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Exploring the Treatment Methods of Urolithiasis

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Abstract

Introduction: Urolithiasis, characterized by the formation and deposition of crystal agglomerates within the urinary tract, is a prevalent condition affecting up to 20% of the global population. This disease is considered systemic, as its rising incidence is linked with comorbidities such as obesity, diabetes, hypertension, and chronic kidney disease. The growth of kidney stones can obstruct urine flow in the kidney, ureter, bladder, or urethra, potentially causing acute symptoms such as renal colic, which manifests as sharp pain in the lower back or abdomen radiating to the groin, accompanied by nausea, vomiting, hematuria, or dysuria.

State of knowledge: Conservative treatment methods for urolithiasis include the administration of non-steroidal anti-inflammatory drugs (NSAIDs) and paracetamol, along with adequate hydration. However, surgical intervention may be necessary in certain cases. Current surgical treatments encompass minimally invasive techniques such as extracorporeal shock wave lithotripsy (ESWL), ureteroscopy (URS), retrograde intrarenal surgery (RIRS), and percutaneous nephrolithotomy (PCNL), as well as traditional open surgical procedures including nephrolithotomy, cystolithotomy, pyelolithotomy, and ureterolithotomy. Additionally, there are modified and combined approaches such as endoscopic combined intrarenal surgery (ECIRS), mini-PCNL, and ultra-mini PCNL.

The aim of this article: This article aims to demonstrate the epidemiology and risk factors associated with kidney stone formation and to provide a comprehensive review of the surgical treatment options for urolithiasis.

Conclusion: The treatment method for urolithiasis should be chosen individually for each patient, taking into account the patient's specific anatomy and characteristics, stone localization and size, past history and the whole clinical picture.

Keywords: Urolithiasis; Kidney stones; ESWL; URS; RIRS; PCNL; ECIRS

Introduction

Urolithiasis is a common disease associated with the formation and deposition of crystal agglomerates in the lumen of the urinary tract, affecting up to 20% of the population worldwide[1]. The exact prevalence varies, depending on the region, socio-economic status, genetic factors, ethnicity, and dietary habits, ranging from 7 to 13% in North America, 5-9% in Europe, and 1-5% in Asia. Urolithiasis is considered a systemic disease[2] with its increasing incidence, connected with obesity, diabetes[1], hypertension, and chronic kidney disease. The condition affects all age groups and is more frequent in men[3], recently narrowing the gender gap[1].

The formation of the stone is usually asymptomatic and small deposits may be excreted without any symptoms. However, when the stones grow and obstruct the flow of urine in the kidney, ureter, bladder, or urethra, it may cause acute symptoms in the form of renal colic, which is a sharp pain in the lower back or abdomen radiating to the groin or crotch, nausea, vomiting, blood in the urine or painful urination.

Urolithiasis may be more frequent in patients with systemic diseases such as obesity, diabetes, and cardiovascular disease[4]. Previous stone history, chronic kidney disease[5], the onset of the disease in childhood, positive family history, recurrent urinary tract infections, hyperparathyroidism, sarcoidosis, polycystic kidney disease, reduced fluid intake, increased ambient temperatures, a diet with high levels of sodium and protein intake, congenital malformations of urinary tract contributes to kidney stone formation[6].

The treatment method for urolithiasis should be chosen individually for each patient, taking into account the stone localization, size, and the whole clinical picture [7]. When the deposit is small, below 5 mm, and has moved into the ureter, a conservative treatment is recommended as 75% of these stones may pass spontaneously[8]. In such treatment, pain control is applied by administering non-steroidal anti-inflammatory drugs, and paracetamol with a proper fluid balance and hydration is recommended[9]. Before the surgical intervention, medical expulsive therapy may be used, facilitating ureteral stone passage with alpha-blockers such as tamsulosin, doxazosin, or alfuzosin, which can be effective for stones larger than 5 mm[10].

However, sometimes surgical treatment is inevitable. Currently, available surgical treatments for urolithiasis include minimally invasive methods such as ESWL, URS, RIRS, PCNL and classic, open surgery methods of stone removal such as nephrolithotomy, cystolithotomy, pyelolithotomy, and ureterolithotomy[11]. There are also combinations and alterations of the abovementioned, such as ECIRS, mini PCNL, and ultra-mini PCNL. This article reviews the methods of surgical treatment of urolithiasis.

Description of the state of knowledge

ESWL

Extracorporeal shock wave lithotripsy (ESWL) is a non-invasive way of disintegrating kidney stones using a powerful acoustic pulse. The main advantages of this method are that it does not require an operating room, overnight hospital stay, and general anesthesia[2]. The physical fundamentals of this method are generating extracorporeal impulse (shock wave) which causes deposit disintegration through different forces, such as pressure, compression, and shear stress[12]. There are various sources of shock generators, based on electromagnetic effect, piezoelectric or electro-hydraulic effect[13].

History

The method was born in the middle of the twentieth century. The patent for using shock waves in kidney stone treatment was made by Lev Alexandrovitch Yutkin in 1950[14]. The first application of the method in urolithiasis treatment was created by Victor Goldberg in 1959 in Riga, Latvia. It was performed using the wave-generating tool constructed by an engineer Leo Rese, according to the principles set by Lev Alexandrovitch Yutkin[15].

Later, the German Dornier Institute in the 1960s, spontaneously discovered how shockwaves affect the human tissues during a project focused on supersonic aircraft and projectiles. One of the employees accidentally touched the plate and felt a shockwave, similar to an electric impulse. However, It occurred that there was no electricity. Furthering their research on this topic, Dornier Institute performed experiments on animal tissues and focused on kidney stones[16]. The research was supported by the German Department of Defense[17]. Finally, in 1974 the successful kidney stone disintegration was made. In 1980, using an HM1 extracorporeal lithotripter, the first patient underwent successful ESWL therapy without subsequent complications.

The American Urological Association resisted embracing new technology at first as they refused a presentation about ESWL. In the following year, the reviewed scientific papers were published and most common complications and contradictions were established, some of them remained. This helped in ESWL becoming the widespread non-invasive method for kidney stone treatment. In 1984 the Food and Drug Administration approved the ESWL to use, entering the USA.

Contraindications And Complications

ESWL is contraindicated in patients with coagulopathy or those using platelet aggregation inhibitors, during pregnancy, with aortic aneurysm, severe or poorly controlled hypertension, or present urinary tract infections[18]. These factors increase the risk of bleeding and perinephric hematoma[19]. In patients with an implanted pacemaker or cardioverter-defibrillator the procedure may be safely performed, however after a cardiologist's approval or changing the device's operating parameters[20].

After ESWL treatment, as after any procedure, complications may occur. Possible complications include:

- pain
- hematuria
- hematoma
- steinstrasse[21]
- renal colic[22]
- infection, including septic infection[23,24]
- arrhythmias
- even bowel perforation[25]

However, ESWL has fewer complications compared to ureteroscopy (URS) or percutaneous nephrolithotomy (PCNL)[24].

Shock Wave Frequency And Ramping

Regarding the technical aspects, it has been shown that reducing shock wave frequency from 120/min to 60-90/min (1,0-1,5 Hz) not only improves stone-free rate after the procedure but also reduces tissue damage[26–29]. To lower the risk of renal damage, a stepwise voltage ramping can be used instead of using a fixed maximal voltage, without sacrificing the effectiveness of therapy[30]. It means starting the procedure with lower energy to provoke constriction of blood vessels and diminish tissue damage and then increasing the energy during the procedure. It has been shown that power ramping increases the stone-free rate[31].

It has been shown that medical professionals with more experience are more efficient in the treatment of urolithiasis using ESWL, therefore effects of treatment are dependent on the operator[32]. A hypothesis is that it enables more accurate localization of deposits and monitoring them during the treatment, using X-rays and ultrasounds.

There are no established rules regarding prophylaxis with a specific antibiotic during ESWL therapy, however, antibiotic prophylaxis is recommended when the patient may be suspected of having infected stones, has bacteriuria, or internal ureteral stent placed[33,34].

URS

Ureteroscopy (URS) is a surgical, minimally invasive intervention that can be used for both diagnostic and therapeutic purposes regarding urolithiasis. Flexible or rigid ureteroscope can be used in this endoscopic technique - rigid can be used for the ureter, and rigid and flexible are both feasible options for the treatment of a proximal ureteric stone, however flexible ureteroscopy is more successful in the case of proximal deposits with 91% stone-free rate[35,36]. URS allows one to directly visualize, using a camera and light source, different parts of the upper urinary tract, such as the ureter, kidney with the renal pelvis, and the renal calyces. After localization, kidney stones are then fragmented using a laser into dust or smaller fragments. Apart from urolithiasis, ureteroscopy can be used in other urological conditions, including the diagnostic process of hematuria, ureteral strictures, or upper urinary tract tumors.

The most obvious advantages of using URS in the surgical treatment of urolithiasis are high success rates defined as stone-free rates, low recurrence rates, high patient satisfaction, reduced morbidity compared to traditional open surgery, and relatively shorter recovery time, therefore usually shorter hospital stay.

As in other surgical techniques, therapeutic success starts with proper patient qualification and preparation prior to the operation, taking into account appropriate patients' selection to the treatment method, the localization of kidney stone, its dimensions, and preoperative imaging using ultrasonography and computer tomography.

Currently, URS is a cornerstone operative procedure in the field of surgical treatment of urolithiasis, with high-quality reviewed sources and meta-analysis, defined guidelines of treatment based on years of experience and research, moreover, with a promising future. A hypothesis, based on ongoing research endeavors including trends of research and development in technology, is that the future evolution of ureteroscopy may include the use of artificial intelligence technologies to assist navigation in the upper urinary tract, which might reduce the operation time.

RIRS

Retrograde Intrarenal Surgery (RIRS) is an established treatment method for the management of kidney stones in the upper urinary tract - upper ureter or deposits in the kidney. This method of surgical treatment of urolithiasis is based on the use of a camera, light source, and a flexible endoscope, which is passed through the external urethral opening, the urethra, the bladder, vesical ureteral opening, the ureter into the kidney. Then, kidney stones are localized after endoscopic direct examination of renal calyces and fragmented using a laser. Smaller kidney stones are extracted using graspers, baskets, or passed out after the operation.

There are various techniques of deposit fragmentation[37]. Dusting involves the use of a relatively low-energy laser setting to pulverize stones into fine particles that resemble dust which can favor the expulsion with spontaneous passage. Smaller kidney stones are eligible for dusting. While using this method, the need for extraction using a basket is reduced, which may reduce the risk of ureteral injury.

On the other hand, a method called fragmentation requires applying higher energy laser pulses to break (fragmentate) larger stones into smaller pieces, which can be more manageable to be retrieved with baskets or graspers. Apart from larger kidney stones, the deposits that are more densely calcified are suitable for this method.

Popcorning or popcorn fragmentation entails rapidly firing laser pulses at the stones' surface which causes their cleavage. This type of kidney stone disintegration resembles preparing popcorn due to the fact that deposits move around and disintegrate when the laser has surface high power contact with many stones. Regarding the laser setting of energy, pulse time, frequency, and power it is a mix of settings of dusting and fragmentation - medium to long pulse time, including high energy and frequency; whereas dusting includes using long pulse of high frequency with low energy. However, fragmentation requires short pulses of high energy with relatively low frequency. The exact values of pulse in microseconds, energy in Joules, frequency in Hz, and power in watts are omitted as they may differ depending on the stone density, used laser, and other variables.

Limitations of RIRS include deposits larger than 2 cm which may need a second stage of operation - a cumulative stone free rate in case of these types of deposits is 91%, with 1.45 procedures per patient[38]. Also, stones may be difficult to reach, especially in the lower renal pole - displacing them into more accessible renal calyx may be necessary[39]. Urethral narrowing may impede the entrance of a flexible endoscope - then a prior stenting with a double-J stent is required.

PCNL

Percutaneous nephrolithotomy (PCNL) is a method of choice for a large renal calculi and complex kidney stones. The procedure involves accessing the renal collecting system through a percutaneous tract under the guidance of ultrasound or fluoroscopy. Kidney stones are disintegrated into smaller pieces and removed directly. PCNL as a method of urolithiasis treatment is associated with high stone-free rates and has been shown to be particularly effective for large calculi. It offers reduced morbidity and shorter hospital stays compared to open surgical treatment methods and is higher than URS or RIRS.

In terms of available instruments, both rigid and flexible endoscopes are feasible, the selection depends on the surgeon's. Access sheats standard sizes are 24-30 F, however, smaller sizes of tract such as 11-13F, which were at first used in pediatric urology, are used more commonly in adults. Miniaturization of sheaths sizes endeavor to achieve improved outcomes and reduce complications, including morbidity. Agrawal et at. shows that ultra-mini-percutaneous nephrolithotomy is an effective and safe procedure for managing stones up to 20 mm[40]. Systematic review of Ruhayel et al. suggest that miniaturizing PCNL results in at least the same efficacy and safety level as the standard sizes in terms of urolithiasis treatment[41]. Another analysis of the pediatric population showed that RIRS and micro-PCNL in the group of 239 children resulted in a similar stone free rate, operative time, urinary tract infection incidence, and requirement for blood transfusion, no significant differences were found. However, micro-PCNL had an advantage in terms of lower requirement of postoperative stenting procedure compared to RIRS[42].

PCNL compared with ESWL has higher three-month success rates with a similar effect on quality of life, however probably leads to more complications[16].

Contradictions to PCNL include[26]:

- severe, uncontrolled coagulation disorder with ongoing, anticoagulant therapy
- infection of the upper urinary tract that is not treated,
- pregnancy,
- kidney tumor that can be potentially malignant,
- skin infection or tumor in the location of the access tract.

ECIRS

Endoscopic combined intrarenal surgery (ECIRS) is a minimally invasive surgical technique, particularly applied for the removal of complex, large kidney stones, located in anatomically challenging positions. It combines two primary approaches: flexible ureteroscopy and percutaneous nephrolithotomy. This modality of dual approach allows access and treatment of kidney stones from both the upper and lower urinary tracts simultaneously[43]. Percutaneous Nephrolithotomy (PCNL) enables the removal of large or multiple stones through the percutaneous tract, made through a small incision in the patient's back to insert a nephroscope directly into the kidney. Flexible ureteroscopy involves the insertion of a flexible ureteroscope through the urethra and the ureter into the kidney, with visualization and lithotripsy of kidney deposits.

ECIRS provides enhanced stone-free rates - through multiple access routes, the chances of achieving complete stone clearance increases. Also, the operating time can be reduced when a combined approach is applied, compared to separate procedures.

In the systematic review of Cracco et al., a reported stone free rate was mostly higher than 80% through a single procedure, ranging from 61% to 97%[43,44]. Standard access sheats sizes (24-30F) and smaller dimensions of kidney deposits are linked with higher SFR[43]. Regarding complications according to the Clavien-Dindo classification, the range was from 5,8% to 44%, correlated with the longer operation time and larger staghorn stones[45]. Most complication grades were 1 and 2, with very rare grade 3 and anecdotal grade 4. No grade 5 complications were mentioned. The mean hemoglobin drop was 0,8-2,1 g/dL, with 0,5% to 3% of patients who required blood transfusion. The additional access was necessary in below 10% of cases (1,6%-10%)[43]. The time of hospital stay ranged from 5,1 to 9,8 days.

The most advantageous conclusion from systematic review of scientific papers regarding ECIRS is that it reduced the need for ancillary procedures, therefore it can be a solution for even large and complex kidney stones during one procedure[46].

Open Surgical Methods

Open surgical methods for the treatment of urolithiasis, although widely supplanted by minimally invasive techniques, remain relevant in specific complex and persistent cases. These methods depends on the deposits position and include nephrolithotomy, cystolithotomy, pyelolityotomy, ureterolithomy. Nephrolithotomy involves a direct surgical incision into the kidney to remove large or complicated stones when other access methods are unsuitable. Cystolithotomy is surgical removal of bladder stones through an incision in the bladder - it can be used for large or hard stones, usually after an attempt to fragmentate them in the other way. Also, when there are multiple stones in the bladder and the time of minimally invasive procedure may be severely prolonged, cystolithotomy may be taken into account. Pyelolithotomy is the surgical excision of stones from the renal pelvis, while ureterolithotomy is the removal of stones from the ureter. Nowadays these methods are reserved for the situation where less invasive approaches are unsuccessful or impractical.

Open surgical methods may be necessary in the case of anatomical abnormalities, significant stone burden, difficult to access or when stones are embedded, or impacted into the mucosa. These procedures are associated with longer hospital stays and recovery times. However, they are very successful in terms of definitive stone removal, especially when less invasive methods fail[47].

Conclusions

The management of urolithiasis should be individualized for each patient, considering specific anatomical and physiological characteristics, stone localization and size, medical history, and the overall clinical context. Conservative therapy is typically adequate for most cases involving small calculi. However, larger stones causing urinary tract obstruction require surgical intervention to prevent renal damage. A variety of minimally invasive techniques are currently available, chosen based on the patient's unique situation. If these methods would be unsuccessful, traditional open surgical methods remain an option, typically providing effective and complete stone removal.

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