REVIEW ARTICLE

Nephrolithiasis in the Era of Precision Medicine: Progression in Diagnostic, Therapeutic and Preventive Strategies

Dharmalingam Kirubakaran[1], Shubham Chandrakant Choudhary[2], S. Mohammed Aashiq[3], Renu Vajjiravelu[4], Santhoshkumar Jayakodi[5]

[1]Department of Pharmacology, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu, India, [2]Department of Urology, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu, India, [3]Department of Paediatrics, Saveetha medical college and hospital, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, Tamil Nadu, India, [4]Department of Biotechnology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, India, [5]Department of Biochemistry, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India

Abstract

Nephrolithiasis is one of the most prevalent urologic conditions globally and is recognized as a considerable clinical public health challenge with its rising incidence and recurrence. The techniques of metabolic evaluation, novel diagnostic imaging and systemic mechanisms that result in greater stone deposition, together with advances in biochemical/molecular characterization relevant to lithogenicity, as well as end-urological instrumentation, have altered the modern approach for detection, tonsorial management and prophylaxis against STONES. We review current imaging modalities, including low-dose dual-energy computed tomography, point-of-care ultrasonography and stone composition analysis techniques/new urinary biomarkers. Pending modern day therapeutic breakthroughs, including thulium fiber laser lithotripsy and new advances in high-fidelity rigid percutaneous nephrolithotomy techniques, ultrathin flexible digital ureteroscopy and robotic surgical interventions as well as improvements in ureteral stenting and access sheaths, are also summarized herein. This updates the contemporary evidence-based preventive strategies with the biggest opportunities around urinary microbiome, genetic predisposition and artificial intelligence-driven predictive modeling to enable precision-based, personalized renal stone disease approaches.

Key words: Dual-energy computed tomography, nephrolithiasis, percutaneous nephrolithotomy, thulium fibre laser, urolithiasis

INTRODUCTION

Renal stone disease is one of the most prevalent diseases affecting the urinary tract[1] that causes considerable pain, discomfort to patients and high worldwide emergency presentations and surgical rates. Moreover, the disease involves crystallization depositions in the kidney or urine pathways as well as genetic predisposition, whilst revolves around metabolic instability stemming from eating practices environmental factors and lifestyle choices. The incidence of renal stone disease has risen sharply within the last decades, consistent with widespread changes in diet and sedentary lifestyle, along with dynamic epidemics of obesity, diabetes and other metabolic diseases. Despite a staggering burden, the majority of kidney stones were treated with open surgical techniques for decades, but with considerable morbidity and prolonged recovery.[2] 3.1 Extracorporeal shock wave lithotripsy (SWL) at the start of the 20th century, SWL was cut edge as a non-invasive method to help stone dismantling. These techniques have added a new frontier to our stone management

Address for correspondence:
Dr. Dharmalingam Kirubakaran, Department of Pharmacology, Saveetha Medical College and Hospital, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai - 602 105, Tamil Nadu, India. E-mail: kirupa1997bsc@gmail.com

Received: 16-05-2026
Revised: 21-06-2026
Accepted: 30-06-2026

armamentarium, making this epoch truly the minimally invasive age of stone surgery.

Current practice highlights an accurate imaging-based localisation of the calculus, with different endoscopic vision and energy[3] based lithotripsy modalities exhibiting far greater stone-free rates by virtue of lower morbidity and shorter hospital stays as compared to standard open surgical techniques. Beyond infection control, major breakthroughs in stone pathophysiology and metabolic assessment have led to better preventive approaches. Renal stone disease is no longer seen as only a localized acute (in either space or time) event, but instead more appropriately considered in the broader context of high-energy diets, sedentary living situations that greatly increase lifetime burden, highlighting the importance of continued metabolic evaluation and preventative therapy based on individual patient profile over a much longer time frame than previously realized. Clinicians must combine these newer diagnostic paradigms[4] with evolving surgical and evidence-based medical therapies to achieve optimal outcomes. Therefore, the purpose of this review was to help clinicians to use it as a reference narrative for clinical insight into diagnostic and therapeutic advances that impact renal stone disease.

EPIDEMIOLOGY AND CHANGING DEMOGRAPHICS

The prevalence of renal stone disease shows a wide geographical variation, with estimates ranging from nearly 1% in some developing countries to 15% in developed ones.[5] Such interstudy diversity has wide variation, which may good at a disagreement between regions, dietary differences, genetic background, other health access, and socioeconomic status may be the responsible factors for such differences in estimating the consequences of high homocysteine levels on health. Kidney stone disease had become an emerging global pandemic, although recently increasing incidence and prevalence are appreciated in most areas of the world. Nephrolithiasis was once regarded as a disease of middle-aged men; however, the most recent data identifies narrowing sex gap with increasing urolithiasis among women. This change is mainly linked with lifestyle changes and higher prevalence of obesity and syndrome 'X' in females.[6] Furthermore, the diagnosis of stone disease occurs more and more frequently in younger people, including pediatric and young adult populations supporting the hypothesis that early life exposure to lithogenic dietary exposures and sedentary behavior can have pathophysiological sequelae resulting in earlier disease onset. Stone pathophysiology is also closely related to environmental and metabolic risk factors. Chronic inaccessibility to water still remains the first cause, since it is closely associated with hot environmental conditions and people who undertake intense physical activity or have insufficient availability of potable drinking water. Other dietary factors relevant to urinary supersaturation of stone-forming salts are high sodium intake,[7] a diet enriched with animal proteins, and oxalate-rich diets. In fact, these genes can be associated with obesity and metabolic syndrome genes, showing through several urinary biochemical changes, including stratification of calcium, oxalate, and uric acid excretion, urinary pH, as well as citrate. Endocrine has a specific risk due to the associated chronic hypercalcemia and hypercalciuria, especially in situations such as primary hyperparathyroidism. Specific drugs from loop diuretics, carbonic anhydrase inhibitors, protease inhibitors, and high-dose VD or calcium have been suggested as potential stone-inducing agents in susceptible patients.[8] Together, these trends illustrate the increasing intersection with renal stone disease and modern metabolic health having implications for both broader popular preventative strategies as well as more tailored risk assessment approaches for individuals.

PATHOPHYSIOLOGY AND STONE COMPOSITION

The mechanism of stone formation is a multifactorial process that occurs due to an imbalance between crystallization promoters and inhibitors at the level of the urotelium. Urinary stone disease is initiated by their supersaturation with one or more of these constituents; all considered "stone-formers".[8] During this condition, individual ions spontaneously aggregate in little crystals that grow, group, and remain next to the renal tubules or at the surface of the renal papillae. If not flushed away with the urine stream or inhibited by protective molecules these crystals can become clinically significant calculi. Countless endogenous inhibitors, some of which can inhibit crystallization and aggregation processes on the predication, have been found in a more physiological milieu. They create a stone-forming microenvironment that reduces inhibitors and localizes lithogenic properties.[9] In fact, we are aware of these types of structural defects in renal papillae triggering the accumulation of crystals followed by stones, for example, Randall's plaques, subepithelial CaP deposits. It covers calcium oxalate, both the monohydrate and dihydrate forms, as well as the calcium phosphate, which comprises most of cases, from 70% to 80% approximately. Cystine stones develop from a genetic defect of amino acid absorption, are often recurrent, and difficult to manage. Infrequently, crystalline stones may be caused by drug metabolites or drugs of poor solubility, such as indinavir and triamterene. Normal urine chemistry alone manages most stone types, but some stones, such as uric acid stones, can dissolve with urinary alkalinization, and others, from infection stones, require complete ureteroscopic clearance and control of underlying infection. Thus, precise stone characterization and metabolic workup are the basis of adjuvant therapy for personalized stone management and its prevention.

DIAGNOSTIC ADVANCES

Imaging

Imaging the kidney is a prerequisite for diagnosis and assessment of renal stone disease, therapeutic planning, and monitoring. All these properties make an ideal imaging modality which is free of risk to the patient, able to identify stones correctly, estimate their size, location, and burden accurately, assess urinary tract anatomy, and exclude complications such as obstruction or infection [Figure 1].[10] For the past year, technological advancements have led to huge improvements in both technical safety and diagnostic accuracy for stone imaging. Computed tomography (CT) scans with Hounsfield unit attenuation values indirectly provide information about stone composition and predict response to alternative modalities of lithotripsy. The awareness of these more clinically relevant problems with cumulative radiation exposure, particularly in children and among patients with recurrent stone disease, has drawn considerable attention to dose reduction techniques.[11] Today, it has been shown that low- and ultra–low-dose CT protocols can minimize radiation exposure without losing almost any diagnostic accuracy for most adult patients, achieving this even in stones >3–4 mm. The use of these protocols is now more established in the emergency and considered somewhat so in elective settings. Moreover, low radiation dose can be compensated by reducing the image noise using an advanced iterative reconstruction algorithm in order not to affect the diagnostic confidence. The recent development of dual-energy CT (DECT) has the potential for material-specific characterization, which is a major advancement in stone imaging. Furthermore, DECT-derived parameters may also be able to predict stone fragility, which are a clinically more relevant consideration in the context of pre-treatment estimation of success at extracorporeal shockwave lithotripsy or laser lithotripsy and procedural planning.[12] It is particularly valuable in pregnant patients, children, and patients receiving repeat imaging.

Stones and laboratory diagnoses analysis

Two cornerstones in modern renal stone management are precisely determining the stone composition (with detailed information needed for assessing potential etiologies and quality metabolic workup.[43] Whenever possible, retrieved stone material should be analyzed, especially in high-risk features, first-time stone formers, and all recurrent stone formers. Compared with conventional chemical spot tests, which have reduced diagnostic accuracy, infrared spectroscopy (IR) and X-ray diffraction (XRD) provide a more reliable approach for the characterization of complex or mixed urinary stones. These techniques accurately differentiate calcium oxalate, calcium phosphate, uric acid, struvite, cystine, and drug-induced calculi, thereby supporting comprehensive metabolic assessment and guiding targeted therapeutic strategies.[13]

Recently, some studies have assessed the collection of blood and/or spot urine samples, but laboratory diagnosis for stone disease prevention is still mainly based on 24-h collections, which are recommended in metabolic evaluation. Urine volume and major lithogenic and inhibitory components, that is, calcium, oxalate, citrate; this quantitative measurement that allows diagnosing these abnormalities: hypercalciuria hyperoxaluria hypocitraturia and hyperuricosuria, which makes it possible for the doctor to individualize dietary recommendations and pharmacological treatment, such as thiazide-type diuretics, citrate supplements, and urate-lowering therapy. A repeat 24-h urine test to monitor is helpful not only for treatment response but also compliance. Serum

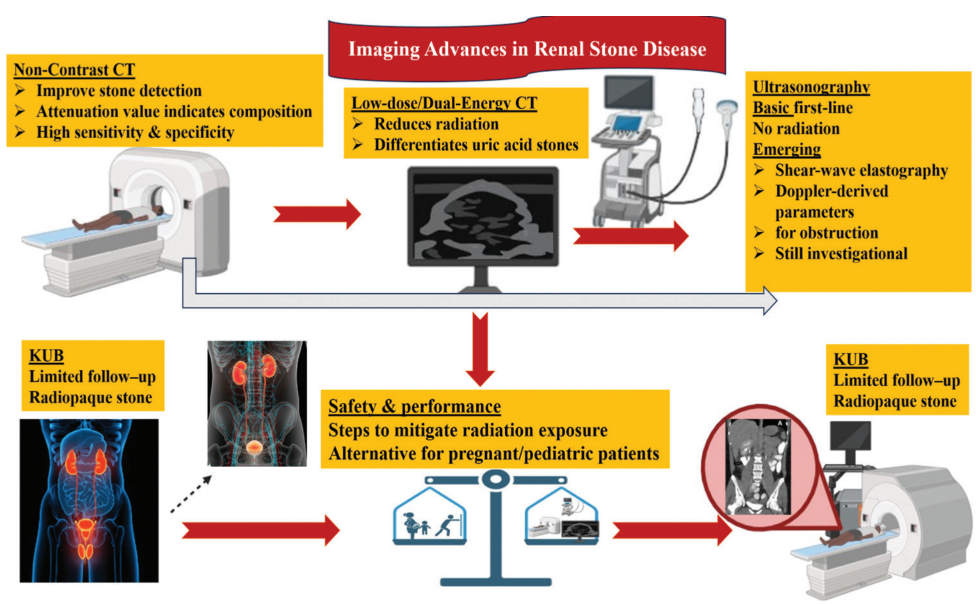

Figure 1: Schematic representation of imaging techniques used in renal stone disease created by bioredner.com

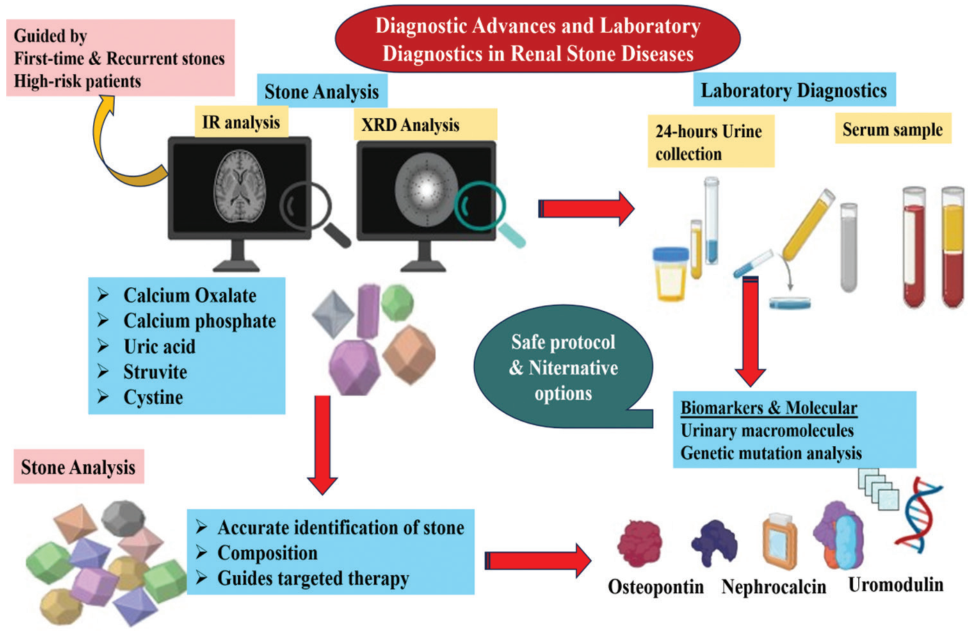

Figure 2: Schematic illustration of diagnostic and laboratory approaches in renal stone disease created by bioredner.com

biochemistry analysis supplements urinary examination, as it can detect systemic abnormalities associated with renal stone disease.[14] The routine measurements usually are: Serum calcium, creatinine, electrolytes, and uric acid. Testing for increased levels to exclude primary hyperparathyroidism should be done in every patient with a previous history of important hypercalcemia and/or calcium-based stones. A combination of these laboratories assessments can be performed to assess global risk and is helpful for targeted prevention.

Biomarkers and molecular diagnostics

Besides classic laboratory analysis, more interest has been directed towards finding urinary and blood biomarkers indicating active stone formation strategies, oxidative stress, inflammatory processes, and tubular injury.[15] Furthermore, potential macromolecular nucleating, growth, and inhibitor markers such as osteopontin, nephrocalcin, Tamm Horsfall protein (uromodulin), bikunin, and other urinary crystallization modulators. More recently, gene panels that include more genes and whole-exome sequencing have begun to be used more broadly clinically in high-risk populations of interest (especially children and young adults with recurrent severe or early-onset stone disease).[16]

AI EN LA SOPORTE A LAS DECISIONES CLÍNICAS

There are substantial opportunities to improve diagnostic accuracy, risk stratification and personalized treatment planning for renal stone disease with artificial intelligence (AI) and machine learning (ML) is the new frontier.[17] ML algorithms trained on CT images, electronic health records and metabolic profiles identified instrumental variables related to predicting stone composition as well as estimating stone fecundity and likelihood of passage or successful alternative treatment. Radiomics- based imaging approach has also been proved useful in the differentiation of uric acid from non–uric acid stones, in predicting response to SWL or laser lithotripsy. In addition, some of the observed recurrence risk and health care utilization in patients with urinary stone disease may be predicted from demographic variables, comorbidities, laboratory parameters, and previous stone history. Decision-support systems might one day help clinicians predict which form of intervention (SWL, ureteroscopy [URS], percutaneous) is likely optimal for each patient based on an individualised risk profile.[18]

Acute management principles

The first line management of patients presenting with renal colic focuses on early relief of symptoms, excluding complications and the need for urgent intervention. Adequate analgesia, often by means of some combination of non-steroidal anti-inflammatory drugs and opioid agents, when medically indicated, mediates pain control. The patients are often managed with intravenous or oral hydration, but high-volume fluid loading is not associated with increased stone passage and should therefore be avoided. In case of a urological emergency, the urinary tract is compromised, and an infection occurred then it is assessed for urinary blockage or infection. These patients need urgent decompression of the collecting system with ureteral stent placement or percutaneous nephrostomy and broad-spectrum intravenous antibiotics. After the acute infectious episode has resolved, definitive stone management can be determined. Management: observation versus intervention depending on stone size, location and patient factors. Small stones, especially distal ureter reason still can be spontaneously passed and instead being offered surgical treatment is usually treated conservatively with a watchful waiting and analgesia. There are so many studies about medical expulsive therapy (MET) with alpha-adrenergic blocker (tamsulosin). Results are mixed in the trials, but perhaps most consistently, they appear to help distal ureteral stones >5 mm clear. Therefore, MET recommendations for general use are heterogeneous, suggesting selective implementation rather than universal adoption.

THERAPEUTIC INNOVATIONS

SWL

Figure 3 shows, extracorporeal SWL remains a logical non-invasive treatment option for optimally selected renal and proximal ureteric stones. It is attractive in part due to the fact that no surgical cutting occurs, procedures are relatively quick, and it delivers ultra-fast treatment times virtually everywhere. Several other technological improvements have also improved safety and efficacy.[19] Face-to-face with concepts of modern lithotripters include enhanced shock wave generators, patient coupling and real-time imaging guidance for stone targeting optimization. The rationale for these devices is that the use of respiratory-synchronized shock delivery and other modalities to reduce urinary stone motion during respiration may allow energy to be delivered at the most appropriate time, maximizing disruption and minimizing trauma to renal structures.[20] In addition, protocols for optimising shock frequency and employing a stepwise energy ramp have been shown to improve fragmentation efficiency at the expense of increased renal parenchymal injury. At the same time, progress with SWL does come with certain limitations. High-density/hard stones, for example, some calcium oxalate monohydrate and cystine calculi, are poorly treated, as is lower pole kidney stone treatment, where gravity-dependent drainage may act against fragment expulsion. As a result, appropriate patient and stone selection continues to be necessary for SWL success.

URS and flexible URS (FURS)

URS has been established as the best recommendation to access stones of the ureter and most any intrarenal cognate system. Data indicate that semi-rigid URS can obtain high stone-free rates with low morbidity[21] for ureteral calculi, and fURS presents as a versatile option that provides effective management of intrarenal stones across the range of size and location. The laser's energy is aimed at those stones and fragmentations with such accuracy that it works better ergonomics improvements have increased operator comfort and procedural effectiveness. In addition, implantable collamer lens (ICL) has also matured. Although traditional practice for this procedure is still based on the Holmium, such as YAG laser, thulium fiber laser (TFL) has shown unique potential to be a game changer at select centers. In this manner, TFL systems have more pulses per time and a smaller diameter of the fibers leading to lower energy variations. With such characteristics, it promotes for better "dusting" and less retropulsion with probably faster stone ablation compared to classic holmium systems. Comparative data in the long term are limited, but anecdotal clinical data suggest similar or better efficacy. Lithotripsy techniques: Dusting and Fragmentation with Basket Retrieval. The process of fragmenting the stones in small particles is known as dusting. For non-negligible stone sizes, Fragmentation with sequential active retrieval

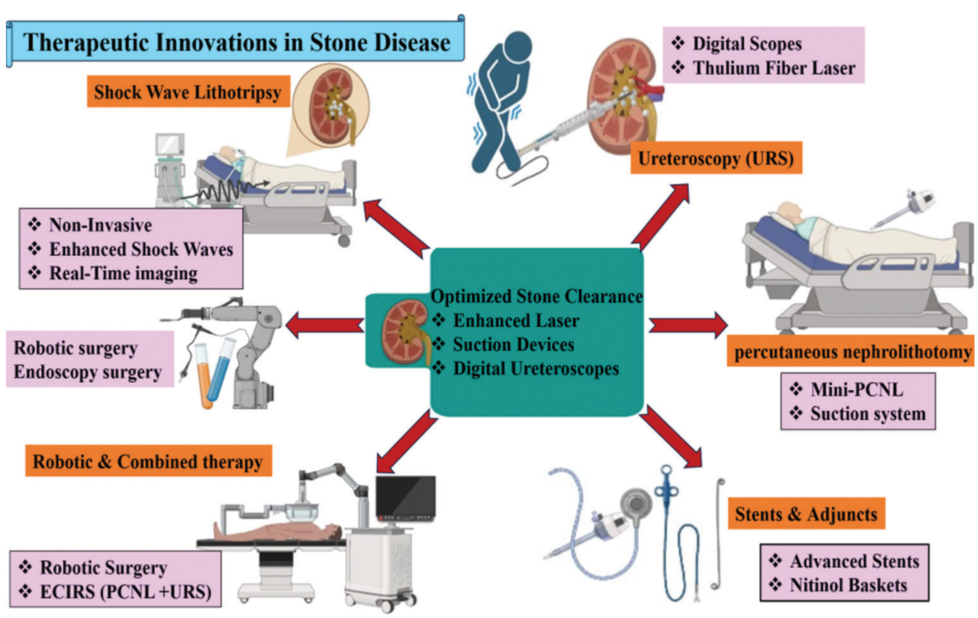

Figure 3: Schematic representation of modern treatment strategies for therapeutic innovations in the management of stone disease created by bioredner.com

may offer greater immediate stone-free rates when compared to other modalities, but logically the operative times of this technique using re-operative instruments have to be longer than alternative operative durations. Preference exists for varying parameters of the stone, such as size, composition and location in addition to a preference for a specific surgeon.[22]

Percutaneous nephrolithotomy (PCNL) and miniaturization

It is the first line when larger (>2 cm) renal stones are complex or extensive, and it has been associated with the highest stone-free rates in a single session. Nevertheless, classic percutaneous nephrolithotomy (PCNL) has also those risks of post-operative bleeding and hospitalization associated to the additional pain and sticking

Robotic and combined approaches

Innovation also created room in stone surgery, such as Robotic-assisted stone surgery, post-surgical platform for improved scope stability, accuracy, and reduction of operator burnout with longer or more advanced procedures.[23] Initial clinical experience, while limited, suggests that these novel methods are technically possible and could be beneficial; corroboration of this will be reflected in the need for further validation and adoption, overcoming cost and availability barriers as well. More recently, endoscopic combined intrarenal surgery (ECIRS), a mixture of antegrade PCNL and one-stage retrograde URS, has been adopted for the management of complex or large stone mass. ECIRS has the advantages of higher calyx accessibility, better stone clearance and possibly fewer interventions.

Renal analogue adjunct devices novel intravenous

Former day such, digital optics, that is, imaging methods in connection with optimized high definition cameras, along with up-to-date lighting resources, made visualization and reliability of the procedure much better. They also demonstrated possible advantages in terms of to reduce infection transmission and overall cost savings, since they would not involve some maintenance costs in the economic considerations, which will vary according to the health care setting. Access to new retrieval devices such as nitinol baskets, grippers and suction-trained sheaths) has also made the removal of fragments sufficiently efficient that better stone-free rate were achieved compared to older techniques.[24]

Stents and drainage technology

Mohtasham and Khalafalla stent-related symptoms: A review ureteral stents constitute an important part of post-operative drainage and obstruction prophylaxis, but the stent-related symptoms have a profound effect on the quality of life. In addition to modifying stent designs in general, there have been efforts to develop more pliable materials/optimized coil configurations, fenestrations, and surface coatings that have a galvanophoretic effect for irritation- and encrustation-reduction, as summarized earlier. Bioabsorbable and drug-eluting stents are also currently under investigation, since they may reduce inflammatory over-response and the need for a second removal procedure.[25]

PERIOPERATIVE AND SAFETY CONSIDERATIONS

The framework of antibiotic stewardship is composed of preoperative urine culture, targeted perioperative prophylaxis, and immediate drainage of infected obstructed systems. Small size access pathways; more efficient energy delivery and suction-assisted techniques greatly lessen the blood loss and infectious complications. The intrarenal pressure is also going into mainstream, likely due to its ability to induce in a predictable manner both bacteremia and post-operative sepsis. It must be feasible to avert excessive tension throughout the outflow road-pedicle antereioring a hemostatic degree that is definitively defect and forceful for any surroundings.

Medical prevention and metabolic management

Preventive measures for recurrent renal stone disease remain an essential component of long-term management and should be implemented in all patients, with special emphasis on those with recurrent stones or risk factors. An integrated approach embraces these dietary modification, pharmacologic therapy,[26] and an individualized follow according to the metabolic evaluation and stone composition determination.

Dietary measures

No 1 and the most universal preventative is stay well hydrated. Target daily urine volumes of >2.0–2.5 L/day have been proposed and will vary on a population-average basis depending on ideal body size, activity and climate conditions. Increased fluid intake decreases urinary supersaturation of stone-forming solutes and significantly lowers the risk for recurrence of all stone types. Reducing dietary sodium is also recommended because high sodium intake activates calcinuria through renal tubular mechanisms. The kidneys of animals whose protein comes primarily from animal muscle try to compensate for circulating acids excreted in the urine as calcium and through uric acid production, specifically because animal-based foods generate acid during metabolism. The limitation of high-oxalate foods, such as spinach, nuts, chocolate, and tea, benefits patients only when dietary calcium intake is adequate.

Table 1: Contemporary advances in diagnosis, management, and prevention of renal stone disease

Domain	Subcategory	Key advances/Approaches	Clinical impact
Epidemiology and risk factors	Changing demographics	Rising incidence worldwide; increasing rates in women and younger adults	Highlights the need for early prevention and metabolic screening
	Major risk factors	Dehydration, high sodium intake, animal protein excess, obesity, metabolic syndrome, hyperparathyroidism, drugs	Identification of modifiable risk factors
Imaging diagnostics	Low-dose NCCT	High sensitivity/specificity with reduced radiation	Gold standard for diagnosis
	Dual-energy CT	Differentiates uric acid versus non–uric acid stones; predicts fragility	Guides therapy selection
	Ultrasound/POCUS	Radiation-free, bedside evaluation	First-line in pregnancy, pediatrics
	KUB radiography	Follow-up of radiopaque stones	Low-cost monitoring
Laboratory and stone analysis	IR spectroscopy/XRD	Accurate stone composition	Guides prevention
	24-h urine testing	Detects metabolic abnormalities	Enables targeted therapy
	Serum biochemistry	Calcium, creatinine, uric acid, PTH	Detects systemic disorders
Emerging diagnostics	Biomarkers	Osteopontin, nephrocalcin, uromodulin	Early risk prediction
	Genetic testing	Cystinuria, primary hyperoxaluria	Precision medicine
	Artificial intelligence	Radiomics, ML prediction models	Decision support
Acute management	Supportive care	Analgesia, hydration, antiemetics	Symptom relief
	Emergency drainage	Stent or PCN for infected obstruction	Life-saving
	MET	Alpha-blockers for distal ureteral stones >5 mm	Selective use
Therapeutic innovations	SWL	Optimized lithotripters, gating, ramping	Non-invasive option
	URS/fURS	Digital scopes, TFL	High stone-free rates
	PCNL/Mini-PCNL	Miniaturized tracts, suction PCNL	Safer large-stone removal
	ECIRS/Robotics	Combined or robot-assisted approaches	Complex stones
Adjunct technologies	Disposable scopes	Reduced infection risk	Efficiency
	Ureteral access sheaths, suction sheaths	Lower pressure, better visibility	Safety
Stents and drainage	Novel stents	Softer materials, drug-eluting, biodegradable	Reduced discomfort
Medical prevention	Diet	High fluids, low sodium, normal calcium, moderate protein	Universal prevention
	Pharmacologic	Thiazides, citrate, allopurinol, tiopronin	Targeted therapy
	Follow-up	US or low-dose CT, repeat urine tests	Recurrence prevention
Special populations	Pediatrics, pregnancy, solitary kidney	Individualized strategies	Risk reduction
Future directions	Microbiome, genetics, AI, novel lasers, biomaterials	Precision stone care	Next-generation management

CT: Computed tomography, POCUS: Point-of-care ultrasonography, NCCT: Non-contrast computed tomography, KUB: Kidneys, ureters, bladder, IR: Infrared, XRD: X-ray diffraction, MET: Medical expulsive therapy, SWL: Shock wave lithotripsy, URS: Ureteroscopy, fURS: flexible ureteroscopy, PCNL: Percutaneous nephrolithotomy, ECIRS: Endoscopic combined intrarenal surgery, AI: Artificial intelligence, ML: Machine learning, TFL: Thulium fiber laser

Table 2: Modern urological approaches to renal stone disease (2026): Diagnostic advances and therapeutic innovations

Domain	Technology/Strategy (2026)	Key features	Clinical advantages	Limitations/Considerations
Imaging diagnostics	Ultra–low-dose NCCT	Radiation <1 mSv with iterative reconstruction	Gold-standard detection with reduced radiation	Limited sensitivity for very small stones
	Dual-energy CT	Stone composition differentiation	Guides medical dissolution versus surgery	Cost, availability
	AI-enhanced CT analysis	Automated stone detection and volume calculation	Faster workflow, reduced reader variability	Still under validation
	Point-of-care ultrasound	Bedside hydronephrosis and stone detection	Radiation-free, rapid triage	Lower sensitivity for small ureteral stones
Laboratory and metabolic evaluation	24-h urine panels (expanded)	Includes supersaturation indices	Precision prevention	Patient compliance
	Automated stone analysis (IR/XRD)	High accuracy composition	Targeted therapy	Requires stone retrieval
	Genetic panels	Detect monogenic stone disorders	Early diagnosis	Cost
Emerging diagnostics	Urinary biomarkers	Osteopontin, uromodulin, nephrocalcin	Early risk prediction	Research-stage
	Radiomics and ML models	Predict fragility and recurrence	Decision support	Limited clinical deployment
Acute management	NSAIDs-first analgesia	Reduced opioid use	Effective pain control	Renal function monitoring
	Rapid decompression protocols	Stent/PCN within hours	Reduces sepsis mortality	Requires urgent access
	Selective MET	Distal ureter stones >5 mm	Non-invasive option	Mixed evidence
Lithotripsy	Thulium fiber laser	High-frequency dusting, low retropulsion	Faster fragmentation	Equipment cost
	Advanced Holmium: YAG (MOSES 2.0)	Improved energy modulation	Efficient fragmentation	Still more retropulsion than TFL
Ureteroscopy (URS/fURS)	Digital flexible scopes	HD visualization	Higher SFR	Fragility, cost
	Disposable scopes	Reduced infection risk	No maintenance	Per-case expense
PCNL and miniaturization	Mini-PCNL/Ultra-mini PCNL	Smaller tracts	Less bleeding, shorter stay	Longer operative time
	Suction-assisted PCNL	Active evacuation	Lower intrarenal pressure	Device-dependent
	Tubeless PCNL	Faster recovery	Reduced discomfort	Patient selection
Robotic and combined surgery	Robotic URS/PCNL	Stable scope control	Complex stones	Limited availability
	ECIRS	Dual antegrade+retrograde	High SFR for staghorn stones	Requires expertise
Adjunct devices	Ureteral access sheaths	Low pressure, better vision	Reduced sepsis risk	Ureteral injury risk
	Smart baskets and suction sheaths	Faster clearance	Efficiency	Cost

(*Contd...*)

Table 2: (*Continued*)

Domain	Technology/ Strategy (2026)	Key features	Clinical advantages	Limitations/ Considerations
Stents and drainage	Silicone/soft polymer stents	Less pain	Better QoL	Still symptomatic
	Drug-eluting stents	Anti-inflammatory	Reduced discomfort	Investigational
	Biodegradable stents	No removal needed	Future potential	In trials
Medical prevention	High-fluid intake protocols	Urine>2.5 L/day	Universal prevention	Adherence
	Thiazides	Hypercalciuria	Reduced recurrence	Electrolyte effects
	Potassium citrate	Hypocitraturia, uric acid stones	Alkalinization	GI intolerance
	Allopurinol	Hyperuricosuria	Uric acid control	Hypersensitivity
Digital health and AI	Recurrence risk calculators	Personalized follow-up	Precision care	Validation ongoing
	Telemonitoring apps	Hydration and diet tracking	Improves compliance	Access issues
Future directions	Microbiome modulation	Prevent infection stones	Novel target	Experimental
	Smart lasers and fibers	Faster ablation	Shorter OR time	Emerging

NSAIDs: Non-steroidal anti-inflammatory drugs, NCCT: Non-contrast computed tomography, IR: Infrared, XRD: X-ray diffraction, MET: Medical expulsive therapy, PCNL: Percutaneous nephrolithotomy, ECIRS: Endoscopic combined intrarenal surgery, AI: Artificial intelligence, ML: Machine learning, QoL: Quality of life, TFL: Thulium fiber laser, SFR: Stone-free rate

Pharmacologic prevention

Treatment with pharmacologic agents is guided by the abnormalities identified on 24-h urine collection and an individual patient risk profile. Thiazide diuretics lead to a major reduction in urinary calcium excretion and are the mainstay of treatment for idiopathic hypercalciuria. Potassium citrate is indicated for the treatment of hypocitraturia in recurrent stone patients; urine potassium and urine pH are increased after oral administration of Kc. In cases of hyperuricosuria or recurrent uric acid stones, with a dietary modification insufficient, allopurinol can be used to treat patients. Case 2: A special management is also required for cystinuria patients such as general fluid intake, urinary alkalinization, and use of cystine binding agents. The selection, combination and duration of pharmacologic therapy must be individualized and regularly assessed according to treatment effect or recurrence risk.[27]

Targeted prevention and follow-up

These are examples of focused preventive strategies based on bladder stone composition, metabolic profile, and clinical risk factors. This is repeatable, linked to 24-h urinary testing, thus aiding quantification of the intervention response and improving compliance. Further imaging, typically using ultrasound or low-dose CT, should only be performed at an appropriate interval according to the risk of recurrence and clinical course to detect new or increasing stone burden.

Special populations and considerations

Due to the higher frequency of inherited and congenital defects in younger patients, children with urolithiasis should undergo a complete metabolic and anatomic workup. This population benefits from miniaturized endourologic instruments and low-radiation imaging protocols [Table 1].[26] Pregnancy is the first and foremost reason for ultrasound tests. Most stones are managed conservatively with intervention reserved for those obstructed or complicated by infection and/or refractory pain. In this setting, temporary measures such as disposable stenting or percutaneous nephrostomy have generally been favored.

Emerging fields and future directions

To this we add the discovery that Rxmol no Rx is one of the key actors in stone formation and recurrence for, if not all, certainly infection-related stones shown in Table 2. Innovative strategies for prevention of chronic kidney disease are based on modifications of the balance between urinary microflora, or direct action on urease-dependant organisms. Genetic and precision medicine advances linked to increased awareness of both monogenic causes, including primary hyperoxaluria and cystinuria, and polygenic risk factors. These strategies may yield more accurate identification of high-risk patients and targeted prevention. Future research areas will center on AI-based predictive analytics with other imaging but also metabolic information and patient characteristic data to inform recommendations as to when/if we should act, and which of the patients are most likely to respond or be at risk for recurrence. Continuous advancements in laser technology, such as thulium fibre laser parameters, applications of pulse modulation and future development of fibers are expected to provide greater fragmentation performance and shorter operating time. Out of which, even technological innovations in biomaterials sciences is leading to newer systems including drug-eluting, anti-encrustation and fully resorbable stent systems.

Practical algorithm for modern management

Patients presenting with renal stone disease usually present with renal colic ± hematuria or infection and should be clinically assessed in an urgent time-relevant fashion, including vitals, pain score, renal function and sepsis,427.[28] The first-line imaging modality performed in routine for sputum during pregnancy and some other limited environments is ultrasonography, but the gold standard diagnostic investigation should be low-dose non-contrast CT in these settings; DECT should also be considered if obtaining information on stone composition is likely to affect clinical management decisions. Supportive treatment consists of effective analgesia, antiemetics and normovolemic status and laboratory tests such as urine analysis with culture; moreover, patients with an obstructively infected collecting system need to be urgently decompressed, such as ureteral stenting or percutaneous nephrostomy before definitive stone treatment. Management considerations regarding intervention comprise stone[29] size/location/composition as well as symptomatic burden, patient preference, anatomic factors and comorbidities according to which treatment strategies may be observation with or without MET versus SWL versus URS, PCNL versus combinations of these approaches. While the management of care long-term is preventive using metabolic evaluation, dietary education and pharmacologic therapy on a regular basis with imaging/periodic assessment of metabolism to assess risk for recurrence or response to treatment.[30]

CONCLUSION

This review agreed that management of stone disease has become individualized as diagnostic workup, endourological instruments, laser energy, and preventive medicine have evolved. Treatments are now safer with new treatment options available to many patient cohorts through miniaturization, less traumatic, and image-guided interventions. Concomitantly, from this area of metabolic assessment, biomarker studies, and precision medicine, we can infer that we might address more specific strategies for prevention 1 day. Future randomised trials, long-term comparative effectiveness studies and real-life registries will be required to delineate ideal strategies in all of the patients that you treat, ultimately ensuring that new technology is safely integrated into clinical practice.

HUMAN AND ANIMAL RIGHTS DECLARATION

All authors hereby declare that there are no ethical concerns related to human or animal rights in this study.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

COMPLIANCE WITH ETHICAL STANDARDS

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

All the authors agreed to publish the data in this journal.

REFERENCES

1. Balawender K, Łuszczki E, Mazur A, Wyszyńska J. The multidisciplinary approach in the management of patients with kidney stone disease-a state-of-the-art review. Nutrients 2024;16:1932.
2. Ahmed K, Dubey MK, Dubey S, Pandey DK. Chronic kidney disease: Causes, treatment, management, and future scope. In: Computational Intelligence for Genomics Data. United States: Academic Press. 2025. p. 99-111.
3. Jalal L, Jaffery Z, Nasir A, Shoukat W, Khalid A, Irfan A, *et al*. Exploring the pathophysiological link between obesity and kidney stone formation: Cost-effective dietary and lifestyle strategies for prevention. Ann Med Surg 2025;87:6521-7.
4. Indurani MS, Alphones D, Rubi P, Shukla AK, Awasthi A. Modern urological approaches to renal stone disease: Diagnostic advances and therapeutic innovations. Kidneys 2026;15:229-40.
5. Liu L, Lin D, Jiao N. Magnetically controlled continuum miniature robot. In: Recent Progress in Medical Miniature Robots. New York: Academic Press; 2025. p. 21-48.
6. Bargagli M, Scoglio M, Howles SA, Fuster DG. Kidney

stone disease: Risk factors, pathophysiology and management. Nat Rev Nephrol 2025;21:794-808.
7. Singh P, Harris PC, Sas DJ, Lieske JC. The genetics of kidney stone disease and nephrocalcinosis. Nat Rev Nephrol 2022;18:224-40.
8. Sharma S, Subbarao N, Jha SK, McKenna S. Revolutionizing healthcare: Cutting-edge technologies and their applications. In: Transforming Healthcare. United States: CRC Press; 2025. p. 204-39.
9. Scotland KB, Armas-Phan M, Dominique G, Bayne D. Social determinants of kidney stone disease: The impact of race, income and access on urolithiasis treatment and outcomes. Urology 2022;163:190-5.
10. Odoms-Young A, Brown AG, Agurs-Collins T, Glanz K. Food insecurity, neighborhood food environment, and health disparities: State of the science, research gaps and opportunities. Am J Clin Nutr 2024;119:850-61.
11. Wang Z, Guo W, Xu Z, Huang X, Shao L. Long-term trends in the incidence of urolithiasis in T he United States and China: A joinpoint regression and age-period-cohort analysis based on GBD 2021. BMJ Open 2025;15:e092440.
12. Neeland IJ, Lim S, Tchernof A, Gastaldelli A, Rangaswami J, Ndumele CE, *et al*. Metabolic syndrome. Nat Rev Dis Primers 2024;10:77.
13. Di Ciaula A, Wang DQ, Sommers T, Lembo A, Portincasa P. Impact of endocrine disorders on gastrointestinal diseases. In: Endocrinology and Systemic Diseases. Cham: Springer International Publishing; 2020. p. 179-225.
14. Dong C, Yang Y, Cheng B, Yang S, Wang Y. Environmental determinants in the development of kidney stone. Urolithiasis 2025;53:43.
15. Mitchell T, Kumar P, Reddy T, Wood KD, Knight J, Assimos DG, *et al*. Dietary oxalate and kidney stone formation. Am J Physiol Renal Physiol 2019;316:F409-13.
16. Goldfarb DS, Modersitzki F, Asplin JR, Nazzal L. Effect of a high-citrate beverage on urine chemistry in patients with calcium kidney stones. Urolithiasis 2023;51:96.
17. Stepanova N. Oxalate homeostasis in non-stone-forming chronic kidney disease: A review of key findings and perspectives. Biomedicines 2023;11:1654.
18. Aljadid AA, Hazazi AA, Alotaibi HA, Alanazi MW, Bin Thari RR, Alqahtani MA, *et al*. Hypercalcemia: A metabolic disorder with wide range of side effects-an updated review for healthcare professionals. Egypt J Chem 2025;68:1185-94.
19. Khan S, Khan AA. Hypoparathyroidism: Diagnosis, management and emerging therapies. Nat Rev Endocrinol 2025;21:360-74.
20. Allam EA. Urolithiasis unveiled: Pathophysiology, stone dynamics, types, and inhibitory mechanisms: A review. Afr J Urol 2024;30:34.
21. Li Z, Meng Y, Yu M, Jiang X, He G. Progress in the regulation of pathological crystallization. CrystEngComm 2023;25:6234-45.
22. Hsu YC, Lin YH, Shiau LD. Effects of various inhibitors on the nucleation of calcium oxalate in synthetic urine. Crystals 2020;10:333.
23. Khan SR, Canales BK, Dominguez-Gutierrez PR. Randall's plaque and calcium oxalate stone formation: Role for immunity and inflammation. Nat Rev Nephrol 2021;17:417-33.
24. D'Alessandro C, Ferraro PM, Cianchi C, Barsotti M, Gambaro G, Cupisti A. Which diet for calcium stone patients: A real-world approach to preventive care. Nutrients 2019;11:1182.
25. Lomiya E. Studies on Canine UTI with Special Reference to Struvite Calculi and its Mitigation by Urine pH Modifiers. India, UP: Indian Veterinary Research Institute Bareilly; 2022.
26. Moussa M, Papatsoris AG, Abou Chakra M, Moussa Y. Update on cystine stones: Current and future concepts in treatment. Intractable Rare Dis Res 2020;9:71-8.
27. Adomako E, Moe OW. Uric acid and urate in urolithiasis: The innocent bystander, instigator, and perpetrator. In: Seminars in Nephrology. Vol. 40. Netherlands: WB Saunders; 2020. p. 564-73.
28. Mavridis C, Bouchalakis A, Tsagkaraki V, Somani BK, Mamoulakis C, Tokas T. Recurrent urinary stone formers: Imaging assessment and endoscopic treatment strategies: A systematic search and review. J Clin Med 2024;13:3461.
29. Haidary M, Tiwari A, Chouhan AP, Verma A, Singh V. Advancements in medical imaging technology for investigating urinary disease: A methodological approach. MISJ-Int J Med Res Allied Sci 2024;2:72-82.
30. Tzelves L, Geraghty RM, Hughes T, Juliebø-Jones P, Somani BK. Innovations in kidney stone removal. Res Rep Urol 2023;15:131-9.

Source of Support: Nil. **Conflicts of Interest:** None declared.