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REVIEW

Innovations in Kidney Stone Removal

Lazaros Tzelves[1], Robert Michael Geraghty[2], Thomas Hughes[3], Patrick Juliebø-Jones[4], Bhaskar K Somani[5]

[1]Department of Urology, Sismanogleio Hospital, National and Kapodistrian University of Athens, Athens, Greece; [2]Department of Urology, Freeman Hospital, Newcastle-Upon-Tyne, UK; [3]Department of Urology, Warwick Hospital, Warwick, UK; [4]Department of Urology, Haukeland University Hospital, Bergen, Norway; [5]Department of Urology, University Hospital Southampton, Southampton, UK

Correspondence: Bhaskar K Somani, Department of Urology, University Hospital Southampton NHS Trust, 19 Tremona Road, Southampton, SO535DS, UK, Tel +44-2381206873, Email bhaskarsomani@yahoo.com

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Abstract: Urolithiasis is a common clinical condition, and surgical treatment is performed with different minimally invasive procedures, such as ureteroscopy, shockwave lithotripsy and percutaneous nephrolithotomy. Although the transition from open surgery to endourological procedures to treat this condition has been a paradigm shift, ongoing technological advancements have permitted further improvement of clinical outcomes with the development of modern equipment. Such innovations in kidney stone removal are new lasers, modern ureteroscopes, development of applications and training systems utilizing three-dimensional models, artificial intelligence and virtual reality, implementation of robotic systems, sheaths connected to vacuum devices and new types of lithotripters. Innovations in kidney stone removal have led to an exciting new era of endourological options for patients and clinicians alike.

Keywords: kidney calculi, ureteroscopy, percutaneous nephrolithotomy, laser, artificial intelligence

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Introduction

The incidence of urolithiasis worldwide is rising, mainly due to a higher utilization of more sensitive imaging methods such as computed tomography (CT) scans and also because of the increasing trends of metabolic syndrome and adoption of Western-type diets and lifestyle.[1,2] The volume of endourological procedures performed is rising, mirroring the increasing number of cases.[3] Excellent stone-free rate (SFR) is the anticipated clinical outcome in most cases, not only due to proper technique followed by trained endourologists, but also with the aid of a plethora of technological innovations.

The aim of this review is to summarize the most clinically important advancements in endourology.

Methods

A literature review was performed in PubMed/MEDLINE up to December 2022. The search terms used were: endourology, robotic, percutaneous nephrolithotomy (PCNL), innovations, advancements, technology, ureteroscopy (URS), urolithiasis, virtual reality (VR), three-dimensional (ED) technology and artificial intelligence (AI). The reference list of eligible studies was also screened. Eligible studies were those on the subject of technological advancements in PCNL and URS, studies on the use of robotic systems for the management of stone disease and those on the utility of AI, 3D technology and VR.

Results

A total of 376 abstracts were initially identified using the search terms. After assessing eligibility by abstract/title screening, a total of 274 were excluded, and 102 records were evaluated after reading the full text. We then included a total of 74 studies.

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Lasers and Fibers

The introduction of the Holmium: yttrium-aluminum-garnet (Ho:YAG) laser revolutionized the endoscopic management of stones more than 15 years ago and is currently the gold standard according to the European Association of Urology (EAU) Guidelines.[4] Stone disintegration is achieved mostly via a photothermal phenomenon, where energy is transferred to water molecules found in cracks and pores of stones, leading to their comminution.[5–7] Initially manufactured with a power output of 15–20 Watt (W) and later with a higher output of 120 W, Ho:YAG machines suffer in terms of low wall-plug efficiency ~1–2%, with the remaining 98–99% of energy being transformed to heat, justifying the need for powerful cooling systems.[7] The enhanced frequency (Hz) and pulse-energy (Joules) settings of new Ho:YAG machines permitted the development of more effective lithotripsy modes such as dusting and pop-dusting, where fine stone particles are produced and are easily expelled from the urinary tract.[8] This enhanced stone disintegration, however, is accompanied by stone retropulsion, most likely due to collapse of the vapor bubble[6] and also damage of the laser fiber tip ("burn back" effect), which leads to longer operative times.[9] Additionally, impairment of the endoscopic view during utilization of high-power settings is commonly encountered ("snowstorm" effect) and can necessitate compensation with an increased irrigation inflow. The latter may lead to an increased risk of elevated intrarenal pressures and increase the risk of infective complications.[10]

Thulium fibre laser (TFL) is a newer laser platform with favourable physical properties compared to Ho:YAG. TFL operates at a wavelength of 1940 nm, which is very close to the water absorption peak (1950nm), compared to 2100 nm of Ho:YAG.[11] This property enables TFL to have a fourfold lower threshold for stone ablation compared to Ho:YAG, whilst permitting disintegration of all stone types, similar to Ho:YAG.[12] TFL functions at a wider range of settings, emitting pulse energy between 0.025 and 6 J at frequencies of up to 2000 Hz, thus giving the capability of very high peak power (~500 W).[7,13,14] This wide range of settings enables TFL to deliver high-power energy through smaller, more flexible fibers of 50 μm, compared to Ho:YAG lower limit of 200 μm.[6] The clinical significance of this difference is the improved scope maneuverability, better irrigation and lower risk of stone retropulsion, which comes not only from smaller fibers and higher frequencies, but also from the creation of smaller water bubbles.[6,7,11,13] It should be emphasized, however, that although these very high frequencies are achievable theoretically, even settings below 50 Hz can create a "blizzard" effect, necessitating the procedure to be paused in order to regain clear vision.[15]

The first randomized trial to compare Ho:YAG with TFL was published in 2020 by Martov et al, who used these two laser platforms for ureteric stones at a present energy of 1 J, frequency of 10 Hz, using fibers of similar sizes.[11] Authors reported that TFL led to significantly less stone retropulsion than Ho:YAG (4% vs 69%, $p < 0.05$), clearer endoscopic view (87% vs 64% of cases, $p < 0.05$), shorter operating (24.7 vs 32.4 min, $p < 0.05$) and laser time (8.4 vs 15.9 min, $p < 0.05$), while stenting rates, complications and SFRs were similar.[11] Going a step further, Ulvik et al compared the two lasers for both ureteric and renal stones with settings starting at 0.4 J and 6 Hz and increased according to stone disintegration, but limited to 0.4 J/6 Hz in ureter and 0.8 J/20 Hz in kidney.[16] Similarly, the operative time was significantly shorter with TFL (49 vs 57 min, $p = 0.008$), while no ureteric access sheath was used, and the post-operative stenting rate was similar. Laser operating time did not differ significantly between the two groups, with the operative time difference being attributed to improved endoscopic view with TFL.[16] Indeed, in the TFL group less bleeding occurred compared to Ho:YAG group (5% vs 22%, $P = 0.014$), explained by the higher TFL energy absorption by water.[16] Ureteric SFRs were 100% for both groups, while in renal stones SFRs were significantly higher for TFL, regardless of whether the definition was that of no residual fragments (23% vs 13%, $p = 0.005$) or residuals ≤3 mm (30% vs 19%, $p = 0.001$).[16] It is important to highlight that in all these comparative studies, traditional Ho:YAG lasers were used and neither high-powered machines or Moses technology were utilized.

Newer Ho:YAG laser machines are able to operate on different pulse emission periods, namely as short (180–330 μs) or long pulse (650–1215 μs).[17] In vitro experiments suggest that long pulse settings benefit from less retropulsion and fiber damage, although real life clinical outcomes are not yet demonstrated.[6,9,18] Ho:YAG machines functioning both at short and long pulse settings deliver energy over one pulse, with the majority of energy being consumed during the creation of the vapor bubble.[7] A new characteristic of high-power machines is Moses technology, where the energy is applied with two pulses: the first creates the bubble, whilst the second transfers the energy through the already formed vapor channel to maximize the effect on the stone.[19] In a preclinical study, it was shown that retropulsion is significantly reduced by 50 times.[20] While in a randomized controlled trial (RCT) the operative time was significantly shorter with Moses technology compared to a conventional mode (50.9 vs 41.1 min, $p = 0.03$), SFRs were similar at 3 months.[21] Head-to-head comparisons between TFL and Moses technology machines are lacking. The higher cost of Moses mode should be balanced with the clinical benefit of reduced operative time. Another emission mode is Virtual Basket™ (Quanta System, Samarate, Italy), which refers to a double-pulse setting where the first pulse creates a bubble, while the second pulse enlarges this bubble to maximum expansion.[22] This double-pulse mode is considered to create a more effective energy transmission to the target stone. In their clinical study, Bozzini et al reported faster stone fragmentation in both ureter (220.4 vs 16.1 min, $p < 0.05$) and kidney (28.7 vs 19.8 min, $p < 0.05$) with similar energy emitted (9.9 vs 10.7 kJ and 13.5 vs 16.1 kJ, $p > 0.05$).[23] Basulto-Martínez et al in an in vitro study concluded that Virtual Basket mode enhanced the ablation rate of Ho:YAG laser at 40 Hz/0.3 J to reach the ablation rate of TFL at the same settings, suggesting that this ablation mode is one of the most effective for Ho:YAG lithotripsy.[22]

The two established methods of stone removal after applying laser energy are basketing and dusting. The use of basketing devices is needed when fragments 2–4 mm exist after stone fragmentation, while dusting refers to production of particles <2mm that can be spontaneously expelled with urinary stream. Many surgeons prefer the dusting technique to avoid multiple manipulation within the ureter and kidney with baskets, which can necessitate the use of ureteral access sheath and may increase tissue trauma and operative time.[24] On the other hand, dusting requires higher frequency settings, which can in turn lead to increased temperature and tissue damage. The use of basket usually requires an assistant who handles the opening and closure of this device to grab and release the stone particles, while the surgeon navigates the scope within the collecting system and ureter. An interesting alternative approach is the one-surgeon basketing technique for flexible ureteroscopy, which has been shown to lead to similar stone-free rates, complications and length of stay when applied by either experienced or novice endourologists.[24]

Ureteroscopes

The pace of technological advancements has also been very favorable for ureteroscopes' design and functionality, leading to modern scopes with unique characteristics, and differences with older technology scopes. Switching from fiberoptic to digital systems enabled surgeons to better visualize anatomy, since the "honeycomb" appearance vanished.[25] Sensors of digital scopes are less sensitive to image flickering caused by laser energy-induced shockwaves, thus offering an unobscured view.[6,26] The main drawback of digital, "chip on tip" systems is the cost and that sensors are currently manufactured at specific sizes, which hinders further miniaturization of digital scopes.[6]

Single-use flexible scopes have also been introduced for some years, leading to non-inferior, if not superior, clinical outcomes compared with reusable scopes.[27,28] Ergonomics of single-use devices seem to be superior, as shown by electromyographic data,[29] thus lowering fatigue levels of surgeons without compromising scope functionality as shown in multiple studies.[27,28,30–32] Another obvious advantage is the non-existent risk of contamination, which can be as high as 12.1% with reusable scopes even after following strict sterilization protocols.[33] An unanswered, yet critical query is the cost-effectiveness of this new technology, for which there is a lack of consensus in the literature.[6] It is the high variability of costs among different companies and countries for buying this equipment, the variability in number of cases that need to be performed before repair is needed for a reusable device (8–29 procedures before repair according to recent reports[34]) and also the different hospital settings (academic, teaching, community) that justify this lack of consensus.[6] Despite this, single-use scopes offer certain benefits and can be considered especially for cases with unfavorable anatomy (lower pole stones with steep infundibulopelvic angle <30–50°, patients with urinary diversion, transplanted kidneys or congenital abnormalities), for patients at risk of urosepsis and also for endoscopic treatment of upper urinary tract urothelial carcinoma.[27]

Artificial Intelligence, 3D Technology and Virtual Reality

The era of the surgical training with "See one, do one, and teach one" has been surpassed and replaced by multi-level theoretical and practical, hands-on surgical training to ensure patient safety and treatment effectiveness. What the surgical community asks for are efficient, affordable and realistic systems, which will gradually train junior doctors, whilst at the same time ensuring a minimum level of surgical expertise before applying acquired knowledge in the surgical field.

Accurate anatomic models can be constructed using 3D printers, aiding in a more realistic and detailed representation of the urinary tract geometry compared to 2D pictures accessed through CT and MRI scans.[35] The main directions in which 3D models can assist urolithiasis management are training, pre-procedural planning, and patient counselling.[36] In a study by Xu et al, 3D models from patients with staghorn stones were created and utilized for training and preoperative planning.[37] Authors prepared for the operation by choosing an appropriate calyx to puncture and performing the procedure on the models using gypsum stones.[37] Post-operative stone volumes of the models compared favourably with those from actual surgery and the Pearson correlation index was $r = 0.972$ ($p < 0.001$), demonstrating very good correlation and reliability of the model.[37] In another study by Ali et al, 3D models were compared with UROMentor^{TM} simulator regarding the training of second year residents on PCNL.[38] After training completion, residents of the two groups were asked using a specific questionnaire about their training experience and authors concluded that 3D printed PCNL models led to significantly improved response metrics compared to simulator for all indices, namely X-ray guided puncture, guidewire placement, identification of proper calyx, placement of nephrostomy tube, assessment of kidney anatomy, feedback of tissue model and discussion about errors.[35,38] Going a step further, Golab et al utilized 3D printed guides created using CT images, to perform renal puncture in a patient with horseshoe kidney and reported that the needle successfully reached the stone in the patient's kidney.[39] Cost implications should also be highlighted, since VR trainers seem to come at costs of ~100.000 dollars, which is clearly not viable for most teaching centers around the globe.[40,41] While these 3D models were helpful in complex cases, widespread uptake of this technology is likely to be limited by time and cost pressures in already stretched health-care systems.

VR-based surgical training flourished with the dominance of robotic systems for treating oncological patients during the last decade. VR systems set up a realistic 3D, virtual environment, which is created using anatomical knowledge and real-life images, offering a high precision view to the user, who is able to virtually interact and perform exercises or steps of a specific procedure.[42]

UROMentor^{TM} is a VR simulator used for training in ureteroscopy and was evaluated by Matsumoto et al, who reported that senior residents achieved better scores compared to juniors and simulator scores correlated well to bench model metrics, suggesting that it is a useful tool to assess surgical competence for tasks such as cystoscopic guidewire insertion, rigid URS and basket manipulation.[43] VR simulators were also helpful in training for flexible ureteroscopy as reported by Cai et al who concluded that after a 4-hour training session, there were improvements in trainee scores (time to complete steps, proficiency of laser use, total laser energy applied, damage to model and scope and size of fragments produced).[44]

Artificial Intelligence (AI) is the field of computational science, where machine is programmed to mimic and perform cognitive tasks normally achieved by the human brain.[45] AI is rapidly incorporated in all fields of medicine, since it has got demonstrably better accuracy than traditional statistical approaches, and can incorporate novel data sources, eg, image or pathology data, and permits the creation of predictive models that are very accurate, using huge amounts of data.[46,47] Specifically for stone disease, AI has already been evaluated for diagnosis, detection of stone composition and several aspects of medical or surgical treatment. Langkvist et al used a machine learning neural network to differentiate between phleboliths and stones in the CT scan, reaching a sensitivity of 100%.[48] Similar algorithms were used by Aldoukhi et al, who managed to differentiate stone composition (between uric acid, calcium oxalate, cystine, struvite) with an overall accuracy of 85%.[49] Accuracy above 90% was reported by Poulakis et al, who developed an algorithm to predict shockwave lithotripsy outcomes (SWL) for lower pole stones by giving input on dynamic urine flow, infundibulopelvic angle, body mass index, stone size and caliceal pelvic height.[50] Regarding PCNL, AI also demonstrates significant predictive ability. In a study by Aminsharifi et al, outcomes of PCNL were predicted with an accuracy of up to 98%.[51] Tzelves et al compared several machine learning models and reached a maximum accuracy of 87.4% in predicting susceptibility of bacterial species in stone disease patients only by knowing the species, thus saving nearly 24 hours until the sensitivity results are reported by the lab.[52] Perhaps further work in AI would mean studies providing code/user interface for further external validation of these models.

Intrarenal Pressure (IRP) and Suction Use During Endourological Procedures

Irrigation fluid use during endourological procedures is inextricably linked with clear visualization. Studies measuring normal IRP report a range of 7.5–14.7 cmH20,[53,54] which can increase up to 25 cmH20 with osmotic diuresis.[53] During endourological procedures, these pressures can increase further leading to several types of pyelorenal backflow, namely pyelovenous, pyelolymphatic, pyelotubular and pyelointerstitial backflow.[55] The main clinical implication of this physiological phenomenon is an increased risk of infection[56] and tissue damage.[57] Suction has been utilized for many years in endourology, usually combined with ultrasound and ballistic energy in PCNL to remove stone fragments efficiently.[58,59] Technological advancements permitted the incorporation of suction technology in ureteral access sheaths and PCNL sheaths or nephroscopes, aiming to increase the effectiveness and safety of endourological procedures.[59] Zhu et al conducted a retrospective cohort study comparing traditional ureteroscopy with ureteral access sheaths (UAS) 12/14 Fr to ureteroscopy with 12/14 Fr modified UAS with a vacuum device connected to it.[60] They detected significantly reduced operative time, length of stay and sepsis rate with improved immediate SFRs for the group where a modified UAS was used.[60] In a similar fashion, Huang et al conducted a RCT to compare miniPCNL (mPCNL) using a 16 Fr sheath connected to a vacuum device with standard 16 Fr sheath.[61] They reported significantly less operative time, intraoperative bleeding, fever rates, renal pelvis perforation rates and length of stay, with a significantly improved SFR at one month.[61] At the same time, real-time monitoring of IRP became available either by using guidewires equipped with pressure sensors[62] or with UAS able to both monitor IRP and apply effective suction intraoperatively.[63]

Robotic Ureteroscopy (RoboURS)

Implementation of robotic systems in urologic oncology has led to improved clinical outcomes.[64,65] Desai et al first reported the use of a robotic system for URS in porcine models.[66] They suggested improved ergonomics when using the Sensei robot, based on surgeons' responses to a visual analogue scale for instrument stability (10/10), reproducibility of access (10/10) and auto-retraction (8/10).[66] A human trial conducted in 2011 by the same team, using RoboURS platform in 18 patients, reported no intraoperative complication, 3-month SFR of 89% and minor postoperative complications; again control of the robot was rated as 8.5/10, stability as 9/10 and stone fragmentation as 9.2/10.[67] Geavlete et al performed a comparative study using RoboURS and standard flexible ureteroscopy, reporting a significantly lower re-treatment rate when using robotic systems (9.1% vs 15%).[68] Rassweiler et al used the Roboflex Avicenna and detected a reduced fluoroscopic time, attributed to the memory function of robot and favourable insertion and retraction of the robotic system.[69] Summarizing existing literature, robotic systems are in their infancy but reportedly lead to improved ergonomics, reduced use of fluoroscopy and decreased operative time due to the memory of these systems; however, cost implication should be considered as well.

Miniaturization of PCNL Sheaths - Innovations in PCNL Lithotripters

Technological advancements permitted the refinement of instruments used during PCNL. One of the most important shifts is the miniaturization of access sheaths from 24–30 Fr (standard PCNL) to 14–20 Fr (mini-PCNL).[70] The main advantage of mPCNL is reduced bleeding and transfusion rate, increased rates of performing a tubeless procedure (75–80%), reduced hospital stay, but at a cost of increased operative time due to laser lithotripsy used during mPCNL.[71]

For many years, the main equipment used during PCNL for lithotripsy combined ultrasonic and ballistic energy, using two probes (dual-probe, dual-energy lithotripters). Recently, single probe – dual energy (SPDE) lithotripters have emerged and proved their effectiveness in preclinical studies. ShockPulse SE (Olympus, USA)[72] and EMS LithoClast® Trilogy[73] are the two representatives of this technology. In a recent systematic review and meta-analysis, Mykoniatis et al concluded that SPDE lithotripters are deemed safe and efficient based on bench studies, but preliminary clinical data show similar SFRs, bleeding complications and operative time compared to both laser lithotripsy and stone fragmentation using older generation devices.[74] The fact that SPDE devices provide simultaneous application of two forms of energy, improves the ergonomics and surgeon satisfaction and whether they will be proved superior remains to be seen when more data become available.[74]

Radiation-Free Protocols for Endourological Procedures

Fluoroscopic guidance is commonly used during endourological procedures.[75] Catastrophic events in Hiroshima and Nagasaki have made clear how harmful ionizing radiation is for human tissues; yet according to a recent survey education is lacking and protective equipment is not used ideally among endourologists.[76] Patients are exposed to radiation during diagnosis, management and follow-up of urolithiasis,[77–79] while surgeons are also prone to its mutagenic effects due to long-term, low-dose exposure.[80] Although not a technological innovation per se, the establishment and adoption of radiation-free protocols for URS and PCNL can drastically reduce radiation exposure and associated risks.[81] It should be highlighted, though, that such protocols should be followed in centers with adequate experience and for non-complicated cases.[81]

Future Perspective

Improved ureteroscopes and vision have also improved the management of upper tract tumors.[82,83] While it also allows the treatment of high-risk patient groups such as in pediatric patients and during pregnancy,[84,85] perhaps future studies should also consider the cost and quality of life aspects of stone treatment.[86,87]

Conclusions

The management of kidney stones has drastically changed from open surgery prior to the early 1990s to minimally invasive procedures in the current era. Continuous technological advancements, however, have led to ongoing improvement of equipment with innovations such as thulium fibre laser, new modes of lithotripsy, digital/single-use and smaller caliber ureteroscopes, applications using AI/3D models and VR, suction sheaths, robotic systems and new lithotripters being already incorporated into clinical practice and expanding armamentarium. These innovations in technique and training render kidney stone removal minimally invasive, safe while continuing to offer improved outcomes as time goes by.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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