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SPECIAL FEATURE: REVIEW ARTICLE

Recent development of diagnostics and therapeutics ultrasound for urological disease

Application of ultrasound imaging in the treatment of urinary tract stones

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Abstract
Urinary tract stones are a common clinical condition that affect millions of individuals worldwide. The management of these stones has evolved significantly over the past 70 years, and ultrasound imaging has emerged as a valuable tool for diagnosis, treatment planning, and follow-up. This review aims to provide an overview of the application of ultrasound imaging in the treatment of urinary tract stones, highlighting its advantages, limitations, and current advancements in the field.

Keywords POCUS · Acoustic shadow · Twinkling artifact · Wideband Doppler · Real-time virtual sonography

Introduction

Urinary tract stones (UTS) are crystalline deposits in the kidneys. The trend in prevalence of urolithiasis is increasing, affecting approximately 12% of the global population [1, 2]. The recurrence rate is also high, estimated to be approximately 50% within 10 years [3]. UTS is a clinically significant condition that can cause significant pain and complications and affect kidney function. The intensity of symptoms may vary depending on the stone location, size, and degree of obstruction. Prompt diagnosis, appropriate management, and preventive measures are essential for alleviating symptoms, preventing complications, and reducing the risk of recurrence.

Broadly, the diagnosis of UTS involves imaging modalities, including ultrasound imaging (US), noncontrast computed tomography (NCCT), and abdominal plain radiography (KUB). The sensitivity, specificity, radiation exposure level, and relative cost vary according to the modality (Table 1) [4–9]. US plays a significant role in the treatment of UTS, while NCCT has become the imaging modality of choice because of its high diagnostic sensitivity and specificity. However, in recent years, US has been recommended as an imaging modality for pediatric and pregnant patients with suspected UTS because of the long-term risks of ionizing radiation exposure [9–11]. Based on the principle of ALARA (As Low As Reasonably Achievable), US will become increasingly important as the first line of investigation for diagnosing UTS.

The clinical use of US for the treatment of kidney stones was first published in 1961 by Schlengel et al., who used intraoperative amplitude (A)-mode US for the localization of kidney stones [12]. Since then, continuous technological innovations in US, such as real-time imaging, have expanded its clinical use. In 1977, Cook et al. first reported the efficacy of intraoperative US using a brightness (B)-mode probe to localize kidney stones [13]. US is widely used for diagnosis, follow-up, percutaneous renal access, shockwave lithotripsy (SWL), ureteroscopic lithotripsy (URSL), and percutaneous nephrolithotomy (PCNL). Recent developments in US technology have focused on improving stone imaging and characterization, as well as enhancing the accuracy and efficiency of stone management. Such technological innovation has the potential to create a paradigm shift in the management of UTS. This review provides an overview of the application of US in the treatment of UTS, highlighting

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Table 1 Characteristics of imaging modalities (data from references 4–9)

Image modality	Sensitivity (%)	Specificity (%)	Radiation exposure (mSv)	Relative cost compared to that of KUB
US	45	88–94	None	5
NCCT	94–100	92–100	10.0	10
Low-dose CT	96.6	94.9	0.9–3.0	10
KUB	40–77	80–87	0.5–1.0	1
MRI	82	98	None	30

US ultrasound; *NCCT* noncontrast computed tomography; *KUB* abdominal plain radiography; *MRI* magnetic resonance imaging

its advantages, limitations, and current advancements in the field.

Ultrasound imaging as a modality for diagnosis of urinary tract stones

Features of ultrasound imaging

Accurate imaging allows for the identification and localization of UTS. Imaging modalities, such as US, NCCT, and KUB, can precisely visualize the presence, size, number, and location of stones within the urinary system. This information is essential for treatment planning and determining the appropriate approach for stone removal, leading to optimal patient outcomes. According to the American Urological Association (AUA) and European Association of Urology (EAU) guidelines, the treatment modality is selected based on the targeted stone size and location [14, 15]. It also assists in estimating the complexity of the procedure, expected surgical time, and potential risks associated with stone removal. The nomogram used to predict PCNL success includes stone burden, location, number, and presence of staghorns [16].

As shown in Table 1, NCCT provides the most accurate diagnosis with high sensitivity and specificity (94–100% and 92–100%, respectively) [4–6]. NCCT can determine stone density, inner structure, surrounding anatomy, and stone size and location, all of which affect the treatment modality [17]. However, its major drawback is high-dose radiation exposure. Several studies have demonstrated the risks associated with cumulative radiation exposure owing to repeated CT scans. Ferrandino et al. reported that 20% of patients received doses in excess of the 50 mSv occupational limit established by the International Commission on Radiological Protection for 1 year [18].

US has several advantages. The first is its portability. Advancements in miniaturization and wireless technology have led to the development of portable handheld US devices. These devices offer convenience and flexibility, allowing for US imaging at the point of care, including in resource-limited settings. Point-of-care ultrasound (POCUS) is the standard practice performed by a physician at the bedside and considered to be an effective alternative to NCCT as an initial imaging modality for the diagnosis of an acute stone event in the emergency department [19]. Smith-Bindman et al. conducted a large multicenter, randomized clinical trial (RCT) to evaluate the sensitivity and specificity of POCUS compared with NCCT. According to the study, POCUS was associated with lower radiation exposure than NCCT (10.1 ± 14.1 mSv vs 17.2 ± 13.4 mSv; $p < 0.001$), with equivalent diagnostic accuracy in the emergency department [20].

The second advantage of US is its noninvasiveness. US is a noninvasive imaging modality that does not involve ionizing radiation, making it a safe option for initial evaluation. Therefore, US is widely used in various patient populations, including children and pregnant women [9–11]. In pediatric patients, US is the primary imaging technique that has high sensitivity and specificity (70% and 100%, respectively), with a 96% positive predictive value and 62% negative predictive value [11]. On the other hand, the sensitivity of US to detect UTS during pregnancy is relatively low, ranging from 34 to 80% [21, 22]. A definitive diagnosis may be difficult because of the patient's body habitus and fetal position. In addition, physiologic changes due to mechanical compression by the enlarged uterus and the effect of progesterone [23] may make it difficult to distinguish between physiologic hydroureter and abnormal findings in the presence of UTS [22]. However, given the serious concern of radiation risk, the AUA and EAU guidelines recommend US as the preferred modality, followed by low-dose CT [14, 15].

The third advantage is its real-time imaging capabilities. US provides real-time imaging for dynamic assessment of stones and their movement within the urinary tract. This feature enables immediate assessment of stone mobility, which may influence treatment options, planning, and monitoring during the examination itself.

Technological innovation of ultrasound in the diagnosis of urinary tract stones

On US, UTS has been identified on grayscale B-mode US as a hyperechoic signal with a hypoechoic shadow called an acoustic shadow (Fig. 1). However, compared to NCCT, inferior sensitivity and limited specificity are critical issues for the detection of UTS (Table 1), because image accuracy depends on the performance of the equipment, patient-related factors (age, visceral fat, and bone), and operator skills. Occasionally, the impaired acoustic shadowing of the UTS may make it difficult to achieve adequate detection. This is caused by the acoustic impedance of the surrounding tissues or an improper balance between the focal distance and transducer power [24]. Moreover, US has limitations in detecting smaller or non-opaque stones, especially those less than a few millimeters in size. Because the kidney has many vasculatures and collecting ducts, B-mode US cannot distinguish UTS from the surrounding organs [25].

To overcome this drawback, technological advances in US equipment have made it necessary to identify UTS. Twinkling Doppler ultrasound (TDU) is a promising alternative imaging modality to NCCT. Twinkling artifacts refer to specific color Doppler and power Doppler signals (Fig. 2). It is commonly observed around highly reflective surfaces such as kidney stones, bones, or certain metallic objects. This occurs because of the interaction of US waves with small reflective structures or rough surfaces, causing a rapid modulation of the Doppler signal and resulting in alternating colors, typically red and blue, or a rapid color change between different shades [26, 27]. Abdel-Gawad et al. conducted a large-scale prospective study to evaluate the efficacy of TDU for stone detection in an acute setting [28]. In this report, the twinkling sign could be observed in 97.1% of patients with ureteral stones, with an associated 97.2% sensitivity and 99% specificity. Similar results could be seen for small stones with high sensitivity (99.12%), specificity (90.91%), and positive predictive values (99.12%) [29]. Although TDU has some issues with low sensitivity (40%) and a high false-positive rate (60%) in patients with

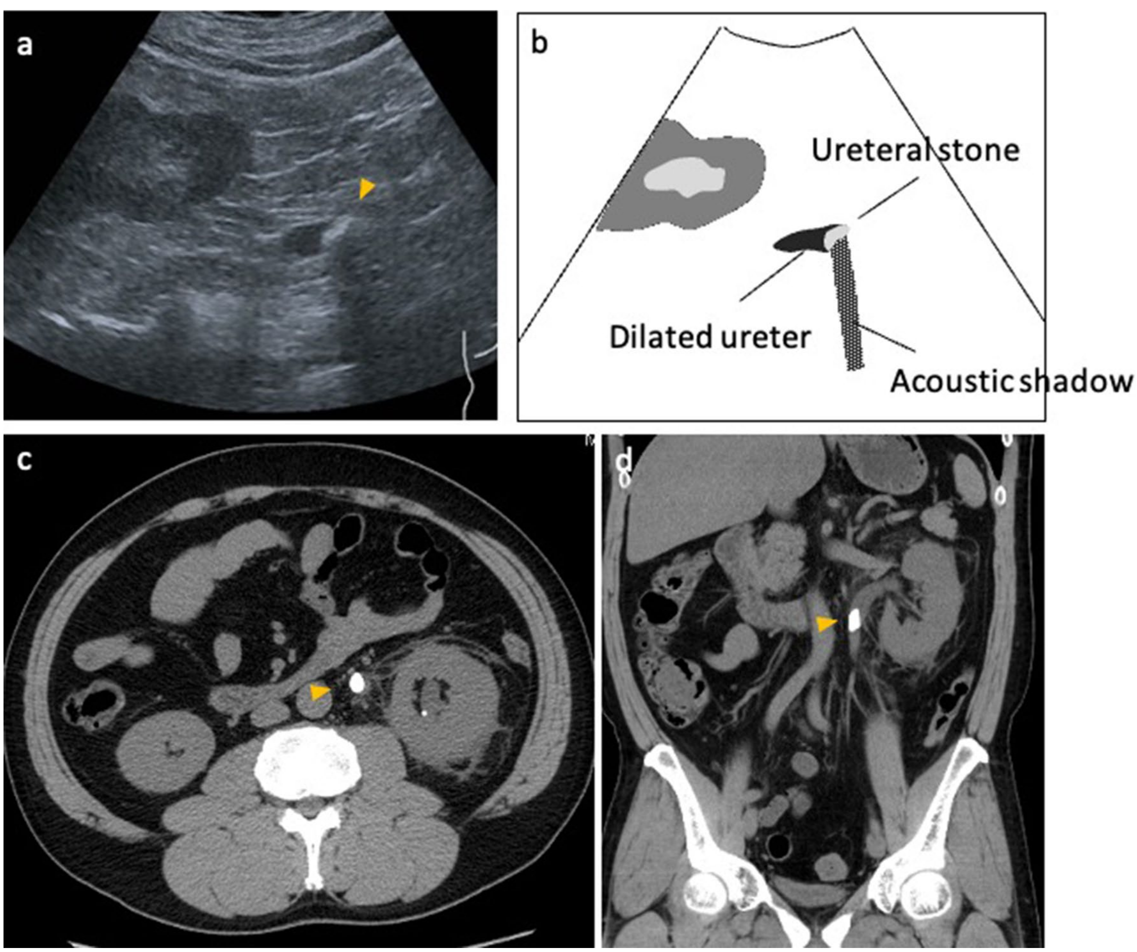

Fig. 1 Images of left ureteral stone. **a** B-mode ultrasound image showing a hyperechoic signal with a hypoechoic shadow, called an acoustic shadow. **b** Sham ultrasound image, **c** transverse plane NCCT, and **d** coronal plane NCCT. The yellow arrow indicates ureteral stone. *NCCT* noncontrast computed tomography

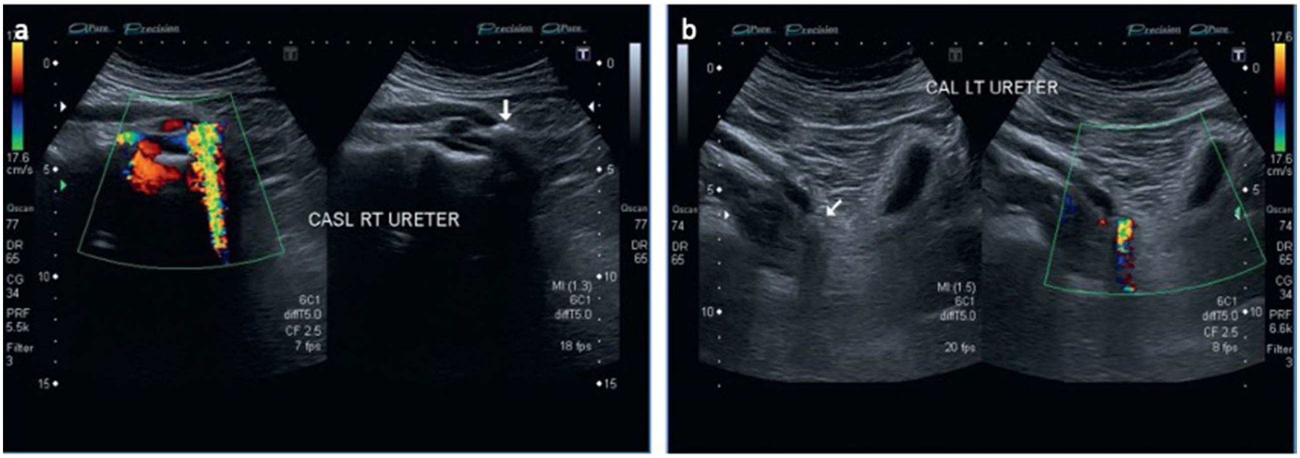

Fig. 2 Twinkling signal of ureteral stones. **a** Proximal ureteral stones. **b** Pelvic ureteral stones. White arrows indicate stones detected using B-mode ultrasonography. Source: Reproduced from [32]

unknown urolithiasis [30], with further developments, TDU might provide imaging quality to compete with NCCT in the future.

Another issue with US is its poor accuracy in measuring stone size. Sternberg et al. reported that US mismeasured renal stone size with an average overestimation of 2.2 mm for stones < 5 mm (mean, 3.3 mm) [31]. Stone size estimation helps to determine the appropriate treatment modality and predicts the possibility of spontaneous passage. Therefore, stone size strongly affects patient decision-making. Ganesan et al. reported in a retrospective study that due to the overestimation of stone size on US, 22% of patients could be inappropriately counselled for clinical decision-making [32].

The discrepancy in stone measurements may be due to patient and equipment factors. Ray et al. reported that measurement errors were associated with skin-to-stone distance, but not with body mass index or stone location [33]. Another report showed that this discordance in stone measurement might increase secondarily with greater depth and gain in commercial equipment [34, 35]. On the other hand, acoustic shadows are generally unaffected by the system setting and US modality. Dunmire et al. demonstrated that accuracy of stone size could be improved by measuring the width of the posterior acoustic shadow instead of stone width on US (Fig. 3), with the average overestimation of stone size being less than 0.5 mm regardless of depth or imaging method modality [35]. Since absence of a posterior acoustic shadow was reported to be a reliable indicator for stones ≤ 4 or 5 mm [35, 36], this technique might be effective for predicting the possibility of spontaneous passage.

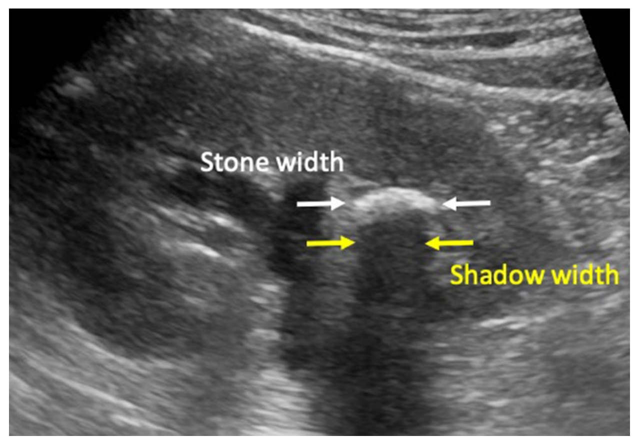

Fig. 3 Stone width and shadow width measurements

Clinical use of ultrasound imaging for treatment planning

Assessment of hydronephrosis

US is valuable for assessing obstruction and associated hydronephrosis. In adult patients, the degree of hydronephrosis on US is generally diagnosed using the Ellenborgen classification [37] (Fig. 4). In patients with renal colic in the ED, the presence of hydronephrosis on POCUS strongly suggests a large UTS (> 5 mm) [38].

Hydronephrosis is a predictive factor for impacted stones. We previously reported that the independent risk factors for stone adhesion to the ureteral mucosa were severe hydronephrosis (grade 2) and prolonged duration until surgery [39]. Ureteroscopic lithotripsy (URSL) is considered a better option than shock wave lithotripsy

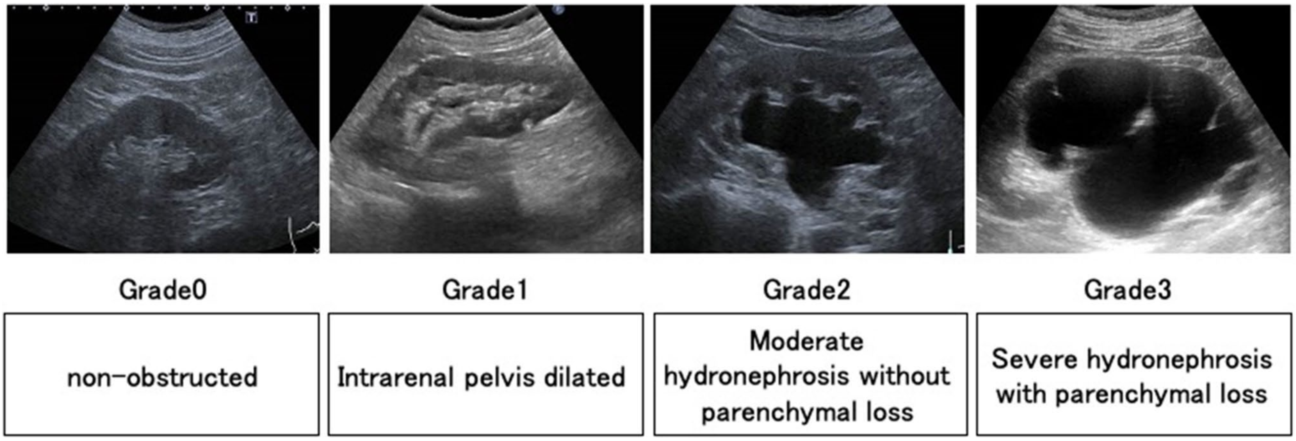

Fig. 4 Hydronephrosis according to the Ellenborgen classification

(SWL) for the treatment of impacted stones [40, 41]. However, even when using flexible ureteroscopy, URSL for impacted stones showed a lower SFR and more intraoperative complications than those for non-impacted stones [40, 42]. In cases of suspected impacted stones, percutaneous antegrade removal and preoperative percutaneous nephrostomy are considered in the treatment planning [14, 43].

Preoperative assessment of calculi and surrounding organs for percutaneous nephrolithotomy

US can generate images in multiple planes, thereby enabling a comprehensive evaluation of the urinary system. It contributes to the accurate diagnosis of stone size, location, and number, as well as real-time visualization of the kidneys, ureters, bladder, and surrounding structures.

Surgeons must consider the optimal treatment strategy before performing PCNL, including the surgical positions and percutaneous access points. Surgical positions commonly used in PCNL include the prone and oblique positions. However, discussions regarding which position is more suitable for PCNL are ongoing [44, 45]. The difficulty of percutaneous renal access also varies according to position. As the lower kidney may be displaced medially and ventrally in the oblique position owing to gravity [46], even if punctured from the same point, the pass-through line will be different for each surgical position (Fig. 5).

The success of PCNL depends on the proper choice of renal calyceal approach. Direct access to the calyx, where most of the calculi are located, is considered ideal. However, visceral organs, including the enlarged liver, spleen, and retrorenal colon, may interfere with the puncture. The superior calyceal approach is anatomically ideal for treating staghorn calculi because of its easy accessibility to many calyces [47, 48]. However, thoracic complications are more common with superior calyceal puncture. Munver et al. [47] reported

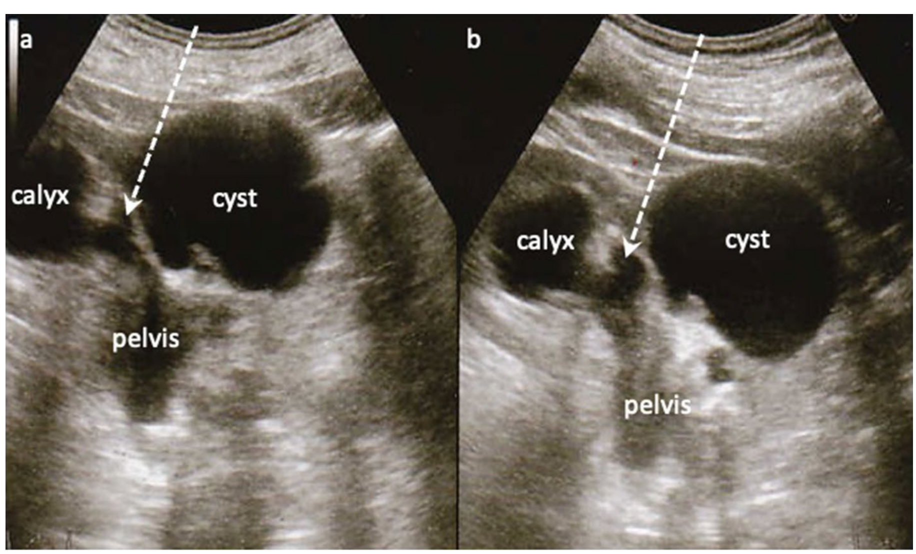

Fig. 5 Ultrasound image in the prone (**a**) and oblique (**b**) positions; the white dotted arrow indicates the puncture line to the target calyx. In the prone position, the puncture line passes through the cyst (**a**); on the other hand, it passes through near the cyst and reaches the target calix in the oblique position (**b**)

that the risk of thoracic complications with supra-11th-rib puncture (23.1%) was 16 times higher than with supra-12th-rib puncture (1.4%). Preoperative check-ups using US in a position similar to that used during surgery may be required to prevent visceral and thoracic injuries.

Clinical use of ultrasound in the treatment of kidney stones

Real-time monitoring during shock wave lithotripsy

SWL is a safe and noninvasive treatment for small calculi; however, the success rate after SWL is relatively low compared to that after URSL [49, 50]. One reason for the low success rate of SWL may be that shock waves could be out of focus due to respiratory motion misalignment and stone migration, resulting in a decrease in the crushing effect [51]. Sorensen et al. reported that 40% of shock waves were misfocused on the stone inaccurately, and these shock waves led to damage to the renal parenchyma and adjacent organs [51]. Generally, stone location is monitored using X-ray imaging; however, excessive monitoring of the respiratory tract leads to a risk of excess radiation exposure.

US is used to overcome these drawbacks. US provides real-time monitoring, facilitates precise targeting of the stone, and allows immediate assessment of treatment outcomes (Fig. 6). Some studies have demonstrated the superiority of US detection in clinical practice [52–54]. Chen et al. [52] documented that a US-based real-time tracking system increased the accuracy of stone targeting by reducing the number of shock waves. Isogai et al. [53] reported

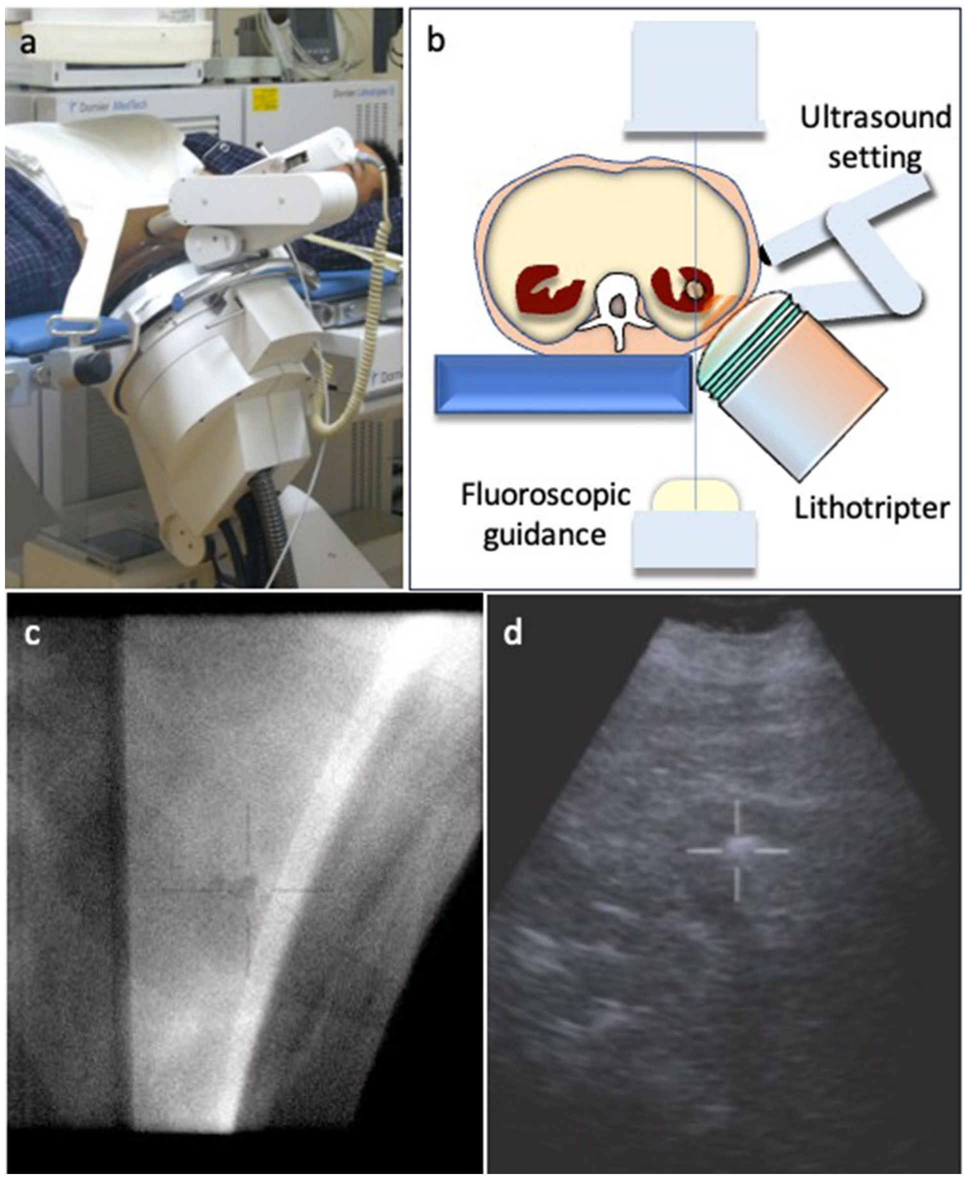

Fig. 6 Clinical image of ultrasound-guided SWL: **a** surgical scene of SWL, **b** schematic of ultrasound-guided SWL, **c** radiography image of targeted stone, and **d** real-time monitoring with ultrasound during SWL

similar results, revealing that the alternative use of US and X-rays led to favorable SWL success for kidney calculi. On the other hand, Besien et al. [54] reported equivalent success rates between US-guided and fluoroscopy-guided SWL, with the clinical benefit of no ionizing radiation in US-guided SWL. US has limited direct therapeutic applications in SWL; however, advances in US technology may change the current trends in stone treatment, shifting away from SWL to URSL.

Ultrasonic propulsion

Shock waves using SWL can efficiently disintegrate calculi; however, the fragments must be passively excreted. As many as 85% of patients had residual fragments on KUB at the time of discharge [55], indicating that fragmented stones could not be expelled immediately. This is especially important for fragments located at the lower pole, where the pelvicalyceal anatomy is unfavorable for spontaneous clearance [56]. Some investigators have reported that the infundibulopelvic angle, width, and length in the lower pole anatomy may influence stone passage after SWL [57, 58].

Ultrasonic propulsion (UP) was developed to overcome this issue and was first reported in 2010 [59]. UP is an application of acoustic tractor-beam technology that uses a short burst of focused US energy to reposition renal calculi [59–62]. In an in vivo study using eight female pigs and artificial calculi of 2–8 mm in size, transcutaneous UP appeared to be safe and efficient. Moreover, 65% of calculi were successfully relocated from the calyces to renal pelvis, ureteropelvic junction, or ureter without histological evidence of renal parenchymal damage [62]. In humans, investigators have shown that UP can facilitate the spontaneous passage of fragments by pushing low-pole stones toward the pelvis. Harper et al. [60] reported in a Food and Drug Administration-approved feasibility study that 65% of calculi showed some extent of migration, whereas 30% were successfully displaced more than 3 mm toward another location (Fig. 7).

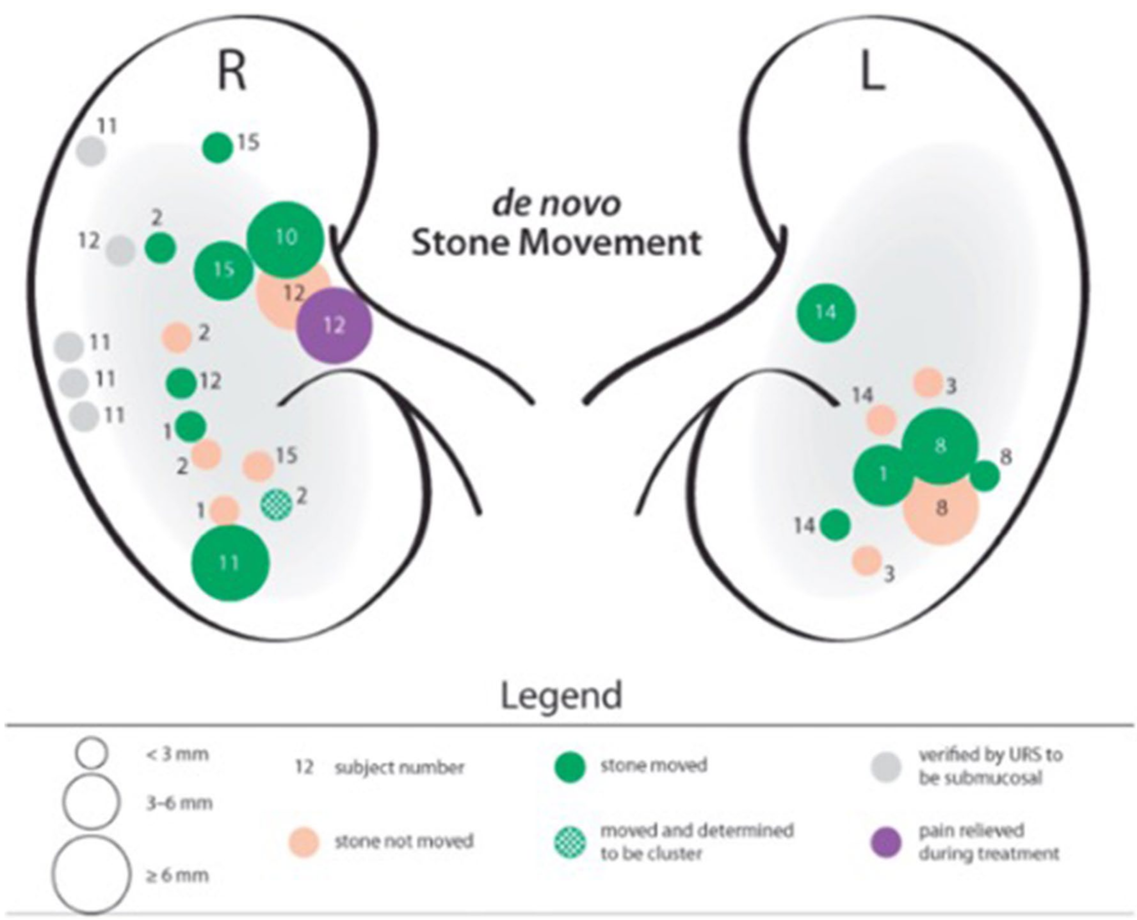

Fig. 7 Summary of the results of a human clinical trial of ultrasonic propulsion following lithotripsy. Green represents stone movement. The arrows indicate participants who reported the passage of fragments. The numbers next to each target indicate the number of participants. Circles of different sizes represent target stone sizes. The grids represent the target identified as a single large stone on imaging, but were determined to be a cluster of small stones on ultrasonic propulsion. Adapted from [65]

Asymptomatic residual fragments less than 4 mm are referred to as "clinically insignificant residual fragments (CIRFs)"; however, many reports indicate its significance in contradiction to the term, because residual fragments after SWL have the potential risk of stone growth or recurrence requiring repeat procedures [63, 64]. Despite the technological innovation of the laser system in URSL, residual fragments after laser dusting have a similar risk of reintervention [65]. If small fragments can be passively excluded before growth, the risk of reintervention might decrease. Therefore, this technology may be established and widely used in the future as an adjunct treatment for lithotripsy.

Ultrasonic stone fragmentation: burst wave lithotripsy

Burst wave lithotripsy (BWL) is an emerging transcutaneous technology used to fragment UTS [66–68]. BWL utilizes real-time US imaging to precisely target and focus bursts of US energy on the stone. Accurate targeting helps minimize the impact on the surrounding organs and reduces the risk of damage. Furthermore, compared to SWL, BWL involves low-amplitude bursts of US delivered at relatively higher frequencies [66], which might result in a low risk of perioperative complications.

There has been a stepwise progression of development with some human clinical trials conducted to date to evaluate the efficacy of BWL. Maxwell et al. [66] reported in an initial in vitro study that broadly focused US bursts break artificial calculi by producing fractures. Preliminary porcine studies have provided safety evidence for this technology [67]. In a human study, Harper et al. [68] documented that 52% of stones were fragmented partially and 39% were fragmented completely within 10 min without severe complications.

Furthermore, recent studies examined the combined efficacy of UP and BWL in fragmenting UTS [60, 69]. An in vitro study revealed that the integration of UP and BWL technology accelerated stone fragmentation owing to the dispersion of fragments from the targeted stone with UP. In a human clinical study, Hall et al. [69] demonstrated that the combined use of UP and BWL without anesthesia provided an efficient and safe treatment to relieve pain and facilitate stone passage by pushing and breaking ureteral stones. In the emergency department or outpatient clinic, noninvasive immediate lithotripsy and active stone expulsion therapy are ideally required to relieve pain and anxiety, and the clinical application of the BWL plus UP combination may open up an entirely new paradigm for noninvasive stone treatment at the point of care.

Ultrasound-guided renal access during percutaneous nephrolithotomy and endoscopic combined intra-renal surgery

PCNL is a conventional treatment that removes stone fragments through the large percutaneous tract. Endoscopic combined intra-renal surgery (ECIRS) is a hybrid therapy that combines PCNL with retrograde intra-renal surgery. These are standard procedures for large renal calculi that can provide higher stone clearance than SWL and URSL [70]. However, severe complications associated with bleeding occur frequently. A systematic review of approximately 12,000 patients revealed that the incidence of transfusion during PCNL was 7% [71]. As bleeding usually results from injury to major renal vessels, such as the interlobar arteries, during renal puncture and tract creation [72], accurate renal access is required to mitigate bleeding-related complications.

Renal access techniques include fluoroscopy- and US-guided punctures. Fluoroscopy-guided puncture has been the preferred US imaging modality since it was first described by Wichham in 1981 [73]. Fluoroscopic guidance can accurately identify the calyx to be punctured; however, it has several disadvantages, including the inability to clearly identify the surrounding organs in real time, limited visualization of vascularity, lack of depth perception, and radiation exposure. In particular, the high radiation exposure during fluoroscopy has become a great concern for surgeons, medical staff, and patients. Considering the ALARA principle, alternative strategies for reducing radiation exposure from fluoroscopy during PCNL may be required by urologists.

US-guided renal access during PCNL was first described in 1999 by Desai [74] in pediatric cases and has since become more widespread. Whether fluoroscopy or US guidance is more suitable for renal access remains unclear [75, 76]. Agarwal et al. [75] reported that US-guided renal access showed higher accuracy, resulting in fewer attempts for successful renal puncture and a lower duration of radiation exposure than fluoroscopy-guided renal access. On the other hand, Corrales et al. [76] demonstrated in their review article that US and fluoroscopic guidance are equally safe and effective for experienced surgeons. US guidance generally eliminates radiation exposure to the surgeon, providing real-time visualization of the renal and suprarenal tissues lying between the skin and the kidney. However, maintaining clear visualization is sometimes difficult because of excessive bowel gas, patient factors such as a high body mass index, anatomical complexity, and the influence of the surgeon's skill on image quality. Some reports have revealed that the learning curve until effective US guidance in PCNL might be steep and require 20–60 cases [77, 78]. Basic US knowledge and training in US techniques for stone surgery are essential for ongoing proficiency.

Two types of US transducers, the convex probe (CVP) and micro-CVP, can be used for renal access (Fig. 8a, b). A CVP is designed to provide a wider field of view and deeper penetration, allowing clear visualization in obese patients, while a micro-CVP is smaller and has a flatter curvature than a CVP, allowing for better maneuverability and imaging of shallow areas. Micro-CVP can be applied to the intercostal space in patients undergoing PCNL in the supine position. As surgeons do not have to lose the tip of the needle during renal access, the ultrasound probe is held by the non-dominant hand by pressing firmly against the skin to fix it in place, and the needle is slowly advanced by the dominant hand while maintaining live imaging (Fig. 8c).

Wideband Doppler ultrasound

US guidance offers another advantage for assessing blood flow using color Doppler imaging. Generally, a percutaneous puncture ideally heads to the fornix of the target calyx through a relatively avascular zone called Brodel's bloodless line. However, it is difficult to identify the running renal blood vessels using fluoroscopy or B-mode US, compared with color Doppler US [79]. Lu et al. demonstrated that color Doppler US provides real-time detection and avoids renal blood vessels, resulting in a decreased incidence of bleeding complications [80]. Tzeng et al. conducted an RCT and reported similar results [79]. However, due to the low resolution of images on conventional color

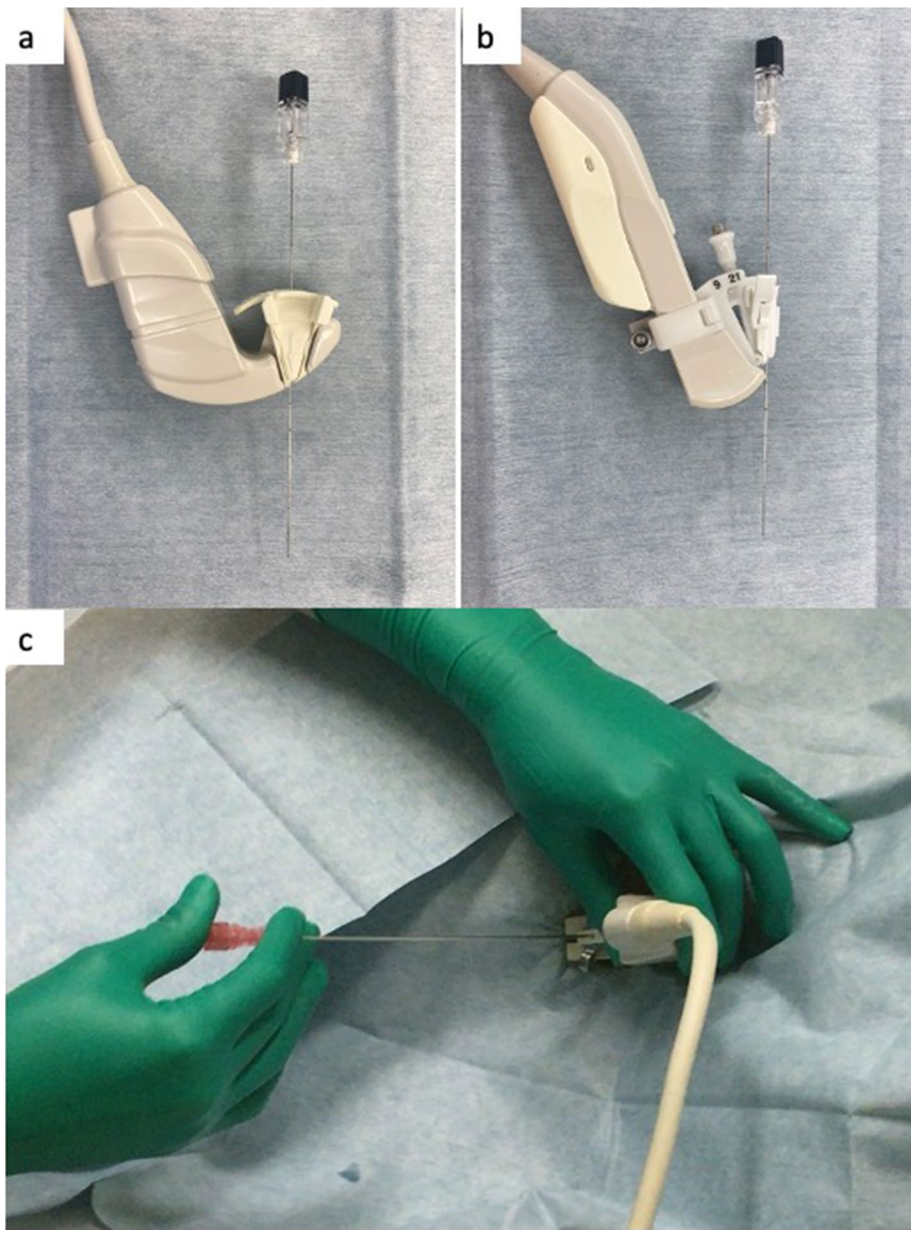

Fig. 8 Images of a transducer commonly used in PCNL and an example of intraoperative ultrasound used for renal puncture. **a** Convex probe, **b** micro-convex probe, **c** non-dominant hand holding the ultrasound probe and pressing firmly against the skin to fix it in place. The needle was slowly advanced while maintaining live imaging

or power Doppler US, visualized blood vessels appear as a color overflowing beyond the far wall of a superficial vessel, a phenomenon called "blooming appearance" [81] (Fig. 9a, b). This makes it difficult for surgeons to accurately confirm a bloodless line. However, recent technological innovations such as wideband Doppler modes have overcome this limitation. Wideband Doppler US refers to a high-resolution blood flow display mode that provides clear visualization of peripheral blood vessels by suppressing blooming (Fig. 9c). In a preliminary report of 41 patients undergoing mini-ECIRS, Inoue et al. reported that wideband Doppler US resulted in low incidence of bleeding complications, showing the average hemoglobin drop was 0.54 g/dl [82]. The renal access monitoring twin-view image (Fig. 9d), which shows both wideband Doppler and B-mode US simultaneously on the screen, may represent a promising new technology for use in PCNL and ECIRS.

Real-time virtual sonography technology

Because US is often regarded as providing less objective information than CT, the quality and interpretation of US findings may be influenced by the surgeon's experience, skill, and technique. Real-time virtual sonography (RVS) was developed to compensate for this weak point of US. RVS is an advanced imaging technique that synchronizes real-time US with CT or magnetic resonance imaging [83, 84]. It allows the overlay of additional information or images onto US images in real time, enhancing the visualization and interpretation of US examinations. We previously applied this technology for percutaneous renal access during ECIRS (Fig. 10) and reported its efficacy compared to using B-mode US, resulting in fewer puncture attempts (1.6 vs 3.4 times, respectively; $p=0.001$) and lower postoperative hemoglobin decrease (0.93 vs 1.39 g/dL, respectively; $p=0.04$), while maintaining a similar stone-free rate [85]. This technology has the potential to improve renal access accuracy and

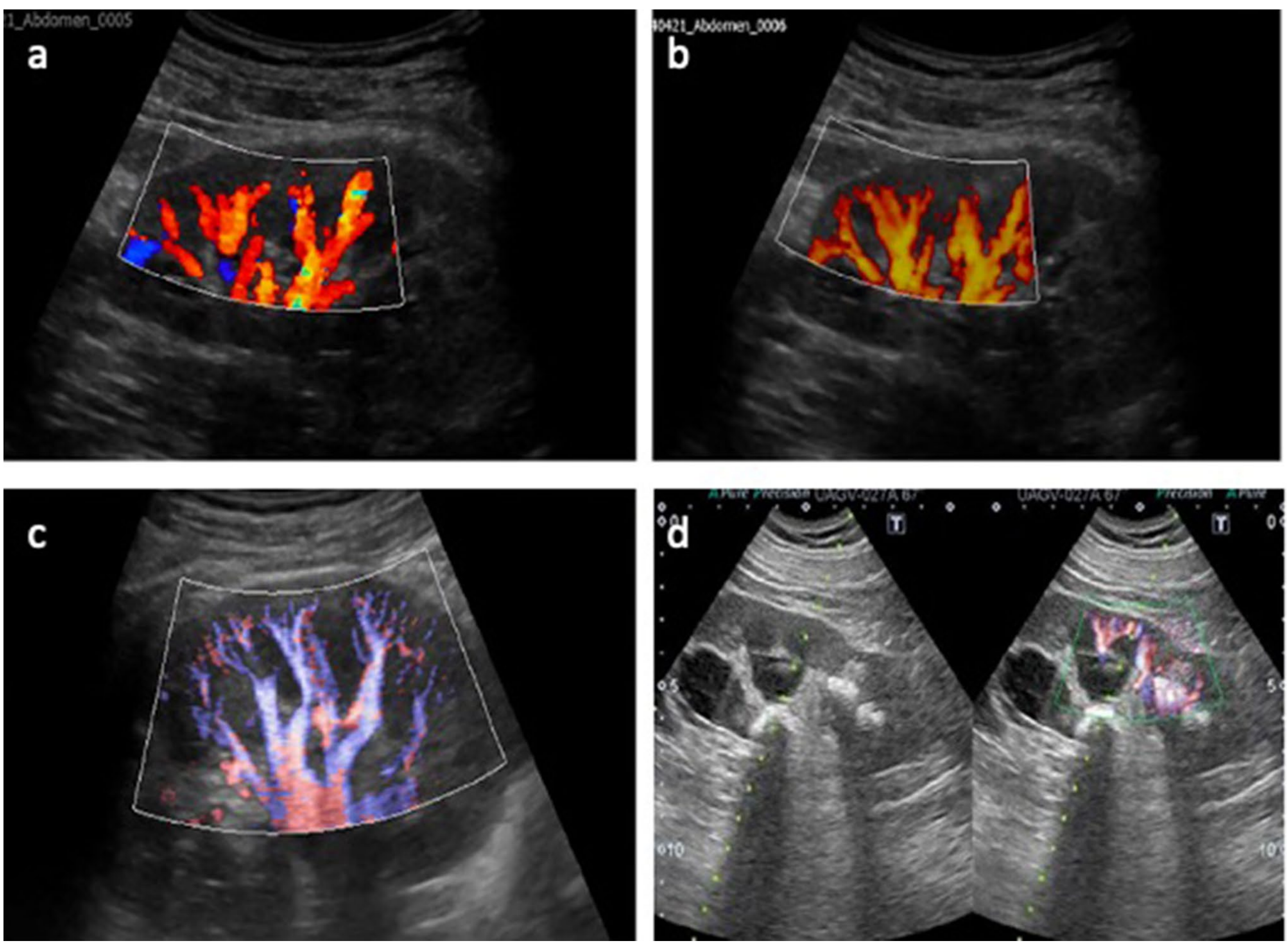

Fig. 9 Doppler ultrasound images. **a** Color Doppler mode. **b** Power Doppler mode. **c** Wideband Doppler mode. **d** Twin-view images combined with B-mode ultrasound and wideband Doppler modes. Source: Reproduced from [84]

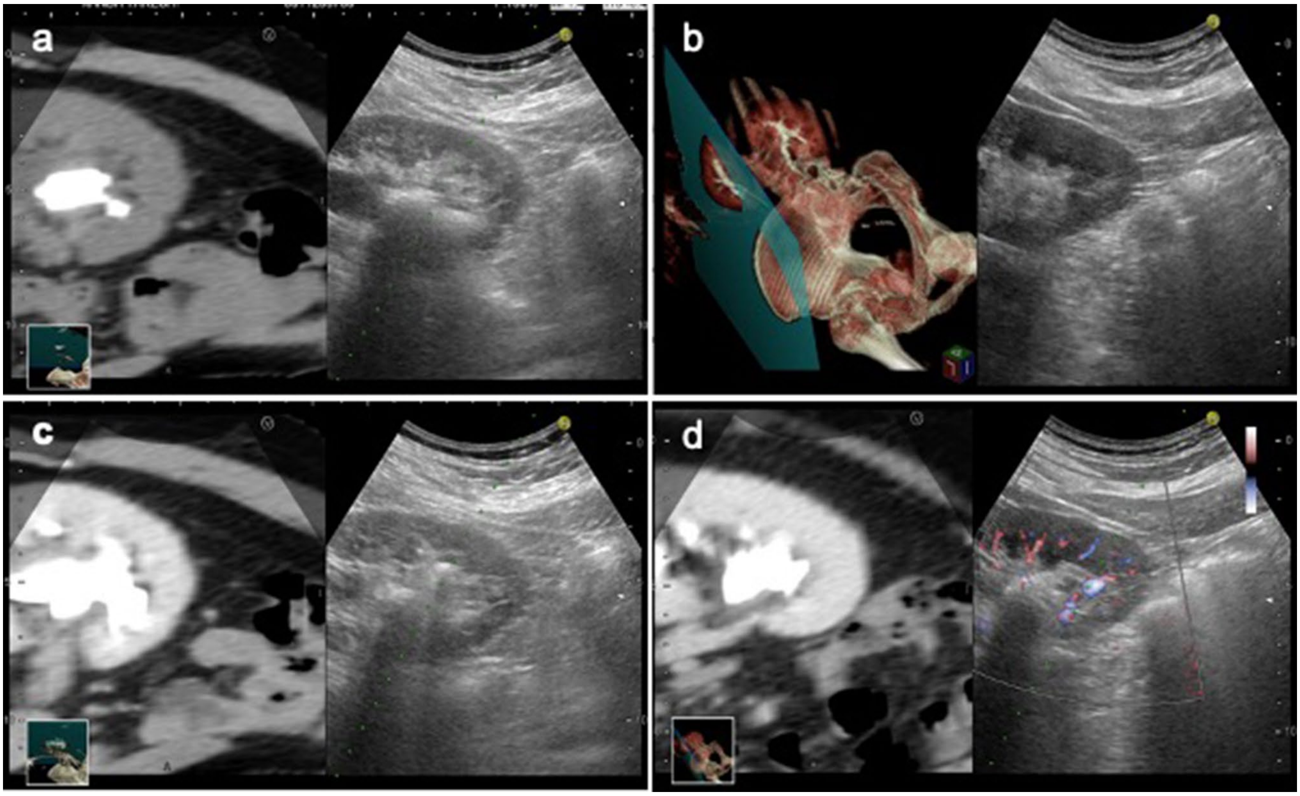

Fig. 10 Screen display of synchronization provided by the real-time virtual sonography system of the reconstructed CT image with the real-time intraoperative US image. **a** Plain CT and B-mode sonography images. **b** Reconstructed three-dimensional CT image is synchronized with a B-mode sonogram. **c** Enhanced CT image synchronized to the B-mode sonogram. **d** Enhanced CT images obtained in combination with wideband Doppler US mode. Adapted from [85]

become a learning tool for developing skills among novice operators.

Follow-up and surveillance

Symptomatic recurrence of UTS that results in clinical care was reported to be approximately 20% after 5 years after first stone event [86, 87]. On the other hand, D'Costa et al. [87] reported that the recurrence rate was 67% in a 5 year follow-up study, with a more comprehensive definition of recurrence, including symptomatic episodes and asymptomatic radiographic changes. As radiographic changes are associated with symptomatic recurrence in clinical care, appropriate radiographic follow-up should be highlighted when managing stone recurrence. The EAU Guidelines Urolithiasis Panel in 2022 recommended closer imaging at 6 and 12 months and annually thereafter in cases with diagnosed urinary metabolic abnormalities or with CIRFs [88].

The imaging modalities available for follow-up included CT, low-dose CT, US, and KUB. However, image accuracy and the risk of radiation exposure are incompatible (Table 1), and physicians must tailor the type of imaging modality and frequency of imaging to the severity of the risk of stone recurrence. NCCT is the gold standard modality for the follow-up of UTS; however, low-dose CT has become an alternative modality with concerns over radiation exposure. Low-dose CT has been defined as < 3 mSv of ionizing radiation, with an estimated sensitivity of 96.6% and specificity 94.9% [7]. The radiation risk can be reduced with the use of low-dose CT [8, 89, 90]; however, it has been shown to have low sensitivity in obese patients or for ureteral stones < 3 mm [89]. Another alternative to NCCT or low-dose CT for follow up-imaging is the combination of US and KUB, which can achieve good rates of accuracy (95%), sensitivity (96%), and specificity (91%) [91]. Fahmy et al. reported the cumulative radiation exposure during a 2-year follow-up period, in which effective radiation significantly decreased from 29.29 in the first year to 8.04 mSv in the second year of follow-up of UTS due to higher combination use of US [92]. Considering the concerns and increased cost of NCCT, the combination of US and KUB may be a reasonable plan for follow-up imaging, except in cases of symptomatic recurrence. With no consensus guidelines for this clinical protocol in patients with a history of UTS, future research is required to determine the optimal imaging surveillance strategy.

Conclusions

The continued evolution of US technology over the past 70 years has yielded superior images and small CVP, focusing on bursts of energy, and seamless integration with existing percutaneous navigation, resulting in an excellent diagnostic and therapeutic modality.

The optimization of US features such as the twinkling signal and posterior acoustic shadow may provide adequate detection and sizing of UTS. The clinical application of ultrasonic propulsion or BWL may open new avenues for noninvasive stone treatment. Furthermore, considering the ALARA principle, US has grown in importance as an alternative strategy for reducing radiation exposure to NCCT and fluoroscopy. Further technological innovation in US has the potential to create a paradigm shift in the management of UTS.

Data availability Data sharing is not applicable to this article.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

Ethical approval All procedures performed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and the Helsinki Declaration of 1964 and later versions. Informed consent was obtained from all patients for inclusion in the study.

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