passage | |
| Proximal ureteral stone < 10mm | * SWL\* * URS# if cystine stone or uric acid stone | |
| Proximal ureteral stone > 10mm | * URS | |
| Mid ureteral stone of any size | * URS | |
| Distal ureteral stone of any size | * URS | |
| **Renal stones:** | |
| Asymptomatic renal stone < 15 mm | * Conservative therapy with surveillance of symptoms and imaging at 6 months and then annually for stone growth and new stone formation | |
| Symptomatic non-lower pole renal stone ≤ 20mm | * SWL or URS | |
| Symptomatic non-lower pole renal stone > 20mm | * PCNL† | |
| Symptomatic lower pole renal stone ≤ 10mm | * SWL or URS | |
| Symptomatic lower pole renal stone > 10mm | * URS or PCNL | |
| Staghorn stones | * PCNL | |
| Involved kidney with negligible function | * Consider nephrectomy if recurrent infection or pain | |

#URS: ureteroscopy;

†PCNL: percutaneous nephrolithotomy

\*SWL: Shockwave lithotripsy. Calcium oxalate monohydrate, brushite and cystine stones are hard and resistant to fragmentation by SWL, thus alternative methods of stone removal are considered (28). SWL has a lower rate of complications and morbidity, but a lower stone free rate in a single procedure than URS.

**MEDICAL MANAGEMENT**

**General Measures for All Patients with Kidney Stones**

Some risk factors (*e.g.* low urine volume, hypocitraturia, high sodium intake, and high animal protein intake) are shared among different types of stones. General dietary measures (summarized in Table 8) targeting these risk factors can be recommended for stone prevention. These can be especially useful when stone analysis and/or 24-hour urine stone risk profile are not available. Results from a 24-hour urine collection (Table 9) can further refine these recommendations.

Low urine volume is a risk factor for nephrolithiasis. High urine volume leads to urinary dilution of lithogenic constituents and reduced crystallization of calcium oxalate, calcium phosphate and uric acid (65, 66). Several prospective studies have demonstrated high urine volume achieved with high fluid intake is associated with reduction in incident stones and recurrent stones (67-69). Fluid intake of 2.5 to 3 liters per day or achieving a urine volume of at least 2-2.5 liters per day is recommended (27-29). Regarding the types of fluid other than water, orange juice, lemonade, coffee (caffeinated and decaffeinated), tea and alcohol have been associated with reduced risk of stone formation although with some controversial results (5, 68, 70-72). Cola and grapefruit juice have been associated with increased risk of stone formation (70).

A high dietary sodium intake is associated with increased risk of nephrolithiasis likely by causing increased urinary calcium and decreased urinary citrate (28, 66, 73, 74). For every 100 mmol/day increase in dietary sodium intake, urinary calcium increases by an average of 40 mg/day in non-stone forming adults and by up to 80 mg/day in hypercalciuric stone formers (66, 74-76). A low sodium diet reduced urinary calcium and recurrent stones in hypercalciuric stone formers (76, 77). Stone formers are therefore recommended to limit their dietary sodium intake to less than 2300 mg/day (or 100 mmol/day) which is equivalent to 5.9 grams of salt (sodium chloride) (27-29).

A high dietary animal protein intake (meat, fish and poultry) is a risk factor for nephrolithiasis in general (69, 78). It is associated with increased urinary calcium, uric acid, phosphate and reduced urinary citrate and pH (79). On average, urinary calcium increases by 1 mg/day for every 1 g/day increase in dietary animal protein intake (80, 81). In a randomized clinical trial of recurrent calcium oxalate stone formers, a diet with limited animal protein (52 g/day) and sodium (50 mmol/day) but normal calcium (1,200 mg/day) reduced stone recurrence by about 50% at 5 years when compared to a low-calcium diet (400mg mg/day) in hypercalciuric stone formers (77). It is recommended to limit dietary animal protein intake to 0.8 to 1.0 g/kg weight per day (28, 82).

Urinary calcium excretion increases with increased dietary calcium intake which can be more pronounced in individuals with hyperabsorptive idiopathic hypercalciuria (66, 83). However, a diet restrictive in calcium has not been demonstrated to prevent nephrolithiasis. On the contrary, several studies showed a lower dietary calcium intake is associated with a higher risk of both incident and recurrent stones than a higher dietary calcium intake in men and women (69, 73, 77, 84). A restricted calcium diet increases enteric absorption of oxalate and urinary oxalate which increases supersaturation of calcium oxalate (85, 86). In addition, a low calcium diet may lead to negative calcium balance and bone loss. Therefore, a normal calcium diet with 1,000-1,200 mg/day is recommended as a dietary measure for stone prevention (27-29). Dietary sources of calcium are preferred. However, if supplemental calcium is needed, it is best taken in divided doses with meals to reduce enteric absorption of oxalate (27-29).

A diet rich in fruits and vegetables is associated with a decreased risk of incident kidney stones (87) and current guidelines on medical management of nephrolithiasis also recommend a diet rich in fruits and vegetables for prevention of stone recurrence (27-29). In normal individuals, elimination of dietary fruits and vegetables decreased urinary potassium, magnesium, citrate and oxalate, and increased urinary calcium, ammonium and relative supersaturation of calcium oxalate and calcium phosphate (88). In hypocitraturic stone formers, introduction of fruits and vegetables in the diet increased urinary potassium, magnesium, citrate, volume and pH, and decreased relative supersaturation of calcium oxalate and uric acid (88).

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| **Table 8. General Dietary Measures for All Stone Formers** (27-29) | |
| **Dietary measures** | **Targeted risk factors** |
| Fluid intake:   * Fluid intake of 2.5 to 3 liters per day * Achieving urine output of 2-2.5 liters per day | Low urine volume |
| Salt intake:   * Sodium intake less than 100 mEq (2,300 mg) per day | Hypercalciuria |
| Animal protein intake:   * 0.8-1.0 grams / kilogram body weight per day | Hypercalciuria  Hyperuricosuria  Hyperphosphaturia  Hypocitraturia  Low urine pH |
| Calcium intake:   * Calcium intake of 1,000-1,200 mg per day divided into 2 doses taken with meals (prefer dietary source over supplemental calcium) | Hyperoxaluria |
| Fibers, vegetables and fruits: | Hypocitraturia  Low urine pH |

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| **Table 9. 24-hour Urine Stone Risk Profile Interpretation** (89) | | | |
| **Urine parameter** | **Reference range** | **Risk factor for stone types** | **Interpretation** |
| Volume | > 2-2.5 L/day | All | * Reflect fluid intake and extra-renal fluid loss * Goal is above 2-2.5 L/day |
| Creatinine | * Male: 20-25 mg/kg body weight/day * Female: 15-20 mg/kg body weight/day | --- | * Assess adequacy of urine collection |
| pH | 5.7-6.3 | * High pH: calcium phosphate and struvite * Low pH: uric acid and cystine | * High pH: distal renal tubular acidosis (dRTA) or UTIs * Low pH: excessive animal protein intake, chronic diarrhea, or idiopathic |
| Calcium | * Male: < 300 mg/day * Female: < 250 mg/day * Either sex: < 4 mg/kg body weight/day | Calcium oxalate  Calcium phosphate | * Hypercalciuria (see details in “Hypercalciuria”) |
| Oxalate | < 45 mg/day | Calcium oxalate | * Enteric hyperoxaluria * > 100 mg/day, consider primary hyperoxaluria |
| Citrate | > 320 mg/day | Calcium oxalate  Calcium phosphate | * Hypocitraturia (see details in “Hypocitraturia”) |
| Uric acid | < 700 mg/day | Calcium oxalate  Uric acid | * High purine intake or production |
| Phosphorus | < 1,100 mg/day | Calcium phosphate | * Excessive protein intake |
| Sodium | < 200 mmol/day | Calcium oxalate  Calcium phosphate | * Excessive salt intake |
| Chloride | < 200 mmol/day | Calcium oxalate  Calcium phosphate | * Varies with sodium and potassium intake |
| Sulfate | < 40 mmol/day | Calcium oxalate  Calcium phosphate  Uric acid | * Excessive animal protein intake |
| Ammonium | < 40 mmol/day | --- | * Excessive animal protein intake * Non-dietary acid load (*e.g.* diarrhea) |
| Potassium | > 40 mmol/day | --- | Low urine potassium:   * Low alkaline intake * Potassium loss (*e.g.* diarrhea) |
| Magnesium | > 80 mg/day | --- | Low urine magnesium:   * Low magnesium intake * Malabsorption |
| Cystine | < 40 mg/day | Cystine stone | * Cystinuria |

**Calcium Stones**

Approximately 80% of kidney stones are calcium stones (calcium oxalate and/or calcium phosphate) (44). The initiating events of stone formation are controversial (90-94), but there are three proposed pathways of stone formation: 1) Randall’s plaque (interstitial calcium phosphate deposit at the renal papilla) grows and erodes the urothelium and becomes a nidus for crystal growth in urine supersaturated with respect to calcium oxalate; 2) Randall’s plug formed by fixed particle mechanism in which a crystal nidus is attached to the apical epithelium of the collecting duct and allows crystal growth in urine supersaturated with respect to the constituents of the stone; 3) Randall’s plug formed by free particle mechanism in which a crystal nidus forms through homogenous nucleation in the lumen of the nephron in the supersaturated environment (92). Randall’s plaque is a prominent feature in idiopathic calcium oxalate stone formers and patients with primary hyperparathyroidism; although plugging is also observed (93, 94). Randall’s plug formed by fixed particle mechanism is seen in brushite stone formers and patients with dRTA and primary hyperparathyroidism. Randall’s plug formed by free particle mechanism is seen in cystinuric stone formers and intestinal bypass patients (92).

Calcium stones can be idiopathic or associated with systemic diseases (see Table 10) (89, 95). Idiopathic calcium stones formers may exhibit various urinary risk factors for calcium oxalate and calcium phosphate stones (Table 11) (89).

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| **Table 10. Systemic Conditions Associated with Calcium Stones (89, 95)** |
| **Systemic diseases:**   * Primary hyperparathyroidism * Sarcoidosis * Bone diseases (*e.g.* fractures, multiple myeloma) * Immobilization * Hyperthyroidism * Distal renal tubular acidosis * Polycystic kidney disease * Bowel disease (e.g. inflammatory bowel disease, chronic pancreatitis, chronic diarrhea) * Bowel resection (e.g. colon resection, ileostomy, small bowel resection, Roux-en-Y gastric bypass) * Cystic fibrosis * Primary hyperoxaluria * Gout * Anatomical abnormalities that impair urine flow (*e.g.* medullary sponge kidney, ureteral stricture, horseshoe kidney, *etc.*)   **Medications**   * Carbonic anhydrase inhibitor (*e.g.* topiramate, acetazolamide, zonisamide) * Calcium and vitamin D supplements * Vitamin C supplement * Loop diuretics * Uricosuric agents (*e.g*. probenecid, benzbromarone) |

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| **Table 11. Risk Factors for Calcium Stones (89)** | |
| **Risk factors for calcium oxalate stones** | **Risk factors for calcium phosphate stones** |
| Low urine volume | Low urine volume |
| High urine calcium | High urine calcium |
| Low urine citrate | Low urine citrate |
| High urine oxalate | --- |
| --- | High urine pH |
| High urine uric acid | --- |

PATHOGENESIS AND RISK FACTORS

*Hypercalciuria*

Hypercalciuria is the most common risk factor of calcium stones and found in 30-60% of calcium stone formers (96). Hypercalciuria is classically defined as 24-hour urine calcium greater than 300 mg/day in men, greater than 250 mg/day in women, greater than 4 mg/kg body weight/day in either sex, or urine calcium > 140 mg calcium/gram creatinine/day (75). Although threshold values are provided to define hypercalciuria, there is no threshold value that predicts risk of stone incidence or recurrence. Rather, risk of stone incidence and recurrence increases progressively with higher urinary calcium excretion (97).

Environmental (diet, supplement, and medications) and metabolic disorders can contribute to hypercalciuria. One way to determine causes of hypercalciuria is to divide it into three broad categories: hypercalcemic hypercalciuria, normocalcemic hypercalciuria, and hypocalcemic hypercalciuria (Table 12).

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| **Table 12. Causes of Hypercalciuria** |
| **Hypercalcemic hypercalciuria**   * *PTH-dependent causes*   Primary hyperparathyroidism   * + Lithium-induced hyperparathyroidism * *PTH-independent causes*    + Granulomatous diseases (*e.g.* sarcoidosis, tuberculosis, histoplasmosis, coccidoimycosis, lymphoma)   + Vitamin D toxicity   + Low level or activity of vitamin D 24-hydroxylase   + Hypercalcemia of malignancy (*e.g.* bone metastases, lymphoma, PTHrP, multiple myeloma)   + Immobilization   + Hyperthyroidism   + Paget’s disease of bone   + Vitamin A toxicity   + Milk alkali syndrome   **Normocalcemic hypercalciuria**   * *Absorptive*   + Excessive calcium intake (diet and/or supplement)   + Excessive animal protein intake   + Sarcoidosis   + Idiopathic hypercalciuria * *Resorptive*    + Excessive animal protein intake   + Hyperthyroidism   + Immobilization   + Paget’s disease of bone   + Osteoporosis   + Glucocorticoid excess   + Distal renal tubular acidosis   + Malignant tumors   + Idiopathic hypercalciuria * Renal leak   + Excessive salt intake   + Loop diuretics   + Mineralocorticoid excess   + Glucocorticoid excess   + Distal renal tubular acidosis   + Idiopathic hypercalciuria   **Hypocalcemic hypercalciuria**   * Autosomal dominant hypocalcemia (activating mutation in *CaSR* or *GNA11*) |

*Idiopathic Hypercalciuria*

Idiopathic hypercalciuria is found in up to 50% of idiopathic calcium stone formers (98). It appears to be familial which suggests a genetic basis (99). It presents with a pattern of variable inheritance, and is likely polygenic in most stone formers, with described base changes in some candidate genes including *CaSR*, *VDR*, *TRPV5*, *TRPV6*, *CLCN5*, *ADCY10,* and *CLDN14* (75, 96). The pathophysiology of idiopathic hypercalciuria involves increased intestinal calcium absorption, renal leak of calcium, and increased bone resorption especially when challenged with a restricted calcium diet (75, 96).

Intestinal calcium hyperabsorption is the most common abnormality in idiopathic hypercalciuria (100). It can be 1,25(OH)2D-dependent or independent. In patients with 1,25(OH)2D-dependent absorptive hypercalciuria, there is generally an increased production of 1,25(OH)2D when compared to normal individuals (101), although some patient with *CYP24A1* mutations exhibit reduced 1,25(OH)2D catabolism. The exact mechanism leading to increased 1,25(OH)2D production remains unclear. There was a suggestion that renal tubular phosphate handling may play a role; however, others found that regulators of 1,25(OH)2D production (PTH, serum phosphorus and renal tubular reabsorption of phosphate) in idiopathic hypercalciuric stone formers were comparable to non-stone formers (102-105). In patients with 1,25(OH)2D-independent absorptive hypercalciuria, intestinal absorption of calcium remains elevated despite a normal 1,25(OH)2D level. Again, the mechanism is unclear. Animal studies demonstrated an increased abundance and half-life of vitamin D receptors (VDR) in the intestines of genetic hypercalciuric rats (106, 107). In male calcium oxalate stone formers with idiopathic hypercalciuria, an elevated level of VDR in monocytes was found when compared to non-stone formers (108). Both suggest increased tissue VDR may contribute to absorptive hypercalciuria in individuals with a normal 1,25(OH)2D level.

Idiopathic hypercalciuric stone formers also display abnormal renal calcium handling with a lower postprandial renal calcium reabsorption than normal individuals without a difference in filtered load (109). There is evidence of defective renal calcium reabsorption in both proximal tubule and distal nephron (110-112). The reduced renal calcium reabsorption could not be explained by sodium excretion and PTH levels (109). The underlying mechanism of decreased renal calcium reabsorption remains to be elucidated.

Hypercalciuric stone formers were found to have lower bone mineral density (BMD) than non-stone formers even in those with absorptive hypercalciuria (21, 113). The decreased BMD is more pronounced in trabecular bone than cortical bone (21, 113). Nephrolithiasis was associated with an increased risk of vertebral fractures in both men and women in a population-based retrospective cohort study (114), and with an increased risk of prevalent vertebral and wrist fractures in men in a cross-sectional study in NHANES III (115). Prior bone histomorphometry studies demonstrated increased bone resorption in fasting hypercalciuria and decreased bone formation in absorptive hypercalciuria (113). The pathophysiology underlying bone loss in idiopathic hypercalciuria is not exactly clear; however, several risk factors have been associated with bone loss in this population. A restricted calcium diet sometimes used by patients or physicians to reduce urine calcium may generate negative calcium balance leading to increased bone resorption and bone loss without reducing risk of kidney stones (77, 116, 117). High dietary salt and protein intake increase urinary calcium excretion and create a subtle metabolic acidosis both of which may contribute to bone loss (21, 75, 113, 118). Inflammatory cytokines such as IL1, IL6, TNF-α and GM-CSF have been associated with hypercalciuria and bone loss by increased bone resorption (113). Idiopathic hypercalciuric stone formers were also found to have increased bone expression of RANKL and decreased expression of TGF-β which may be the mediators for increased bone resorption and decreased bone formation and mineralization, respectively (119). High 1,25(OH)2D and/or increased expression of VDR found in idiopathic hypercalciuria may also increase bone resorption and decrease bone formation (21).

*Hypocitraturia*

Urinary citrate is an endogenous inhibitor of calcium stone formation. It forms a more soluble calcium citrate complex than calcium oxalate and calcium phosphate (89, 96). It reduces urinary supersaturation with respect to calcium oxalate and calcium phosphate (89, 96). Hypocitraturia is generally defined as urine citrate less than 320 mg/day and is a well-described reversible risk factor that is present in 20-60% of calcium stone formers (89, 96). Extracellular and intracellular pH affects renal citrate excretion. Systemic acidosis increases urinary citrate reabsorption and leads to hypocitraturia (120). Intracellular acidosis increases intracellular citrate metabolism in the cytosol and mitochondrial via the TCA cycle (120). Thus, hypocitraturia occurs mainly in conditions with extracellular or intracellular acidosis (89). Table 13 summarizes common causes of hypocitraturia (89, 96, 120).

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| **Table 13. Causes of Hypocitraturia** (89, 96, 120) |
| **Systemic diseases:**   * Complete dRTA (hypocitraturia, frank metabolic acidosis, hypokalemia, hypercalciuria, high urine pH) * Incomplete dRTA (hypocitraturia without frank metabolic acidosis, high urine pH) * Hypokalemia * Chronic diarrhea * Chronic kidney disease * Primary hyperaldosteronism * Idiopathic hypocitraturia   **Dietary:**   * High animal protein intake * High sodium intake * Low fruit / vegetable intake   **Medications:**   * Carbonic anhydrase inhibitor (e.g. topiramate, acetazolamide, zonisamide) * Angiotensin converting enzyme inhibitors * Angiotensin II receptor blockers * Diuretic-induced hypokalemia |

*Hyperoxaluria*

High urinary oxalate increases urinary supersaturation with respect to calcium oxalate (96). Hyperoxaluria is generally defined as urinary oxalate greater than 45 mg/day (0.5 mmol/day) (89). It is encountered in 8-50% of calcium stone formers (121). Etiologies of hyperoxaluria can be divided into three categories: 1) increased endogenous oxalate production due to inborn error of metabolism, 2) increased intake of foods rich in oxalate or its precursors (Table 2) or increased intestinal bioavailability of oxalate, and 3) increased intestinal oxalate absorption (89, 121). Table 14 summarizes causes of hyperoxaluria.

Primary hyperoxalurias (PH) are a group of rare autosomal recessive disorders involving overproduction of oxalate which results in markedly increased urinary oxalate excretion. There are three genetic forms: PH1 due to mutations in *AGXT* (encodes for a pyridoxal-5’-phosphate-dependent hepatic peroxisomal alanine-glyoxylate aminotransferase, AGT), PH2 due to mutations in *GRHPR* (encodes for glyoxylate reductase and hydroxypyruvate reductase, GRHPR) and PH3 due to mutations in *HOGA1* (encodes for hepatic mitochondrial 4-hydroxy-2-oxoglutarate aldolase, HOGA) (122, 123). Deficiency in AGT in PH1 results in decreased conversion of glyoxylate to glycine. The accumulated glyoxylate is in turn converted to oxalate by lactate dehydrogenase (LDH) leading to increased production of oxalate (123). Deficiency in GRHPR in PH2 results in decreased conversion of glyoxylate and hydroxypyruvate to glycolate and D-glycerate, respectively. The accumulated glyoxylate and hydroxypyruvate are converted to oxalate and L-glycerate respectively by LDH (123). Mutations in *HOGA1* in PH3 result in decreased enzymatic activity of HOGA which converts 4-hydroxy-2-oxoglutarate (HOG) to pyruvate and glyoxylate. This results in accumulation of HOG which inhibits mitochondrial GRHPR (which is the deficient enzyme in PH2) activity, thus increasing oxalate production (122, 124). Primary hyperoxalurias should be suspected if urinary oxalate is greater than 90 mg/day (1 mmol/day) (125). Measurement of other urinary metabolites including glyoxylate and L-glycerate can be helpful, but genetic testing is required for definitive diagnosis of primary hyperoxaluria (123).

Dietary oxalate is estimated to range between 50 and 1,000 mg/day (121). Oxalate is absorbed mainly in the small intestine and to a lesser extent in the colon (121). Intestinal absorption of oxalate varies between 10% and 72% (121). On a normal calcium diet (1,000 mg/day calcium), urinary oxalate increases by 2.7 mg/day with every 100 mg/day increase in dietary oxalate between 50mg to 750mg/day (126). Table 2 provides a list of foods rich in oxalate and some alternative options with low oxalate content (24). Although there is considerable variation in the reported oxalate content in foods among the available online sources, the simplest strategy is to avoid the foods with high oxalate content (127). Attention should be paid to portion size even with foods with low to moderate oxalate contents. Excessive intake of vitamin C more than 1,000 mg/day is associated with increased urine oxalate because vitamin C is metabolized into oxalate in the body (128, 129).

A restricted calcium diet increases enteric oxalate availability for absorption and results in increased urinary oxalate (85, 86). Patients with chronic diarrhea, pancreatic insufficiency, inflammatory bowel diseases, or small bowel resections may have malabsorption of bile acids and/or fatty acids which can complex with luminal calcium in the intestine, resulting in increased bioavailability of oxalate to be absorbed and subsequently excreted in the urine (89, 96). This is also termed enteric hyperoxaluria. Increased bioavailability of luminal oxalate can also result from decreased colonization by *Oxalobacter formigenes* which is a Gram-negative obligate anaerobe that utilizes oxalate as the sole energy source. *O. formigenes* alsoincreases secretion of endogenous oxalate from plasma to the gut lumen which results in decreased urinary oxalate (126). Colonization by *O. formigenes* is associated with decreased bioavailability of intestinal oxalate for absorption, decreased urinary oxalate, and reduced risk of calcium oxalate stones (130, 131). Use of certain antibiotics to which *O. formigenes* are sensitive (macrolides, tetracyclines, chloramphenicol, rifampin and metronidazole) within the past 5 years is associated with a reduction in colonization when compared to non-users (132), and has been separately associated with greater incidence of stone disease (133). Furthermore, patients with cystic fibrosis or inflammatory bowel disease who receive frequent antibiotic courses were found to have lower prevalence of colonization by *O. formigenes*, which may contribute to their higher oxalate excretion and increased kidney stone formation (134, 135).

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| **Table 14. Causes of Hyperoxaluria** |
| **Primary hyperoxaluria**   * Primary hyperoxaluria type 1 (mutations in *AGXT* gene) * Primary hyperoxaluria type 2 (mutations in *GRHPR* gene) * Primary hyperoxaluria type 3 (mutations in *HOGA1* gene)   **Secondary hyperoxaluria**   * High intake of oxalate rich foods (See Table 2) * Vitamin C intake > 1,000 mg/day * Low calcium intake * Pancreatic insufficiency * Inflammatory bowel disease (Crohn’s disease) * Small bowel surgeries * Cystic fibrosis * Decreased colonization by *Oxalobacter formigenes* |

*Elevated Urine pH*

Urine pH higher than 6.7 is a risk factor for calcium phosphate stones. The pKa for monohydrogen phosphate (HPO42-) is ~ 6.7. At a pH higher than the pKa, there is an increased abundance of HPO42- which complexes with divalent cation calcium (Ca2+) to form brushite (CaHPO4.2H2O) and eventually to hydroxyapatite [Ca10(PO4)6(OH)2] (96). Table 15 summarizes potential causes of high urine pH.

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| **Table 15. Causes of High Urine pH** (89, 96) |
| * Distal renal tubular acidosis (RTA) * Urinary tract infections * Primary hyperparathyroidism * Carbonic anhydrase inhibitors * Alkali therapy |

*Hyperuricosuria*

Hyperuricosuria is defined as urinary uric acid greater than 800 mg/day in men and 750 mg/day in women (136). It is found in 40% of calcium stone formers and associated with increased risk of calcium oxalate stones (96). There are three main proposed mechanisms by which hyperuricosuria promotes calcium oxalate crystallization: 1) calcium oxalate precipitation on monosodium urate crystals through heterogeneous nucleation (137, 138), 2) removal of calcium oxalate crystallization inhibitors by colloidal urate particles (139), and 3) increased urate concentration decreases the solubility of calcium oxalate and leads to precipitation of calcium oxalate from solution by a salting-out mechanism (140). Hyperuricosuria is generally caused by increased purine intake, increased production of uric acid, or increased urinary excretion primarily from acquired conditions, although inherited causes of hyperuricosuria are also described (Table 16) (89, 136).

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| **Table 16. Causes of Hyperuricosuria** (89, 136) |
| **Acquired Conditions:**  **Increased intake:**   * High purine rich diet (e.g. red meat, fish and poultry)   **Increased production:**   * Gout * Myeloproliferative and neoplastic disorders   **Increased urinary excretion:**   * Uricosuric drugs   **Inherited Conditions (rare):**  **Disorders of uric acid metabolism:**   * Lesch-Nyhan syndrome * Glycogen storage disease type 1A   **Disorders of renal uric acid reabsorption:**   * Renal hypouricemia |

MANAGEMENT OF CALCIUM STONES

*Lifestyle Measures*

A diet high in fluid (fluid intake of 2.3-3 liters per day or achieving urine volume of at least 2-2.5 liters per day), rich in fruits and vegetables, low in sodium (less than 2300 mg/day or 100 mmol/day), animal protein (limit to 0.8 to 1.0 g/kg body weight/day) and oxalate (less than 100 mg/day) and normal in calcium (1,000 to 1,200 mg/day preferably from dietary source) is recommended for calcium stone prevention (27-29, 95, 96). These were previously addressed in section “General measures for all patients with kidney stones” (Table 8).

*Pharmacotherapy*

Thiazide and thiazide-like diuretics:

Hypercalciuria is the most common risk factor for calcium stones. Thiazide (hydrochlorothiazide or HCTZ) and thiazide-like diuretics (indapamide and chlorthalidone) can reduce urinary calcium by two proposed mechanisms: 1) blockage of NaCl symporter in distal convoluted tubule leads to decreased distal sodium and water reabsorption and volume contraction, which results in increased sodium and water reabsorption in the renal proximal tubule, resulting in increased calcium reabsorption by passive transport (141), and 2) increased distal tubular calcium absorption by increased abundance of transport proteins TRVP5 and calbindins (142, 143). The hypocalciuric dose-response to HCTZ has been studied in six healthy adults which demonstrated hypocalciuric effect at 12.5mg, 25mg, and 50mg daily; however, it was subtherapeutic for 12.5mg and 25mg daily when compared to 50mg daily (144). Several randomized controlled trials on thiazide diuretics with an average follow up of ~ 3 years showed reduction in the risk of recurrent stones in both hypercalciuric and normocalciuric stone formers (145). This underscores the lack of threshold effect of urinary calcium in predicting stone risk. Rather, the risk of stone formation increases progressively with increasing urinary calcium excretion even within the “normal range” (97). It also supports the empiric use of thiazide diuretics in recurrent calcium stone formers, even those with normocalciuria (27, 146). The doses used in these trials were HCTZ 25mg BID, 50mg and 100mg daily, indapamide 2.5mg daily and chlorthalidone 25mg and 50mg daily (145). A recent retrospective cohort study suggests lower doses of thiazide diuretics (HCTZ or chlorthalidone ≤ 12.5 mg daily or indapamide ≤ 1.25 mg daily) appear to have a similar protective effect against stone formation as higher doses in older adults (147).

Thiazide diuretics have also been shown to improve bone health. They reduce urinary calcium excretion resulting in positive calcium balance and reduced PTH which may reduce bone turnover (96). They have also been shown to stimulate osteoblast differentiation and function and inhibit osteoclast differentiation *in vitro* (21, 115, 148). HCTZ 50mg daily improved cortical BMD in healthy postmenopausal women without baseline hypercalciuria (149, 150). In postmenopausal women with osteoporosis and hypercalciuria, addition of indapamide 2.5mg daily to alendronate 70mg weekly resulted in a reduction in urinary calcium and an additional increase in BMD at the lumbar spine over 12 months compared to alendronate single therapy (151). A meta-analysis of five observational cohort studies showed thiazide diuretics use was associated with a reduction in risk of hip fractures (152). Although there is no randomized placebo-controlled trial available, a secondary analysis of the Antihypertensive and Lipid-Lowering Treatment to Prevent Heart Attack Trial (ALLHAT) showed a reduction in hip and pelvic fracture risk in patients on chlorthalidone 12.5mg to 25mg daily compared to those on lisinopril or amlodipine (153).

Thiazide diuretics use may be associated with hypokalemia which may induce hypocitraturia, thus potassium supplements are often needed. Potassium citrate is superior to potassium chloride given its ability to increase urinary citrate and pH and to further lower urine calcium excretion (154). Combination of thiazide diuretics with a potassium sparing diuretic (*e.g.* amiloride) can also be considered.

In summary, thiazide diuretics are recommended to patients with recurrent calcium stones with and without hypercalciuria (27).

Alkali therapy:

Potassium citrate treatment increases urine pH and urine citrate, decreases urine calcium, and decreases urinary supersaturation with respect to calcium oxalate (155). Several placebo-controlled randomized trials demonstrated potassium citrate and potassium magnesium citrate treatment reduced recurrent stone events in calcium stone formers with and without hypocitraturia (156-158).

Potassium citrate treatment may also prevent bone loss. Potassium citrate treatment increased BMD at the spine in idiopathic calcium stone formers (159) and increased BMD at the spine, femoral neck, and total hip in healthy elderly men and postmenopausal women without osteoporosis (160).

The proposed mechanisms by which potassium citrate improves BMD include systemic alkalization, increased osteoblastic activity, and reduced osteoclastic activity demonstrated by bone turnover markers, and positive calcium balance created by reduced urinary calcium excretion (21, 160, 161).

Currently, potassium citrate therapy is recommended for patients with recurrent calcium stones with and without hypocitraturia (27).

Xanthine oxidase inhibitors: Allopurinol and Febuxostat:

There is only one published randomized placebo-controlled trial on allopurinol in prevention of calcium nephrolithiasis. In this study, calcium oxalate stone formers with hyperuricosuria and normocalciuria treated with allopurinol 100mg TID had a lower rate of stone events than those treated with placebo over 24 months (162). Allopurinol is recommended for patients with recurrent calcium oxalate stones with hyperuricosuria and normocalciuria (27).

Febuxostat was studied in a randomized controlled trial comparing febuxostat 80mg daily with allopurinol 300mg daily or placebo on the effect of stone prevention in calcium stone formers (calcium oxalate and/or calcium phosphate) with hyperuricosuria and normocalciuria over 6 months (163). Febuxostat led to a greater reduction in urinary uric acid than allopurinol or placebo, but percent change in stone size was similar to allopurinol or placebo. This study was not powered to detect difference in stone events in the three groups. Currently, there is insufficient evidence to support the routine use of febuxostat for stone prevention in hyperuricosuric calcium stone patients, except in those who may be allopurinol-intolerant (29).

Pyridoxine:

Pyridoxine (vitamin B6) supplementation is helpful in primary hyperoxaluria type 1 (PH1) with specific mutations, namely Gly170Arg, Phe152Ile and Ile244Thr. A trial of pyridoxine for 3 months with a starting dose of 5 mg/kg body weight/day titrated to a maximum of 20 mg/kg body weight/day can be attempted in patients with suspected primary hyperoxaluria. Response to therapy is defined as more than 30% reduction in urinary oxalate from baseline (123).

**Uric Acid Stones**

Uric acid stones generally represent around 10% of all stones analyzed, although their prevalence has markedly increased in recent years, in parallel with the diabetes and obesity epidemics (164, 165). In a series of 2,464 calculi, the proportion of uric acid stones was 35.7% in patients with type 2 diabetes and 11.3% in patients without type 2 diabetes (166). Reciprocally, the proportion of patients with type 2 diabetes was significantly higher among uric acid than among calcium stone formers (27.8 versus 6.9%) (166). In fact, several epidemiological and metabolic studies have reported an association of uric acid stone disease with various features of the metabolic syndrome including obesity, type 2 diabetes, hypertension, dyslipidemia, hyperglycemia, hepatic steatosis, and greater visceral adiposity (167).

PATHOGENESIS AND RISK FACTORS

The three main factors implicated in the development of uric acid nephrolithiasis are low urine pH, hyperuricosuria, and low urine volume (Table 17) (168). Of these, low urine pH is the primary determinant of uric acid nephrolithiasis, as acidic urine favors the protonation of urate, forming relatively insoluble uric acid which precipitates in this overly acidic urinary environment. In fact, a decline in urine pH from 6.0 to 5.0 increases urinary uric acid concentration six-fold, whereas states of increased urate production typically increase urate excretion two-fold. Therefore, uric acid stone formation is more determined by pH than by urine volume or urine uric acid concentrations. Low urine pH may result from excessive intake of animal proteins (81), gastrointestinal alkali loss (from chronic diarrhea or laxative abuse), or may be idiopathic as frequently observed in patients with obesity, type 2 diabetes, and/or the metabolic syndrome (164, 168). Human metabolic studies have identified greater acid excretion and reduced urinary buffering by ammonia as the two culprits of aciduria in uric acid nephrolithiasis (169). Hyperuricosuria is less frequently encountered in patients with uric acid nephrolithiasis, and may result from inherited and/or acquired conditions (Tables 16 and 17). Finally, low urine volume due to extra-renal fluid losses contributes to increased urinary saturation with respect to uric acid, leading to stone formation.

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| **Table 17. Risk Factors and Etiological Conditions Associated with Uric Acid Nephrolithiasis** | | |
| **Urinary Risk Factor** | **Type of Abnormality** | **Etiological conditions** |
| Low urine pH | Inherited Conditions | Inherited uric acid lithiasis (unknown genetic abnormality) |
| Acquired Conditions | Metabolic syndrome, obesity, diabetes, CKD, high animal protein intake, gastrointestinal alkali loss |
| Medications | Laxatives |
| Hyperuricosuria | Inherited Conditions | Disorders of uric acid metabolism (e.g. Lesch-Nyhan);  Disorders of uric acid excretion (e.g. renal hypouricemia);  Glycogen storage disorder type 1A (glucose-6-phosphatase deficiency) |
| Acquired Conditions | Gout, myeloproliferative disorders, hemolytic disorders, high purine intake |
| Medications | Uricosuric agents: Losartan, Probenecid, Benzbromarone |
| Low urine volume | Acquired Conditions | Chronic diarrhea, excessive perspiration, low fluid intake |
| Medications | Laxatives |

MANAGEMENT

Since uric acid stone formation is more determined by urine pH than by urine volume or urine uric acid concentrations, the cornerstone of therapy is urinary alkalinization.

*Lifestyle Changes*

Dietary restriction of animal protein intake is helpful in decreasing ingestion of proton sources, which reduces aciduria and aids with urinary alkalinization. At the same time, animal protein restriction also lowers uric acid excretion through a reduction in purine intake. Conversely, greater ingestion of alkali-rich fruits and vegetables aids in raising urine pH. Finally, higher fluid intake in general aids in raising urine volume, while intake of certain fruit juices such as orange juice can increase urine pH (along with the concomitant rise in urine volume). Still, one should be cautious about the sugar load imparted by fruit juices in uric acid stone formers with pre-diabetes or frank diabetes.

*Pharmacological Therapy*

Medical dissolution therapy of uric acid stones with alkali therapy (potassium citrate, to raise 24-hour urine pH to 6.0 to 6.5) is the cornerstone of uric acid management. Alkali therapy is well-tolerated by most uric acid stone formers and effectively dissolves stones, potentially avoiding the morbidity of urological interventions (170, 171). In patients who cannot tolerate potassium citrate, alternative alkali regimens include sodium bicarbonate and potassium bicarbonate. Occasionally, xanthine oxidase inhibitors (allopurinol or febuxostat) are added to potassium citrate in patients with hyperuricosuria whose uric acid stones recur despite alkali therapy. A recent study has suggested that the thiazolidinedione pioglitazone may aid in raising urine pH in uric acid stone formers (172), although the risk/benefit ratio of this medication needs to be considered.

**Cystine Stones**

PATHOGENESIS AND RISK FACTORS

Cystine represent around 1-2% of stones in adult patients, but account for 5-8% of stones in pediatric patients. Cystine stones result from inactivating mutations in genes that encode renal tubular transporters that reabsorb the amino acid cysteine (173). The complexation of two molecules of the dibasic amino acid cysteine results in the formation of cystine which is relatively insoluble. Cystine normally appears in urine in small amounts that are insufficient to cause supersaturation, crystalluria, or stone formation. Due to defects in renal cysteine reabsorption, patients with cystinuria exhibit greater than a 10-fold increase in urine cystine excretion (as well as greater excretion of the other dibasic amino acids lysine, ornithine, and arginine). As a result, the solubility limit of cystine in the urine (250 mg/L) is exceeded. Homozygous inheritance results in more severe phenotype, whereas heterozygous inheritance is associated with variable increases in amino acid excretion and an intermediate increase in cystinuria. Cystine stones form in the upper urinary tract as early as the first decade of life, and tend to be large, staghorn, bilateral, and highly recurrent (173). Stone formation may manifest as obstruction, infection, hematuria, and renal failure. Cystine stones are visible on standard abdominal radiographs because of the relative density of the sulfur constituent of cysteine (Table 6).

MANAGEMENT

The goal of therapy in cystinuria is to reduce cystine excretion and increase urinary cystine solubility (173, 174). This is accomplished using a combination of lifestyle changes and pharmacological interventions.

*Lifestyle Changes*

Large urine volumes of 3-4 liters per day may be effective at reducing cystine concentration and reducing stone recurrence in some patients, although this is difficult to institute in children and even adult patients. Dietary protein restriction to around 1 g protein/kg body weight/day reduces cysteine intake, and may cause small decreases in cystine synthesis (175), although this should be avoided in growing children and adolescents. A low sodium intake can also contribute to reduced cystine excretion (176).

*Pharmacological Therapy*

When fluid and dietary therapy fail, then pharmacologic therapy may be effective. Alkaline pH in the 7.0-7.5 range will reduce cystine solubility and can be achieved by the addition of alkali therapy such as potassium citrate (177). Tiopronin (Thiola®) and D-penicillamine reduce cystine formation in urine by preventing cysteine-cysteine complexation and the formation of more soluble thiol-cysteine disulfides that are more readily excreted in the urine. Both agents however have potentially serious side effects (proteinuria, abnormal LFTs, others) and therefore they are not used as first-line treatment (174).

**Struvite (Infection) Stones**

PATHOGENESIS AND RISK FACTORS

Struvite (magnesium ammonium phosphate) stones form only in the presence of bacteria that produce urease. Common urease-producing bacteria that may populate the urinary tract are proteus, klebsiella, pseudomonas, and enterococci. Urease-mediated splitting of urea and the generation of ammonium results in an alkaline urine. Urine pH above 7.0 normally is associated with very low urine ammonium levels of less than 10 mEq/day. However, urine ammonium excretion exceeding 30 mEq/day along with 24-hour urine pH > 7.0 virtually make the diagnosis of struvite stones. Other constituents of the stone may include calcium carbonate and brushite (calcium phosphate), which form crystals in the very alkaline urine. Patients who form struvite stones do not pass them spontaneously, but rather are at high risk for bleeding, obstruction, and decreased renal function. Some infection stones begin as calcium oxalate stones that become infected with a urease-producing bacterium. Spread of infection to the contralateral kidney may occur.

MANAGEMENT

Because untreated staghorn calculi will require nephrectomy in 50% of patients, definitive treatment is indicated (178). Growth of infection stones and their progressive damage to kidney tissue may be limited by shockwave lithotripsy and percutaneous nephrolithotomy (PCNL); however definitive treatment of struvite stones is surgical removal. Extended antibiotic therapy has proven ineffective in eradicating the infection and does not substitute for complete removal of even the smallest particulate of the stone (178). Management with PCNL followed by careful follow-up and medical management minimizes stone recurrence and maintains kidney function in the majority of patients (179). Larger stone burden pre-operatively, residual stones after surgery, and presence of medical comorbidities are independent risk factors for stone recurrence or residual stone-related events (179). Acetohydroxamic acid inhibits urease produced by the bacteria and has been shown to be effective in eradicating chronic infection of struvite stones (180). Use of the drug has been limited, however, as it is associated with potentially serious side effects such as hemolytic anemia and venous thromboembolic disease.

**CONCLUSIONS**

In conclusion, urinary stones are common, morbid, and highly recurrent. The pathophysiology of kidney stone formation is diverse, and includes a combination of genetic and environmental factors. Several endocrinological disorders increase the risk of stone formation. Metabolic evaluation of patients with kidney stones helps to identify the underlying etiological factors and provides an opportunity to institute preventive lifestyle and/or pharmacologic measures to reduce stone recurrence risk.

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