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MODERN METHODS FOR THE TREATMENT OF UROLITHIASIS: A LITERATURE REVIEW

Quziyev Sohib Salokhiddin ugli

Abstract: Urolithiasis, or urinary stone disease, remains one of the most prevalent urological disorders worldwide, affecting up to 10% of the global population. Advances in diagnostic and therapeutic technologies over the past decade have dramatically improved patient outcomes while reducing invasiveness and complication rates. This literature review analyzes recent developments in the treatment of urolithiasis based on scientific publications from 2015–2025. Modern management focuses on minimally invasive and non-invasive techniques such as flexible ureteroscopy (FURS), thulium fiber laser (TFL) lithotripsy, and extracorporeal shock wave lithotripsy (ESWL), as well as emerging methods like burst wave lithotripsy (BWL) and robot-assisted ureteroscopy. In addition, the review discusses metabolic and preventive strategies, including alkali citrate therapy, which target stone recurrence and long-term patient management. The analysis reveals that the combination of endoscopic innovation, laser technology, and artificial intelligence is transforming clinical approaches to urolithiasis. However, challenges remain in optimizing stone-free rates for large or complex calculi and in developing individualized, metabolically oriented treatment protocols. Future directions emphasize precision medicine, robotic assistance, and AI-based prediction models to enhance treatment efficiency and recurrence prevention.

Keywords: Urolithiasis; urinary stone disease; kidney stones; flexible ureteroscopy (FURS); thulium fiber laser lithotripsy (TFL); extracorporeal shock wave lithotripsy (ESWL); burst wave lithotripsy (BWL); robot-assisted ureteroscopy; minimally invasive surgery; metabolic therapy; prevention; artificial intelligence; precision medicine.

Introduction. Urolithiasis, commonly known as urinary stone disease, is a global health problem with significant medical, social, and economic implications. It is estimated that 5–10% of the population will experience urolithiasis at least once in their lifetime, with recurrence rates reaching up to 50% within ten years (He et al., 2024). The pathogenesis of urinary stones is multifactorial and involves complex interactions among metabolic, genetic, dietary, and environmental factors (Türk et al., 2022). The most common stone components include calcium oxalate, calcium phosphate, uric acid, and struvite, each associated with distinct risk factors and management strategies (Tzou et al., 2023).

Traditionally, the management of urolithiasis has relied on open surgical procedures, which were often associated with significant morbidity, prolonged hospital stays, and a high recurrence rate. However, the past three decades have witnessed a paradigm shift toward minimally invasive and non-invasive methods that aim to achieve high stone-free rates with reduced trauma and faster recovery (Skolarikos & Papatsoris, 2019). Modern technological advances, particularly in the fields of endoscopy, laser lithotripsy, and imaging, have transformed urolithiasis management into a highly specialized and patient-centered field.

Recent innovations such as flexible ureteroscopy (FURS), thulium fiber laser (TFL) lithotripsy, and robot-assisted endoscopic systems have significantly enhanced the precision and safety of stone removal (He et al., 2024). Moreover, non-invasive techniques like extracorporeal shock

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wave lithotripsy (ESWL) and the newly developed burst wave lithotripsy (BWL) provide additional therapeutic options, particularly for smaller or less complex stones (Chew et al., 2021). At the same time, metabolic evaluation and preventive pharmacotherapy, including alkali citrate supplementation, have become integral components of comprehensive stone management (Liu et al., 2020).

Given these rapid advancements, a thorough understanding of the latest treatment modalities is crucial for optimizing outcomes and minimizing recurrence. This article presents a comprehensive review of the most modern and effective treatment methods for urolithiasis, with an emphasis on evidence-based innovations, clinical effectiveness, and future perspectives.

Literature Review

1. Evolution of Urolithiasis Treatment. The evolution of urolithiasis treatment reflects a transition from invasive open surgeries to highly refined minimally invasive and endoscopic procedures. The introduction of extracorporeal shock wave lithotripsy (ESWL) in the 1980s revolutionized stone management by offering a non-invasive method to fragment renal and ureteral calculi using acoustic pulses (Lingeman et al., 2018). Despite its advantages, ESWL remains less effective for large, hard, or complex stones, with stone-free rates typically below 70% in such cases (Miller & Lingeman, 2020). As a result, endoscopic and laser-based methods have increasingly become the gold standard.

2. Flexible Ureteroscopy (FURS) and Laser Lithotripsy. Flexible ureteroscopy (FURS) has emerged as one of the most significant advances in endourology. The use of digital high-resolution imaging and laser technology allows for precise fragmentation and removal of stones with minimal complications (He et al., 2024). The advent of single-use digital ureteroscopes has further reduced infection risk and maintenance costs while maintaining high image quality (Zhu et al., 2023).

Laser lithotripsy—especially with the thulium fiber laser (TFL)—represents a major breakthrough in stone disintegration. Compared to the traditional holmium:YAG laser, TFL provides finer dusting, faster ablation rates, and less retropulsion of stone fragments, thereby increasing the stone-free rate (Taratkin et al., 2021). Clinical data suggest that TFL achieves a 90–95% success rate in stones smaller than 2 cm with a low incidence of complications (He et al., 2024). These developments have positioned FURS combined with TFL as the current gold standard for many types of renal and ureteral stones.

3. Extracorporeal and Emerging Non-Invasive Methods. Although ESWL remains a commonly used option due to its non-invasive nature, recent innovations have aimed to improve its efficiency and safety. Burst Wave Lithotripsy (BWL), a novel technology that uses focused, low-pressure ultrasound bursts to disintegrate stones without anesthesia, has shown promising early clinical results (Maxwell et al., 2022). Initial trials report high tolerability and effective fragmentation for stones up to 10 mm, suggesting a potential alternative for outpatient management (Duryea et al., 2023).

4. Robot-Assisted and AI-Enhanced Endourolog. The integration of robotic and artificial intelligence (AI) systems into urolithiasis management marks a new era of precision medicine. Robot-assisted ureteroscopy enhances operator dexterity and stability, allowing for more precise laser targeting, especially in complex intrarenal anatomies (Chew et al., 2021). AI-assisted imaging systems are also being developed to automate stone detection, classify stone composition, and guide energy settings during lithotripsy (Zhou et al., 2023). Such approaches have the potential to standardize outcomes and minimize human error.

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5. Metabolic and Preventive Management. Beyond mechanical stone removal, attention has increasingly shifted toward prevention and metabolic control. Dietary modification, hydration, and pharmacotherapy are central to preventing recurrence. Alkali citrate therapy, for instance, alkalinizes urine and inhibits calcium oxalate and uric acid stone formation, significantly reducing recurrence rates (Liu et al., 2020). In addition, thiazide diuretics, allopurinol, and magnesium supplements remain key agents in metabolic prevention (Türk et al., 2022).
However, adherence to preventive regimens remains suboptimal, and personalized approaches based on metabolic evaluation and genetic profiling are increasingly being recommended (Tzou et al., 2023). The integration of telemedicine and AI-driven patient monitoring may further improve long-term outcomes.
In summary, modern urolithiasis management encompasses a spectrum of methods ranging from highly precise minimally invasive procedures (FURS + TFL) to novel non-invasive technologies (BWL). Robotic and AI-enhanced techniques continue to improve precision and safety, while metabolic therapies address the underlying causes of stone formation. The convergence of these approaches offers the potential for a fully integrated, personalized model of care that minimizes recurrence and maximizes patient satisfaction (He et al., 2024; Chew et al., 2021; Liu et al., 2020).

Methods. This literature review was conducted using peer-reviewed studies published between **2015 and 2025**. Databases searched included PubMed, Scopus, Web of Science, and ScienceDirect. Search terms included *"urolithiasis," "kidney stones," "ureteroscopy," "laser lithotripsy," "thulium fiber laser," "extracorporeal shock wave lithotripsy," "burst wave lithotripsy," "robot-assisted ureteroscopy," "artificial intelligence in urology,"* and *"metabolic prevention of stones."*
Studies were included if they (1) focused on modern or emerging techniques in urolithiasis treatment, (2) reported clinical or experimental outcomes, and (3) were published in English. Review papers, meta-analyses, and clinical guidelines were also incorporated to ensure comprehensive coverage. Data were extracted regarding treatment type, mechanism of action, clinical outcomes, complication rates, and technological advancements. Information was analyzed qualitatively to synthesize trends and evaluate the relative efficacy of different therapeutic modalities.

Results

1. Endoscopic and Laser-Based Innovations. Endoscopic procedures have become the cornerstone of modern urolithiasis management. Flexible ureteroscopy (FURS) allows direct visualization and fragmentation of stones throughout the urinary tract, including the intrarenal collecting system (He et al., 2024). The introduction of digital single-use ureteroscopes has improved image resolution while eliminating the need for sterilization and repair, reducing costs and infection risk (Zhu et al., 2023).
Laser lithotripsy, particularly using thulium fiber laser (TFL), has emerged as the most efficient stone fragmentation technique. Compared with the holmium:YAG laser, TFL provides higher ablation efficiency, lower retropulsion, and improved visibility, leading to faster procedures and higher stone-free rates (Taratkin et al., 2021). In a comparative trial, TFL achieved up to **95% success** in stones <2 cm, with fewer complications and shorter operative times (He et al., 2024).

2. Non-invasive lithotripsy methods. Extracorporeal Shock Wave Lithotripsy (ESWL) remains an important first-line option for selected patients. However, its success depends on stone size,

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location, and density; effectiveness declines for stones >2 cm or in lower pole calyces (Miller & Lingeman, 2020). Recent advancements in energy modulation and real-time imaging guidance have modestly improved stone fragmentation efficiency (Lingeman et al., 2018).
A newer technology, **Burst Wave Lithotripsy (BWL)**, utilizes short, focused, low-intensity ultrasound bursts to fragment stones without anesthesia or significant tissue injury (Maxwell et al., 2022). Early studies demonstrate fragmentation success rates of 80–90% for stones ≤10 mm (Duryea et al., 2023). Its simplicity and tolerability make it promising for outpatient or emergency settings.

3. Robotic and artificial intelligence applications. Robot-assisted ureteroscopy has recently gained attention for its potential to enhance precision and ergonomics. These systems enable fine control of ureteroscope motion and laser targeting, reducing surgeon fatigue and improving accuracy (Chew et al., 2021).
Artificial Intelligence (AI) is being integrated into urology to improve stone detection, predict composition, and optimize energy settings during lithotripsy (Zhou et al., 2023). Deep-learning algorithms trained on endoscopic and CT images can classify stone type with >90% accuracy, which could guide individualized treatment protocols (Tzou et al., 2023).
Together, robotic and AI technologies represent a major step toward personalized, data-driven urolithiasis management.

4. Metabolic and preventive strategies. Beyond mechanical stone removal, addressing the metabolic causes of urolithiasis is essential to reduce recurrence. Preventive therapy includes dietary counseling, hydration (>2.5 L/day), and pharmacologic interventions (Türk et al., 2022). Alkali citrate is one of the most effective agents, increasing urinary pH and citrate concentration, thus preventing calcium oxalate and uric acid stone formation (Liu et al., 2020).
Additionally, thiazide diuretics reduce urinary calcium excretion, while allopurinol decreases uric acid levels in hyperuricosuric patients (Skolarikos & Papatsoris, 2019). These therapies, combined with patient education and regular metabolic evaluation, significantly lower recurrence risk.

Discussion. The current literature highlights that the treatment of urolithiasis has entered a new era characterized by minimally invasive precision techniques and technological integration. Flexible ureteroscopy and thulium fiber laser lithotripsy now constitute the gold standard for most small and medium-sized stones, offering high success rates and minimal morbidity (He et al., 2024). Their advantages include superior visualization, fine control, and reduced need for secondary procedures.
However, treatment selection must be individualized. For large or staghorn calculi, percutaneous nephrolithotomy (PCNL) or combined approaches may still be required (Türk et al., 2022). Similarly, ESWL remains valuable for smaller, radiolucent stones, but its efficacy varies depending on patient anatomy and stone density (Miller & Lingeman, 2020).
The rise of robotic and AI-based systems marks a significant shift in surgical precision and clinical decision-making. These technologies can standardize outcomes, reduce complication rates, and potentially automate intraoperative decisions (Zhou et al., 2023). However, cost, accessibility, and training remain major limitations, especially in developing healthcare systems.
Equally important is the prevention of recurrence, which requires a comprehensive metabolic evaluation and lifestyle modification plan. Despite the effectiveness of pharmacologic

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interventions such as alkali citrate and thiazides, patient adherence is often poor, highlighting the need for improved education and digital health monitoring (Liu et al., 2020). Future developments may involve integrating wearable sensors and telemedicine platforms for continuous patient management.

Overall, modern urolithiasis management emphasizes a multimodal and patient-specific approach combining technological innovation, minimally invasive procedures, and preventive care. The convergence of robotics, AI, and personalized medicine promises to further improve outcomes, reduce costs, and minimize recurrence.

Conclusion. Modern approaches to urolithiasis treatment prioritize minimally invasive surgery, technological precision, and metabolic prevention. Flexible ureteroscopy combined with thulium fiber laser lithotripsy offers superior clinical outcomes and safety, while non-invasive options like ESWL and BWL expand therapeutic versatility. The incorporation of robotics and AI represents the next frontier, enabling personalized and automated treatment planning. Preventive strategies remain essential to reduce recurrence and enhance long-term success. Future research should focus on integrating these innovations into standardized, cost-effective clinical protocols.

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