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From Stones to Signals: Harnessing Artificial Intelligence for Precision Diagnosis and Recurrence Prediction in Urolithiasis: A Comprehensive Review

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Abstract

Urolithiasis is a common urological disorder with increasing global prevalence and a high recurrence rate, creating significant clinical and economic burdens on healthcare systems worldwide. Advances in medical imaging, minimally invasive surgery, and artificial intelligence (AI) technologies have transformed the diagnosis and management of urinary tract stones. This review aimed to evaluate the role of AI and modern therapeutic innovations in improving diagnostic accuracy, treatment planning, and prediction of clinical outcomes in patients with urolithiasis. A comprehensive literature review was conducted using electronic databases, including PubMed, Scopus, ScienceDirect, SpringerLink, and Google Scholar. Relevant articles published between 2016 and 2026 were selected based on inclusion and exclusion criteria related to AI applications, imaging technologies, and minimally invasive interventions in urolithiasis management. The findings demonstrated that AI-based technologies, particularly machine learning and convolutional neural network algorithms, significantly improved the detection and classification of urinary stones through CT scan and ultrasound imaging. AI also contributed to individualized therapy planning, prediction of stone recurrence, and optimization of minimally invasive procedures such as ESWL, URS, PCNL, and RIRS. In addition, innovations in laser technologies, including Holmium:YAG and Thulium Fiber Laser, enhanced stone fragmentation efficiency and reduced complications. In conclusion, AI and technological advancements have substantial potential to support precision medicine and improve clinical outcomes in urolithiasis management, although further large-scale clinical validation remains necessary.

INTRODUCTION

Urolithiasis is one of the global health problems whose prevalence continues to increase every year. This disease occurs due to the formation of stones in the urinary tract and is influenced by various factors such as age, gender, ethnicity, and geographical location. These factors contribute to the increasing incidence of urolithiasis and have a significant impact on the health, quality of life, and economic burden on patients and the healthcare system. It is estimated that about 10–15% of the world's population will experience urolithiasis at least once in their lifetime (Li et al., 2022; Xu et al., 2023). If not treated properly, urolithiasis can lead to complications such as recurrent urinary tract infections, urinary tract obstruction, and decreased kidney function (Budaya et al., 2024).

Along with the development of technology and medical science, the management of urolithiasis has undergone many changes, ranging from diagnosis methods to therapy. Urolithiasis is often found in clinical practice through routine diagnostic examinations such as X-rays, ultrasounds, and CT scans. Some urolithiasis patients are asymptomatic and do not require special intervention, but in certain cases active therapies such as conservative and minimally invasive therapy are required. Conservative and minimally invasive therapies such as extracorporeal shock wave lithotripsy (ESWL), ureteroscopy (URS), and percutaneous nephrolithotomy (PCNL) are currently the main choices in the management of urolithiasis (Sulaksono et al., 2019; Turney et al., 2023). According to the European Association of Urology, the selection of a therapy strategy should take into account the characteristics of the stone, the patient's clinical condition, the patient's preferences, as well as the availability of healthcare facilities to achieve optimal therapy outcomes, faster recovery times, and lower complication rates (Cassell et al., 2020; Given et al; 2022; Sigh & Zaeshan, 2023).

The development of digital technology also encourages the use of artificial intelligence (AI) in the health sector, including in the field of urology. Artificial Intelligence is a data-based technology and algorithm that is able to analyze large and complex medical data to assist doctors in the process of diagnosis, therapy planning, and prediction of patient clinical outcomes. AI in identifying data patterns and relationships more quickly and accurately than conventional methods, in addition to AI has the potential to improve the accuracy of diagnosis, the accuracy of therapy selection, and the efficiency of health services (Diprose & Buist, 2016; Hameed et al., 2021).

One of the branches of AI that is widely used in the medical field is machine learning, which is an algorithm-based learning method that is able to learn patterns from data and make predictions or decisions without being explicitly programmed. In the field of urology, machine learning is widely used in medical imaging such as ultrasonography, CT scan, and magnetic resonance imaging (MRI) to help detect stones, determine the composition of stones, plan surgical actions, and predict therapy success and recurrence risk. In the medical field, AI is generally divided into two categories, namely virtual and physical. Virtual AI includes data-driven learning systems such as electronic health records, clinical decision support systems, and predictive algorithms, while physical AI includes technologies such as robotics and nanotechnology used to improve the efficiency and safety of surgical procedures (Rome, 2019).

In addition, the development of laser technology in urological surgical procedures, especially laser lithotripsy, has also brought significant advances in the management of urolithiasis because it is able to increase the effectiveness of stone fragmentation and reduce the risk of complications during the procedure (Enrique et al., 2023; Nazim, 2023). The International Alliance of Urolithiasis has also developed various guidelines to optimize the use of technology in the management of urolithiasis in various healthcare facilities (Zeng et al., 2023). The integration of Artificial Intelligence technology with medical imaging techniques and minimally invasive surgical procedures is expected to improve diagnostic accuracy, aid in more effective surgery planning, increase therapy success, increase patient satisfaction, and reduce recurrence rates (Zeng G & Zhu., 2023; Tzelves et al., 2022). Based on these developments, a comprehensive review is needed to examine the role and development of Artificial Intelligence technology in the field of urology. Therefore, this review aims to explore the latest updates and innovations, namely the contribution of Artificial Intelligence in the management of urolithiasis, starting from diagnosis to therapy.

Based on the formulation of the problem, this study focuses on analyzing the role of Artificial Intelligence (AI) in the management of urolithiasis, especially in improving the accuracy of diagnosis, assisting in the determination of therapy, predicting clinical outcomes, and assessing the effectiveness of its use based on various published studies. AI is known to have the ability to detect urinary tract stones more quickly and accurately through the analysis of medical images such as CT-scans, ultrasound, and X-rays, and helps determine the most appropriate therapy based on the characteristics of the patient and the stone. In addition, AI also plays a role in predicting therapy success, risk of recurrence, and other possible clinical outcomes so that it can support more precise and personalized clinical decision-making. Thus, this study is expected to provide a comprehensive overview of the effectiveness and potential of AI implementation in improving the quality of diagnosis and management of urolithiasis patients.

This research is expected to make a scientific contribution in the field of urology, especially related to the use of artificial intelligence (AI) in improving the accuracy of diagnosis, therapy planning, and prognosis prediction in urolithiasis. In addition, this research is expected to be a reference for future research related to the application of Artificial Intelligence technology in the field of urology. Assist doctors in clinical decision-making in urolithiasis patients. Help determine the most appropriate treatment option and according to the patient's condition. Helps predict the risk of recurrence in urolithiasis patients. Increases the effectiveness of therapy and lowers the risk of complications. Reduce healthcare costs in urolithiasis patients through more appropriate and efficient therapy selection. This research is expected to increase the knowledge and insight of researchers in the field of urology, especially related to the development and application of Artificial Intelligence technology in the medical field, especially in the diagnosis and management of urolithiasis. This research is expected to be a consideration for hospitals or health services in the development and application of Artificial Intelligence technology to improve service quality, therapy effectiveness, and cost efficiency of treatment in urolithiasis patients.

The purpose of this study is to provide a comprehensive review of the role and effectiveness of the use of artificial intelligence (AI) in improving diagnosis, therapeutic determination, and prediction of clinical outcomes in urinary tract stone patients. Analyzing the capabilities of Artificial Intelligence in the field of urology, especially urolithiasis. Assess the role of Artificial Intelligence in predicting the need for intervention in urolithiasis patients. Evaluate the use of Artificial Intelligence in predicting the success of therapy in urolithiasis patients. Analyze the role of Artificial Intelligence in predicting the risk of recurrence of urolithiasis.

RESEARCH METHODS

Research Design

This research was a comprehensive review, namely a literature review that aims to thoroughly examine the latest developments related to Artificial Intelligence in diagnosis, therapy planning, and outcome prediction in urolithiasis. This comprehensive review includes various types of research such as randomized controlled trials, cohort studies, case control studies, systematic review, meta-analysis, and experimental studies relevant to the research topic.

Data sources and Literature search strategies

Literature searches are carried out electronically through several international scientific databases, including Pubmed, Scopus, ScienceDirect, SpringerLink, Google Scholar. Keywords used in the literature search included a combination of "Urolithiasis", "Kidney Stone", "Artificial Intelligence", "Mechine Learning", "Deep Learning", "Urolithiasis management", "Treatment planning", "ESWL", "PCNL", "URS", "RIRS". Literature search is limited to articles published in the range of 2016-2026 to obtain the latest information and technological developments.

Inclusion and Exclusion Criteria

1. Kriteria Inklusi
   a. Original research articles, comprehensive reviews, meta analysis, and article reviews
   b. Articles that discuss the use of Artificial Intelligence in the diagnosis, therapeutic planning, or external prediction of urolithiasis
   c. Articles in English
   d. Full-text articles
   e. Articles published in reputable scientific journals.
2. Exclusion Criteria
   a. Articles in the form of case reports
   b. Articles that do not discuss Artificial Intelligence in urolithiasis
   c. Articles with incomplete data
   d. Articles other than English
   e. Duplicate articles.

Literature Selection and Data Analysis Process

The literature selection process is carried out in several stages, namely article identification through a database using keywords, then screening based on titles and abstracts, selection based on full text according to inclusion and exclusion criteria, then articles that meet the criteria are analyzed and synthesized narratively.

The data extracted from each article included the name of the author and year of publication, the design of the study, the artificial intelligence method used, the diagnosis modality (CT, ULTRASOUND, MRI), the type of intervention (ESWL, URS, PCNL, RIRS), the outcomes measured and the main results of the study. The data that has been obtained is then analyzed using the narrative descriptive analysis method, by grouping the results of the research based on three main focuses, namely artificial intelligence in the diagnosis of urolithiasis, artificial intelligence in therapy planning, and artificial intelligence in predicting clinical outcomes.

RESULTS AND DISCUSSION

Definition and Epidemiology of Urolithiasis

Urolithiasis is a condition characterized by the formation of stones due to the deposition of crystals from urine in the urinary tract, which can occur in the kidneys, ureters, bladder, and urethra. Urinary tract stones are generally composed of calcium oxalate, calcium phosphate, uric acid, magnesium ammonium phosphate (struvit), xanthin, cysteine, silicate, and other compounds. The chemical composition of urinary tract stones has an important role in determining prevention and therapy strategies, especially to prevent recurrence of urinary tract stones (Skolarikos et al., 2024).

Urolithiasis is a health problem that is quite common around the world, especially developed countries such as the United States, where about 5–10% of the population has experienced urolithiasis. The incidence rate of urolithiasis is estimated to reach 13% in adult males and 7% in adult females (Stamatelou & Goldfarb., 2023). In Indonesia, urinary tract stones are still one of the most common cases in the field of urology, although exact national prevalence data are still limited. This disease includes the three most common diseases in the field of urology in addition to urinary tract infections and benign prostatic hyperplasia. By sex, urolithiasis is more common in males than females with a ratio of about 3:1, with the peak incidence occurring at age 40–50 years. The high incidence rate and high risk of recurrence make urolithiasis a health problem that requires comprehensive treatment, both in terms of diagnosis, management, and prevention of recurrence (Haryadi, 2020).

Etiology of urolithiasis

The formation of urinary tract stones is a multifactorial process that is influenced by various conditions, including urinary flow disorders, metabolic disorders, urinary tract infections, dehydration, and idiopathic factors. Based on its composition, about 80% of urinary tract stones are composed of calcium oxalate or calcium phosphate. Other types of stones include uric acid stones (±9%), struvit or magnesium ammonium phosphate (±10%), and cystine (±1%), which have a lower prevalence than calcium-based stones. The variation in this type of stone is influenced by differences in risk factors such as diet, previous history of stones, environmental factors, and the use of certain medications (Turk et al., 2021).

Common risk factors for the formation of urinary tract stones include low fluid intake, high consumption of animal protein, high oxalate intake, and excessive salt consumption. Oxalate is found in foods such as nuts, chocolate, spinach, potatoes, and certain drinks. Adequate fluid intake is highly recommended to produce a urine volume of about 2.5 liters per day to reduce the risk of crystal supersaturation in the urine. Some types of liquids such as water, coffee, and low-sugar fruit juices can be consumed, although drinks with high oxalate or sodium content should be limited (Wagenius et al., 2022).

Citrate has a protective role against the formation of stones by inhibiting the aggregation of crystals through the formation of complexes with calcium in the urine. About 60% of patients with calcium stones are known to have hypocitraty. Low calcium intake can actually increase the risk of stone formation, because reduced calcium in the gastrointestinal tract will increase oxalate absorption, thereby increasing oxalate excretion in urine. In addition, the consumption of high doses of vitamin C and fish oil has also been reported to increase the risk of calcium stone formation (Sofia et al., 2016).

A previous history of urolithiasis is a strong risk factor for recurrence. Several comorbid conditions such as chronic kidney disease, hypertension, gout, hyperlipidemia, type 2 diabetes mellitus, obesity, endocrine disorders, and malignancy also contribute to an increased risk of stone formation. Obesity and insulin resistance, especially in type 2 diabetes mellitus, play a role in metabolic changes that increase the excretion of calcium and uric acid in the urine, thereby increasing the risk of calcium oxalate stones and uric acid stones. In addition, the gastrectomy procedure can increase the risk of calcium oxalate stone formation by up to three times due to malabsorption conditions that cause an increase in urinary oxalate and a decrease in urinary citrate (Wang K et al., 2022).

Drug-induced urolithiasis is relatively rare, accounting for about 2% of all cases. Medications that are often associated with stone formation include protease inhibitors such as atazanavir and indinavir used in HIV therapy, as well as sulfadiazines. Stones due to protease inhibitors are generally difficult to detect on CT scans without contrast and have a gel-like consistency that makes them difficult to destroy with lithotripsy, and often cause urinary tract obstructions that require interventions such as ureteral stenting. In addition, long-term use of ceftriaxone is also known to increase the risk of stone formation (Sohgura & Bigoniya., 2017).

Struvit stones, known as infection stones, are formed as a result of infection with urease-producing bacteria, such as Klebsiella. The urease enzyme breaks down urea into ammonia thereby increasing the pH of the urine (>8) and facilitating the formation of magnesium ammonium phosphate crystals. These stones can develop into large staghorn stones and fill the pelvic system of the kidneys. Meanwhile, cystine stones are a rare type and are caused by genetic abnormalities due to mutations in the SLC3A1 and SLC7A9 genes that cause impaired amino acid transport, especially cystine, resulting in cystinuria. This stone generally appears at a young age and can also develop into staghorn stone (Chen et al., 2023; Peerapen & Thongboonkerd., 2023).

Diagnosis advanced in urolithiasis

Non-contrast computed tomography (NCCT) is the imaging modality with the highest sensitivity and specificity in the diagnosis of urolithiasis, reaching 95–100%. NCCT has several advantages over other imaging modalities because it does not require contrast media, so it can reduce examination time and still provide accurate results in detecting urinary tract stones of various sizes and compositions (Smith et al., 2018; Firas, 2021; Raza et al., 2024). NCCT's ability to visualize the entire urinary tract makes it a very important modality, especially in acute conditions such as renal colic. In addition, the use of low-dose CT protocols has begun to be widely developed to reduce radiation exposure due to repeated CT examinations (Firas, 2021; Raza et al., 2024; Soliman et al., 2020).

Ultrasound (ultrasound) is a widely used imaging modality because it does not use ionizing radiation and is safer to use in certain patient groups such as pregnant women and children. Ultrasound is good enough to detect large stones and evaluate the degree of hydronephrosis, but has a lower sensitivity in detecting small stones. Therefore, according to the recommendations of the European Association of Urology, ultrasound is recommended as a first-line examination in patients with suspected urinary tract stones, especially in non-acute conditions. The integration of ultrasound with other imaging modalities such as NCCT can improve diagnostic accuracy as well as provide a more comprehensive evaluation of the urinary tract (Bozan et al., 2022; Al-Beltagi et al., 2023; Nuswanto & Anggraini., 2024).

The latest development in urolithiasis imaging is the use of dual-energy computed tomography (DECT), which is able to classify stones based on their chemical composition as well as improve the detection of uric acid stones that may be difficult to distinguish in conventional NCCTs. This technology provides an advantage in therapeutic planning because the composition of the stone greatly determines the choice of therapy to be carried out (Magistro e.g. et al., 2019; Arminana et al., 2023). The use of Artificial Intelligence (AI) in the diagnosis of urolithiasis is a promising innovation in improving the accuracy and efficiency of diagnosis. Machine learning models, particularly those based on Convolutional Neural Network (CNN), have shown an accuracy rate of more than 90% in detecting stones on CT scan imaging. In addition, AI-based three-dimensional (3D) reconstruction technology allows for more detailed visualization of the stone, helping clinicians to more accurately assess the size, shape, and anatomical location of the stone and assist in the planning of surgical actions. The use of AI-based software can also improve the accuracy of ultrasound interpretation through automated image analysis systems, thereby reducing interpretation errors and improving diagnostic accuracy (Yang et al., 2020; Liang et al., 2023; Xing et al., 2024).

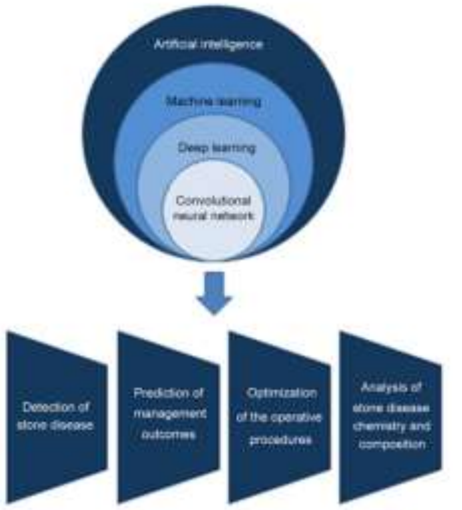

Figure 1 Subsets of artificial intelligence with emergent role in stone disease management.

In addition to imaging techniques, the diagnosis of urolithiasis can also be supported by biochemical examination and molecular diagnosis. One method being developed is the urinary indole-reacted calcium oxalate crystallization index (COCI), which has the potential to be used to distinguish between calcium oxalate and non-stone forming individuals with high sensitivity and specificity. This examination can complement imaging techniques by providing information about metabolic factors that play a role in stone formation (More-Krong et al., 2020). In addition, the latest research also explores the use of hyperspectral imaging techniques as a non-invasive diagnosis method in urinary tract stone patients. This technique allows the detection of spectral marks in urine to identify stone-forming components, so it is hoped that the disease can be detected early and managed before further disease progression occurs. The development of imaging technology, molecular diagnosis, and Artificial Intelligence integration suggests that the management of urolithiasis in the future will increasingly lead to a more accurate, personalized, and technology-based approach (Sun et al., 2024).

Urolithiasis pathophysiologists

The formation of kidney stones, or biomineralization, is a complex biochemical process that is mainly controlled by two factors, namely promoters and inhibitors. Metabolically, promoters are components that facilitate crystallization, including low urine volume, acidic urine (low pH), and high levels of calcium, sodium, and uric acid. On the other hand, inhibitors are factors that inhibit the biochemical processes involved in the formation of stones. Common inhibitors include inorganic substances such as citrate and magnesium, as well as organic components such as urinary prothrombin fragments, glycosaminoglycans, and oseopontins. The process of kidney stone formation takes place through several well-documented stages, namely saturation (solutes in urine), supersaturation (concentration of solutes exceeding their solubility limits), nucleation (initial crystal formation), crystal growth or aggregation (large crystals or merging with each other), crystal retention (crystals attach to the renal epithelium or trapped in tubules), and stone formation (aggregated crystal masses develop into stones clinically meaningful) (Antony et al., 2023; Kackhkoul et al., 2023).

Saturation and supersaturation are the main concepts in the formation of kidney stones which are defined as a comparison between the concentration of dissolved salts in the urine with their solubility level. Supersaturation indicates the potential of urine to precipitate and aggregate solid crystals. Most studies show that the initial strength of stone formation comes from the condition of the already saturated urine. When salt is added to the solvent, it will begin to dissolve. At some point, there will be no more salt that can dissolve in the solvent. This point is referred to as the saturation point between the solvent and the salt. If more salt is added to the solvent, it begins a crystallization process called the Thermodynamical Solubility Product (KSP). Calcium oxalate monohydrate, calcium phosphate such as octaxicalcium phosphate, uric acid, and struvite are important substances that also play a role in the process of urinary superregulation (Wu et al., 2024)

Crystal nucleation is the biochemical process of the formation of urinary tract stones starting with the aggregation of excretory particles that undergo supersaturation, such as free atoms, ions and salt molecules that gather and form a crystal nucleus. Nucleation is the process of forming crystals which are divided into two types. Primary and secondary nucleation. Primary nucleation occurs when crystals from the precipitating phase form spontaneously without the involvement of pre-existing particles. The primary nucleation then becomes a homogeneous nucleation when nucleation occurs spontaneously when supersaturation reaches a sufficient level. Secondary nucleation occurs when an already existing surface, such as the membrane of an epithelial cell, cell debris, another crystal, red blood cells, or urine flow. Based on the literature, this type of nuleation is called heterogenous nucleation. Mitochondrial dysfunction is known to alter the mechanisms of energy production, oxidative stress regulation, and intracellular calcium homeostasis which are important factors in the formation of crystal nuclei (Tamborino et al., 2024).

The growth and aggregation of crystals causes urinary tract stones to be dimna Crystals in the urine to aggregate to form a hard mass. Crystallization begins when the crystal core forms in the nephron, and exposure to urine will encourage further growth through the process of encrustization (mineral deposition). Crystal growth can occur through two mechanisms. The mechanism by which free particles involving crystals grows and aggregates in the urine in the renal tubules. As the crystal enlarges, it becomes unable to remove and remains trapped in the kidney. The second mechanism, the fixed particle mechanism, occurs when crystals attach to calcified plaques on the surface of the kidney papilla, known as Randall's plaque. These plaques serve as the basis for further accumulation of Crystals thus leading to the formation of stones at specific Locations. These two mechanisms contribute to the growth of urinary tract stones within the nephro (Pfau & Knauf., 2016).

Crystal cell interactions are crystals that have grown perfectly and stick to the surface of the kidney epithelium. Experimentally, in vitro studies, Crystal-cell adhesion experiments using Madin Darby Canine Kidney (MDCK) strain I cell culture showed that healthy and intact epithelial cells are not easily attached to Crystal OK, which means that crystallal does not easily adhere to the normal surface of the kidney epithelium. However, if there is an injury or injury to the surface of the epithelium, the surrounding pericellular matrix rich in hyaluronan plays an important role in increasing the adhesion of crystal-cells. In this interaction, the adhesion of the crystal to the damaged cell causes crystal retention and potentially helps the process of forming kidney stones (Letavenier & Daudon., 2018; Sadeghi et al., 2020).

Cell Injury and Apoptosis suggest that Crystals within the renal tubules can directly damage epithelial cells, thereby triggering a series of intracellular events. Crystals can cause mechanical damage to cell membranes resulting in increased oxidative stress, inflammation, and mitochondrial dysfunction. Cell damage will biologically trigger or activate the apoptosis pathway, so the affected cells will experience cell death. In particular, extrinsic and intrinsic apoptosis pathways can be activated in response to injury caused by Crystals. The extrinsic pathway is triggered by crystalline adhesion to the cell surface receptor and the intrinsic pathway is activated by cellular stress such as oxidative damage or mitochondrial dysfunction. Exposure to high oxalate levels or calcium oxalate crystals can lead to epithelial cell injury leading to apoptosis and cell death. This causes inflammation in kidney cells and causes kidney damage (Kachkoul et al., 2023; Alelign & Petros., 2018).

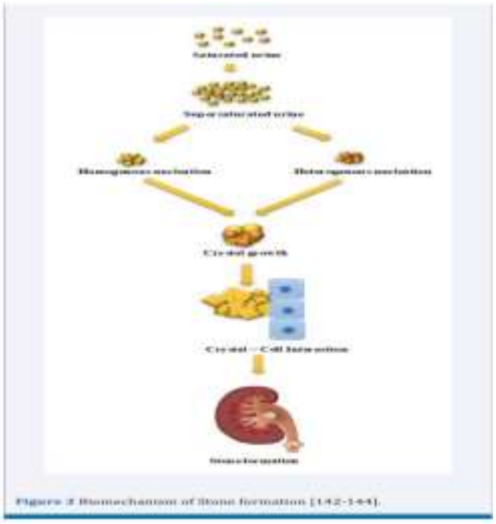

Figure 2 Pathophysiological Mechanism of Urinary Stone Formation

Therapy Urolithiasis

The management of urolithiasis depends on the size of the stone, the location of the stone, the composition of the stone, the degree of obstruction, the patient's clinical condition, and the availability of health care facilities. Common urological intervention actions include Extracorporeal Shock Wave Lithotripsy (ESWL), Ureteroscopy (URS), and Percutaneous Nephrolithotomy (PCNL). Ureteroscopy (URS) is one of the most commonly used methods in the management of urinary tract stones. This procedure is carried out with an endoscopic approach that is inserted through the urethra to the bladder, ureter, and kidney calices. This technique allows for direct visualization of the urinary tract as well as allows for the act of fragmentation and extraction of stones. URS is an effective therapeutic option for ureteral stones and kidney stones less than 1.5–2 cm in size. In addition, URS is also safer to use in patients taking anticoagulant or antiplatelet drugs because it has a lower risk of bleeding than other procedures (Assimos et al., 2016).

Extracorporeal Shock Wave Lithotripsy (ESWL) is a non-invasive method that uses shock waves to break the stone into small fragments so that it can be excreted through the urine. The location of the stone is determined using imaging such as fluoroscopy or ultrasonography. ESWL procedures are generally performed with intravenous sedation or general anesthesia and can be performed on an outpatient basis. However, the effectiveness of ESWL is influenced by the size, location, and composition of the stones, where cystine stones and some calcium oxalate monohydrate stones tend to be more resistant to this therapy. In some cases, the installation of a ureter stent is required after the procedure to aid in the removal of stone fragments and prevent ureteral obstruction (Liu et al., 2023; Pheng et al., 2023).

Percutaneous Nephrolithotomy (PCNL) is a minimally invasive procedure that is the preferred option for large (>20 mm) kidney stones, staghorn stones, or in patients who have failed ESWL or URS therapy. This procedure is done by making a small incision in the flank area to insert a nephroscope directly into the kidney so that the stone can be broken and removed. PCNL is usually performed under general or spinal anesthesia. Contraindications to the action of PCNL include pregnancy, uncontrolled coagulation disorders, and active urinary tract infections (Mahmood et al., 2022; Shetthawong et al., 2023)

Acute urinary tract obstruction accompanied by infection is a urological emergency condition that requires immediate decompression to prevent permanent kidney damage and sepsis. Decompression can be performed through ureteral stenting or percutaneous nephrotomy. In addition to interventional measures, medicated therapy and lifestyle modification also play an important role in the prevention of kidney recurrence. In patients with calcium stones, therapy may include the administration of thiazide diuretics, increased fluid intake, and dietary modifications. Struvit stones generally require surgical intervention because they are associated with infection and are at risk of forming staghorn stones. The management of cystine stones includes increasing fluid intake to produce urine of about 3 liters per day, limiting sodium and animal protein intake, and giving potassium citrate and thiol drugs. Gout stones can be managed by dietary modifications, urinary alkalinization using potassium citrate, and the administration of uric acid-lowering drugs such as allopurinol to prevent recurrence. Choosing the right management method is essential to increase the stone-free rate, reduce the risk of complications, and prevent recurrence. Therefore, technological developments such as advanced imaging and Artificial Intelligence are beginning to be used to help determine the most appropriate treatment option for each individual patient (Geraghy et al., 2023).

Transforming theraphy intervention for urolithiasis

Minimally invasive procedures have become a key pillar in the management of urolithiasis because they offer high effectiveness with lower morbidity compared to conventional procedures. Percutaneous nephrolithotomy (PCNL) remains the preferred choice for large (>20 mm) or complex kidney stones, including staghorn stones. Recent studies have shown that PCNL can also be performed on difficult anatomical conditions, such as ectopic kidneys. Despite having a high success rate, this procedure is associated with greater morbidity than other minimally invasive techniques (Wang et al., 2019; Hossain et al., 2023).

Ureteroscopy (URS) is a minimally invasive method that allows direct visualization as well as extraction of stones from the urinary tract. This procedure is particularly effective for ureteral stones, especially on the distal ureter, and can be performed with or without the help of laser lithotripsy. URS has a high success rate and is often an option in medium-sized to large stones or in cases that are unresponsive to Extracorporeal Shock Wave Lithotripsy (ESWL) (Xheng et al., 2024; Kumar & Sharma, 2024).

The development of laser technology, especially Holmium:YAG (Ho:YAG), has revolutionized the management of urolithiasis. This laser is known as the gold standard in lithotripsy because of its ability to break down almost any type of stone, including calcium oxalate and struvit stones. Various studies have shown that the use of Ho:YAG lasers results in a high stone-free rate (SFR) with a low complication rate, both in URS and PCNL procedures (Moriyama et al., 2019; Guler et al., 2021).

The latest innovation in laser technology is the use of Thulium Fiber Laser (TFL), which offers several advantages over Ho:YAG, including higher fragmentation efficiency, shorter operating time, and a lower risk of tissue thermal damage. Several studies and meta-analyses show that TFL has potential as a superior alternative in lithotripsy, especially in improving the efficiency of procedures and lowering postoperative complications. Additionally, advances in laser delivery systems allow for more precise access to hard-to-reach stone locations in the anatomy of the urinary tract (Chua et al., 2023; Miyoshi et al., 2023).

Table 1. Comparison of Laser Technologies in Urolithiasis

Parameter	Ho: YAG Laser	Thulium Fiber Laser (TFL)
Stone Types	All (especially calcium oxalate)	Uric acid, cystine
Penetration Depth	0.5–1.0 mm	0.2–0.4 mm
Operative Time	Moderate	Shorter
Cost	Moderate	High
Best For	Large/hard stones	Small/soft stones

Source: Adapted from recent studies on laser technologies in urolithiasis management.

Retrograde Intrarenal Surgery (RIRS) has also developed as an important alternative in the management of kidney stones, particularly in patients who are unable to undergo more invasive procedures. This technique uses a flexible ureteroscope inserted through the ureter to reach the kidneys without the need for a skin incision. RIRS is effective for small to medium-sized stones and provides a high stone-free rate with minimal postoperative pain and complications. The combination of RIRS with modern laser technology further enhances the success of therapy, especially in patients with difficult stone locations or with certain comorbidities (Inoue et al., 2021)

In addition, laparoscopic procedures such as pyelolithotomy and ureterolithotomy may be an alternative in certain cases, especially when other minimally invasive techniques are not possible. This approach allows stone removal through small incisions with good results and faster recovery times compared to open surgery. Although it requires higher technical skills, laparoscopy has a lower morbidity rate compared to conventional approaches (Cassell et al., 2020).

Open surgery, which was previously the main treatment for urolithiasis, is now increasingly rare since the development of minimally invasive techniques. Currently, open surgery is only considered in cases with a very large stone load, complex anatomical abnormalities, or repeated failures of minimally invasive procedures. However, this method is associated with higher morbidity, longer recovery time, and a greater risk of complications, making it the last resort in the management of urolithiasis (Akram et al., 2024).

In addition to surgical intervention, pharmacological therapy also plays an important role, both as the main therapy and as a prevention of recurrence. Medical expulsive therapy (MET) using alpha-blocker drugs, such as tamsulosin and silodosin, has been shown to be effective in helping the removal of ureteral stones by relaxing the ureteral smooth muscles. Recent research has also explored the use of sodium-glucose cotransporter 2 (SGLT2) inhibitors, such as empagliflozin, which have the potential to affect urinary supersaturation and lower the risk of stone formation (Schietzel et al., 2022; Jung et al., 2022). In addition, therapies based on natural ingredients are also starting to be researched a lot. Plant extracts such as Cymbopogon proximus and Enhydra fluctuans are reported to have antiurolithiasis effects through inhibition of calcium oxalate crystal formation. Other approaches such as the use of probiotics also show potential in lowering the risk of stone formation through modulation of oxalate metabolism. Furthermore, nanotechnology-based therapeutic innovations, such as nanoparticles for photothermal therapy, are being developed to eliminate the bacteria that cause stone infections, thereby potentially lowering the risk of recurrence. Overall, the development of minimally invasive technologies, laser innovations, and pharmacological and biotechnology-based therapies have significantly improved the effectiveness and safety of urolithiasis management. The integration of modern technologies, including Artificial Intelligence, is expected to further optimize the selection of the right therapies as well as improve patient clinical outcomes in the future (Young et al., 2022; Arya et al., 2019; Klein et al., 2021).

Economic and Patient-Reported Outcomes in the Management of Urolithiasis

The management of urolithiasis creates a significant economic burden on healthcare systems around the world. This burden is caused by high medical costs, the need for repeated hospitalizations, interventional measures, and the loss of productivity due to work absences and decreased patient work capacity. Surgical procedures, especially in the case of complex or repetitive stones, are associated with a large cost. In developed countries, where the prevalence of urolithiasis continues to rise, annual expenditure on the treatment of urinary tract stones increases significantly. For example, in the United States, the cost of urolithiasis treatment reaches billions of dollars each year and continues to increase due to postoperative complications and the need for repeated procedures (Kirkali et al., 2016)

The economic impact can be greatest in resource-constrained countries, where limited access to advanced technology and specialist personnel exacerbates health care disparities. Repeated stone formation often requires multiple interventions, which leads to longer recovery periods and can lead to long-term disability. Preventive efforts such as dietary modification and pharmacotherapy actually have the potential to significantly reduce treatment costs, but are still underutilized due to low patient education and adherence to therapy. To address these economic challenges, a shift towards value-based care is needed, emphasizing early diagnosis, the use of minimally invasive therapies, and personalized prevention strategies. This approach aims to reduce direct and indirect costs due to urolithiasis while improving the quality of health services (Lee et al., 2017)

In addition to the economic burden, patient-reported outcomes (PROs) and quality of life (QoL) are important aspects in evaluating the overall impact of urolithiasis and its therapy. Acute episodes of renal colic and kidney recurrence are often associated with severe pain, anxiety, disruption of daily activities, as well as decreased physical function. Studies have shown that patients with urolithiasis often score lower on aspects of mental health, vitality, and social functioning than the general population. Therefore, the intervention focuses not only on stone-free status, but also on the psychological and social well-being of the patient. Recent evidence suggests that minimally invasive techniques play a role in improving patients' PROs and QoL.

For example, ureteroscopy with laser lithotripsy is associated with shorter recovery time, milder postoperative pain, and fewer complications, so that patients can return to activity more quickly. However, QoL results can still vary depending on the type of therapy, stone load, recurrence rate, and socioeconomic factors of the patient. The integration of QoL and PROs parameters in clinical decision-making can assist clinicians in determining the therapy that best suits the patient's clinical condition and preferences. This approach ultimately links technological advances in the management of urolithiasis with the real experience and well-being of patients, resulting in more comprehensive, effective, and patient-centered healthcare (Modersitzki et al., 2020; Ryan et al., 2022).

CONCLUSION

Urolithiasis is a global health problem with an ever-increasing prevalence and significant clinical and economic burden. Technological developments in diagnosis and management, especially through minimally invasive approaches such as ESWL, URS, PCNL, and RIRS, have increased the effectiveness of therapy and reduced patient morbidity. However, high recurrence rates, variations in therapeutic responses, and complexity in clinical decision-making remain major challenges in the management of urolithiasis. Over time, the management of urolithiasis has evolved in line with advances in technology, surgical techniques and the understanding of pathology. The integration of artificial intelligence (AI) in the diagnosis and determination of therapy protocols has also improved treatment outcomes. Understanding the biochemistry of stone formation, dietary needs, and genetic factors is very important in preventing the formation of urinary tract stones. AI plays a role in improving diagnostic accuracy through medical imaging analysis, aiding in more precise and individualized therapy planning, and predicting clinical outcomes such as therapy success, risk of complications, and recurrence. This approach supports the concepts of precision medicine and value-based care, which focus on optimizing clinical outcomes and cost-efficiency of health services. Nonetheless, the implementation of AI in clinical practice still faces a variety of challenges, including ethical and data privacy issues, limited model transparency, and the need for further validation through large-scale clinical studies. Therefore, future research should prioritize longitudinal studies of AI-based diagnostics to validate real-world effectiveness, randomized controlled trials comparing TFL lasers with Ho:YAG in complex stone anatomy, and development of targeted pharmacotherapies for genetic subtypes (such as cystinuria).

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