Ultrasound Guided Access

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Abstract Percutaneous nephrolithotomy is widely performed for treatment of large stones or stone burden. Historically, renal access is considered the most challenging step of the procedure with the greatest impact on the success of the case. Renal access is typically obtained under fluoroscopy by practicing urologists. There are however many disadvantages to fluoroscopic guidance, most prominently being the difficulty of learning this skill and radiation exposure to the patient, surgeon, and operating room staff. Advances in ultrasound technology have increased popularity of its use for renal access due to its many advantages including shortened learning curve, reduction or complete elimination of any ionizing radiation exposure, real time imaging of the renal anatomy and surrounding visceral organs, and improved operating room and surgeon ergonomics. Herein we review the history of ultrasonography and ultrasound-guided renal access in urology as well as the features of this modality and how it compared to fluoroscopy. In addition, we provide a practical overview of ultrasound fundamentals and technology and a step-by-step guide to performing ultrasound-guided renal access.

Keywords Nephrolithiasis · Nephrolithotomy · Percutaneous · Interventional ultrasonography · Radiation · Ionizing · Radiation exposure · Fluoroscopy · Learning curve

Abbreviations

CT	Computed tomography
ECIRS	Endoscopic combined intrarenal surgery
ESWL	Extracorporeal shockwave lithotripsy

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OR Operating room
PCNL Percutaneous nephrolithotomy
TGC Time-gain compensation

1 Introduction

Percutaneous nephrolithotomy (PCNL) is the recommended first line procedure for renal stones ≥ 20 mm, including staghorn calculi, due to its superior stone free rate and its limited morbidity when compared to extracorporeal shockwave lithotripsy (ESWL) or ureteroscopy (Turk et al. 2016; Assimos et al. 2016). The critical steps of a PCNL include obtaining renal access, dilation, lithotripsy and drainage. Obtaining renal access, the first step of this procedure, poses the most technical challenge to urologists, as demonstrated by survey data showing that only 11% of practicing urologists who routinely perform PCNL obtain their own access (Bird et al. 2003).

Fluoroscopy has been the preferred imaging modality for percutaneous access amongst urologists and is the most commonly used technique for PCNL access (Andonian et al. 2013). A Clinical Research Office of the Endourological Society report showed 86% of patients had fluoroscopic access versus just 14% with ultrasound guidance. Despite its popularity, fluoroscopy has many associated disadvantages including inability to identify surrounding organs or vasculature around the kidney, difficulty with assessing posterior calices and radiation exposure to the patient, surgeon, and operating room (OR) staff.

Considering these limitations to fluoroscopy, ultrasound technology has risen as a promising alternative, offering real time renal imaging with the potential to decrease the technical barriers to widespread use and improve patient outcomes. The objectives of this chapter are to review the evolution of ultrasound technology in urology, the benefits and learning curve of ultrasound guided access and the fundamentals of ultrasonography before describing a step-by-step approach to renal access.

2 History of Ultrasound Guided Access

In the 1950s, ultrasound technology was first applied in the medical field with early experiments used modified radar and sonar equipment in medical imaging (Wild 1950). The first use of ultrasound for nephrolithiasis was described in 1961 when Schlegel et al. reported on the use of intraoperative amplitude (A)-mode ultrasonography for renal stones. This was rudimentary however and the image generated was only a single spike representing a reflection from the stone (Schlegel et al. 1961). While these early images were crude and unusable for making medical diagnoses, they demonstrated the feasibility of applying this technology to medicine. It was not until the 1970s that innovations by Watanabe et al. and advancement of ultrasound technology made possible the first interpretable images of the prostate, bladder and kidney (Watanabe et al. 1976). At a time when most stones were identified by plain radiographs of the kidney, ureter and bladder or by intravenous pyeloureterograms, ultrasound imaging also showed promise in diagnosis of radiolucent matrix and uric acid stones (Pollack et al. 1978).

Subsequently in 1977, the first report of using intraoperative ultrasound to guide nephrolithotomy was published. Cook and Lytton used the brightness (B)-mode ultrasonography to localize a stones or stone fragments and access the collecting system (Cook and Lytton 1977). It was not until 1999 however that Desai and colleagues were the first to publish a large series of ultrasound-guided PCNLs with 45 procedures performed in pediatric patients (Desai et al. 1999). Next several randomized trials directly comparing ultrasound guided versus fluoroscopic PCNL were published demonstrating the safety and effectiveness of ultrasound guidance (Basiri et al. 2008; Karami et al. 2010; Agarwal et al. 2011; Jagtap et al. 2014).

3 Advantages of Ultrasound Guided Access

The advantages of ultrasound guided access include the reduction or complete elimination of any radiation exposure, real time imaging and improved ergonomics (Table 1). One in 11 people in the United States will suffer from a kidney stone over their lifetime, and 30% of these patients will develop a subsequent stone within 10 years (Turk et al. 2016; Assimos et al. 2016). Given the high recurrence of kidney stone disease, the cumulative exposure to radiation over a patient's lifetime from diagnostic imaging and treatment can be significant. For providers who routinely perform procedures to manage this disease, there is also a cumulative exposure to radiation which can lead to increased risk of cataracts, cancers, or other disease states that have been associated with radiation exposure for operators (Fulgham and Gilbert 2013). The decreased ionizing radiation exposure from utilizing ultrasound guidance can thus positively impact not only patients but providers as well. In populations especially vulnerable to the deleterious effects of ionizing radiation such as pediatric or pregnant patients, ultrasound is the preferred first line imaging modality for the diagnosis and treatment of kidney stones (Assimos et al. 2016).

The benefit of real time imaging of not only the kidney but also the surrounding viscera, pleura and vasculature allows the surgeon to minimize the risk of inadvertent injury during renal access (Andonian et al. 2013). In transplant and anomalous kidneys (ectopic, horseshoe) where the kidney is in an unfamiliar location, having the capability to identify surrounding organs in real time offers a distinct advantage. As no retrograde contrast is required to visualize the collecting system, ultrasound imaging can be utilized in cases even where retrograde access is not possible. Additionally, posterior calyces that are difficult to identify fluoroscopically are more straightforward to access using ultrasound guidance. Finally, examination of residual radiolucent stone fragments is not possible with fluoroscopy, but these fragments can be identified with ultrasonography.

Table 1 Advantages of ultrasound guided renal access

Radiation exposure
• Decreases or eliminates ionizing radiation exposure
• Visualization of radiolucent calculi
• Easy identification of posterior calyces
• Safer for use in the pediatric and pregnant populations
• Real time imaging
Real-time visualization of renal and stone configuration
• Visualization of surrounding visceral organs, pleura and vasculature, especially helpful in cases of transplant or anomalous kidneys
• Doppler flow imaging helps avoid vascular injury
Ergonomics
• Applicable to all patient positions
• Decreased operating room footprint
• Decreased physician and personnel fatigue and long-term orthopedic issues due to lack of lead aprons
• Lower cost of capital equipment
• Easier to teach and learn compared to fluoroscopic PCNL

Ultrasound guided access also offers advantages in ergonomics. This modality can be utilized for patients in a variety of positions and requires only minor adjustments to the OR set up or technique to obtain renal access compared to fluoroscopy. The smaller footprint of an ultrasound console as compared to a c-arm lends itself to use in tight-spaced ORs. Physicians and OR personnel also do not need to wear protective lead necessary for fluoroscopy use that can lead to orthopedic complaints and fatigue throughout the day.

4 Learning Curve

The steep learning curve for PCNL mastery is mostly related to achieving renal access. The importance of formal training in renal access was demonstrated in a survey that showed 92% of urologists trained in PCNL continued to perform PCNL in practice whereas only 33% of those untrained did ($p < 0.001$) (Lee et al. 2004). Furthermore, those trained in renal access performed a mean of 14 PCNLs per year versus 3.3 per year in the untrained. However only 27% of urologists trained in percutaneous access obtained their own access compared to 11% of those who were untrained ($p = 0.33$) highlighting again the difficultly with learning renal access. The major reported reasons included radiologists having better equipment or skills, access requiring extra time and surgeon comfort.

A critical review on renal access for PCNL recommended 24 PCNLs during residency to achieve basic proficiency, 60 to achieve competency and > 100 to reach excellence (Andonian et al. 2013). The studies this review was based on followed consecutive PCNL cases performed by novice surgeons or endourologists and found that operative/fluoroscopic time, renal access time, tract dilation time and complication rate improved over time and performance metrics approached that of expert surgeons within 60 to 100 cases (Allen et al. 2005; Tanriverdi et al. 2007). In transition from fluoroscopy to ultrasound guided PCNL access, one study reported the learning curve was as low as 20 cases for an experienced endourologist (Usawachintachit et al. 2016) Another study reported the learning curve for ultrasound guided access for a novice surgeon was 60 cases, similar to that of fluoroscopic PCNLs (Song et al. 2015). Overall, the learning curve for adopting ultrasound for renal access is shorter and more achievable by practicing urologists compared to fluoroscopy.

In obtaining ultrasound guided renal access, the urologist is faced with two technical challenges. First, one must be able to image the kidney and accurately interpret the displayed images. Second, one must be able to coordinate the needle and imaging hands when advancing the needle into the desired target. Early on in one's learning curve, failures may occur due to suboptimal imaging, misinterpretation of images or inaccurate needle placement. One consideration to improve the learning curve is to utilize a needle guide (Desai 2009). Needle guides fix the needle into a plane of imaging which can facilitate more accurate needle placement, especially when one is first starting to learn renal ultrasound, allowing the learner to focus on accuracy in imaging and reducing the need for accuracy of needle control. There are limitations however for needle guides in that the guides only allow for fixed angles of entry into the kidney. In addition, needle guide may limit one's ability to adjust to scenarios where a steeper or shallower trajectory to the skin is required to avoid bony structures. Ultimately, mastering both imaging and freehand needle control skills are important to applying ultrasound guidance for renal access.

5 Ultrasound Versus Fluoroscopy

Over the past decade, as PCNL technique and technology have progressed, ultrasound use has become more widespread. Given fluoroscopic guidance was heretofore the gold standard for access, randomized trials comparing this against fluoroscopic guidance were designed and published comparing them on several measures including time to puncture, radiation exposure, puncture attempts and complications.

The first randomized trial of fluoroscopy- versus ultrasound-guided access was published in 2008 and included 100 patients at a single center. The success rate for obtaining access was > 90% in either group with no differences in complications (Basiri et al. 2008). The ultrasound group had decreased radiation exposure and slightly longer access durations ($p < 0.01$). Another randomized trial of 60 patients in the flank position, 30 randomized to ultrasound guided access, showed similar operating and access times without any difference in complications or stone free rate

(Karami et al. 2010). In an additional randomized trial of 224 patients undergoing PCNL at a single center by a single provider, patients were randomized to fluoroscopic versus ultrasound guided access. Here the mean time to successful puncture was slower in the fluoroscopic group (3.2 min versus 1.8 min, $p < 0.01$), with increased radiation (28.6 s versus 14.4 s, $p < 0.01$) and with higher puncture attempts (3.3 versus 1.5, $p < 0.01$) and longer tract formation time with higher radiation exposure ($p < 0.01$) (Agarwal et al. 2011). There was no difference observed in complications.

While the aforementioned randomized trials all included experienced endourologists, there has been one trial that evaluated the trainee experience with ultrasound guidance. In a randomized trial of fluoroscopy versus ultrasound guided PCNL among trainees all with an experience of less < 25 PCNLs, there were no differences in operative time, post-operative complications, bleeding, analgesic requirement, length of stay or stone clearance (Jagtap et al. 2014). The authors noted however that while both methods of access were safe and effective, almost 20% of the ultrasound group required fluoroscopy as an adjunct for access due to lack of or mild hydronephrosis. This highlights an important point—while ultrasound and fluoroscopy have comparative different advantages and disadvantages, they are both excellent tools for facilitating renal access. The competent urologist should be familiar with both methods of access to be effective in all scenarios.

In most published trials, ultrasound guidance was used only in access and tract formation was performed under fluoroscopy, even if access was initially obtained using ultrasound. This is likely due to the level of provider comfort and familiarity with ultrasound imaging. This approach, however, only reduces and does not eliminate radiation exposure. Ultrasound-only PCNL, where ultrasound imaging is used to guide all portions of the case including tract dilation and placement of drainage tubes has been shown to be safe and efficient and of course completely avoids any radiation exposure (Yan et al. 2013). Applying ultrasound imaging guidance to renal tract dilation and drainage tube placement is outside the scope of this chapter, but achievable with a longer learning curve and stronger familiarity with the principles of excellent renal ultrasound imaging.

6 Ultrasound Guided Renal Access: Overview of Ultrasound Technology

Ultrasound guided renal access has been shown to provide safe and comparable access to fluoroscopically guided access with the advantages outlined above. Prior to our step-by-step description of ultrasound access, we recommend at least a superficial understanding of the basis of ultrasound technology to appreciate its strengths and limitations especially as it applies to imaging the kidney for renal access.

7 Fundamentals of Ultrasound Technology

Ultrasound waves are mechanical waves created by applying alternating electrical current to piezoelectric crystals housed in a transducer (Fulgham and Gilbert 2013). The piezoelectric effect (from Greek *piezein* meaning to squeeze or press) is the electric charge that accumulates in solid materials in response to mechanical stress (Katzir 2006). This alternating expansion and contraction of these crystals thus creates a mechanical wave that is transmitted via a coupling medium to the body. The waves produced are longitudinal, with particle motion in the same direction as the wave propagation. As the wave encounter tissue of different density and echogenic properties, they are reflected back towards the transducer with different characteristics depending on the tissue properties. In this way, the transducer works as both a receiver and transmitter of sound waves. The mechanical sound waves are then converted back into electrical energy and converted by the ultrasound machine into a displayed image.

8 Ultrasound Terminology

8.1 Ultrasound Modes

Gray-scale (Fig. 3A).

In gray scale imaging, a two-dimensional image is created where each pixel has a varying brightness. The image is created by measuring the time of travel for the soundwaves which determines the location of the pixel on the screen. The intensity on the other hand is reflected by the brightness of a given pixel. The image is typically refreshed at a rate of up to 40 frames per second giving the user a live image.

Doppler (Fig. 3B).

The doppler effect occurs when the frequency of sound waves are shifted after impacting a moving object based direction and velocity. Applied to medical imaging, color doppler ultrasound allows for evaluation of objects in motion in the human body such as blood flow. This is displayed with a color map, with greater velocities shown as brighter colors.

8.2 Transducers

Linear transducers are more commonly used for imaging superficial structures such as male genitalia and testes. Curved array transducers are more commonly used in abdominal imaging. This is because the curved probe allows for complete contact of the transducer with the skin after it is pressed onto the abdomen. In diagnostic renal ultrasonography, the ideal curved transducers are set to a frequency of 3.5 to 5.0 MHz. For special circumstances in renal imaging, a higher frequency transducer may be preferable. In pediatric patients, higher frequency transducers may be useful. Linear transducers of 6 to 10 MHz are utilized intraoperatively and laparoscopically for renal ultrasonography. The important principle guiding transducer selection to keep in mind is that higher frequency transducers offer greater detail and resolution of imaging while lower frequency transducers facilitate greater depth of penetration.

8.3 Contrast Agents

Nondilated systems, even with the use of retrograde saline or water injection, may be difficult to access due to poor collecting system visualization. To facilitate access, contrast agents containing gas microbubbles have been injected retrograde. Once struck by ultrasound waves, these bubbles oscillate and produce a return signal that can be more easily identified. One randomized trial demonstrated the use of contrast-enhanced ultrasound improves success rate for renal access while decreasing the number of access attempts and time to access in non-dilated collecting systems (Xia et al. 2021).

8.4 Echogenicity

Echogenicity refers to the capacity of a tissue or structure to reflect ultrasound waves compared to another structure. As echogenicity increases, so does the brightness of the target structure. An anechoic structure is one that reflect no sound waves and instead appears as black on the image. The most commonly encountered anechoic structures seen with genitourinary ultrasound imaging are fluid filled, including the bladder, blood vessels or collecting system, since fluid is generally anechoic (Fig. 1A). Hyperechoic structures are those who reflect more sound waves than surrounding structures and will appear bright on ultrasound imaging. This includes pleura, bones, and urinary stones (Fig. 2A). In contrast, hypoechoic structures reflect less than surrounding tissue and include subcutaneous fat and muscle (Fig. 1A). Notably some fat such as hilar fat or angiomyolipomas may be hyperechoic depending on the presence of connective tissue or other interfaces within the fat. Lastly isoechoic structures are those who reflect similar echoes. Typically, the liver, spleen and kidney are isoechoic.

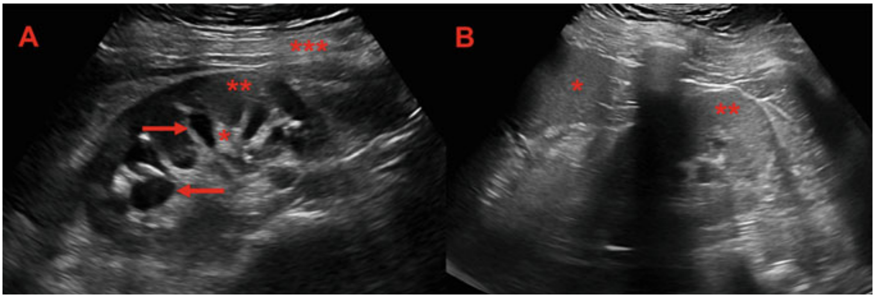

Fig. 1 Typical appearance of renal anatomy under ultrasound. A) Hypoechoic dilated collecting system denoted by arrows with subcutaneous fat (***), renal parenchyma (**) and sinus fat (*) also visible. B) Isoechoic spleen (*) visualized next to renal parenchyma (**)

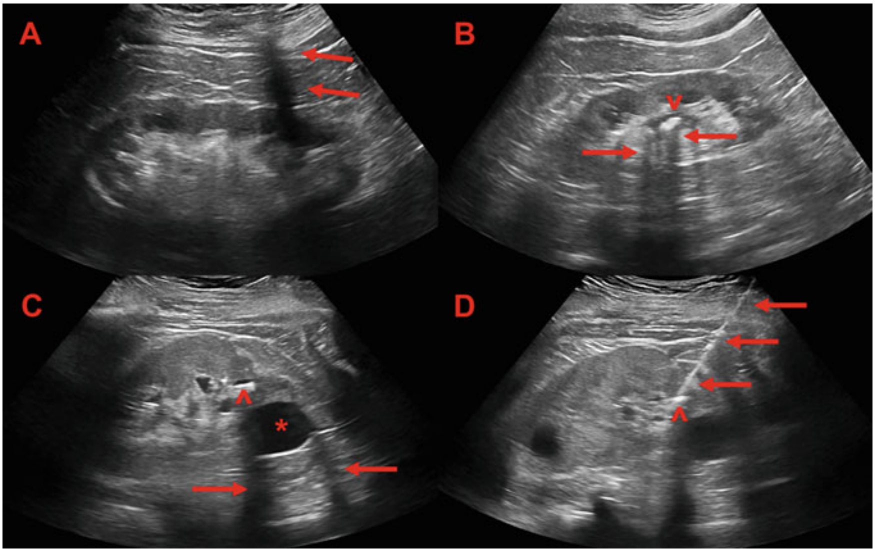

Fig. 2 Commonly encountered artifacts while performing ultrasound guided renal access. A) arrows denote rib shadowing due to acoustic shadowing B) post-acoustic shadowing denoted by arrows due to renal pelvis stone (v) C) Edging artifact denoted by arrows from rounded edges of a renal cyst (*) with peripherally located renal stone (^) with black rim denoting collecting system D) echogenic needle (denoted by arrows) traversing subcutaneous tissue and renal parenchyma, directly accessing a peripheral calyx containing a kidney stone (^)

8.5 Attenuation

Attenuation occurs when sound waves interact with tissues and fluid in the body resulting in a loss of kinetic energy (Fulgham and Gilbert 2013). Attenuation occurs via three major mechanisms: absorption, reflection and refraction. Absorption occurs

Fig. 3 Typical ultrasound machine setting controls including A) Gray scale mode, B) color doppler mode, C) frequency and depth, D) gain, E) time-gain compensation and F) field of view

when part of the kinetic energy of the sound wave is converted to heat after interacting with tissue. When a sound wave encounters an interface at an angle other than 90 degrees, refraction occurs which is when a portion of that sound wave is reflected while the other continues forward, leading to a loss of information. Finally, reflection occurs when sound waves interact with an interface between two unlike structures leading to scattering, especially if the interface is small or irregular, of the reflected wave. These interactions with tissue and interfaces within the body produce ultrasound artifacts that can interfere with accurate imaging.

8.6 Artifact

Ultrasound artifacts are commonly encountered during ultrasonography and may be due to scanning technique or intrinsic properties of the imaging modality. Understanding of ultrasound artifacts is important not only to improve image quality and avoid misdiagnosis but also some aid in the diagnosis of anatomy or pathology.

Acoustic shadowing occurs when there is a signal void behind a structure due to significant attenuation leading to loss of information distal to the interface. This occurs most often with solid structures, such as bone, where molecules are densely packed together. For the purposes of ultrasound guided renal access, the most commonly encountered shadowing is from the patient's ribs when attempting to visualize the kidney (Fig. 2A) or kidney stones within the collecting system (Fig. 2B). To avoid the former, the probe can be rotated on the body surface so that it is parallel to the ribs.

Edging artifact can be seen most often with rounded structures such as the upper or lower pole of the kidney, renal cyst walls, or testicles. This artifact occurs when sound waves impact a curved surface at a critical angle leading to refraction and loss of signal return to the transducer. Changing the angle of the ultrasound probe can help avoid this artifact.

The comet tail artifact occurs during gray scale ultrasonography due to reverberation of ultrasound signals between two closely spaced reflective surfaces. The bevel of an echogenic needle takes advantage of this artifact to give the tip of the needle more contrast compared to the surrounding tissue to make tracking the needle as it traverses to the target anatomy easier (Fig. 2D). Other foreign bodies may also cause this artifact such as catheter tips or surgical clips.

The twinkle artifact, also known as the color Doppler comet tail artifact, occurs in doppler mode due to reflection of sound waves from a strongly reflecting structure. This leads to machine noise and appears as a focus of alternating colors behind the structure mimicking turbulent blood flow. This is useful in identification of hyperechoic objects in the kidney such as kidney stones.

9 Patient Selection

For providers early in their learning curve for ultrasound access, we generally suggest choosing patients who have limited comorbidities and who are not morbidly obese. When imaging obese patients, the extra tissue between the initial needle puncture site and the kidney can make it difficult to image the kidney and track the needle through its subcutaneous trajectory. Choosing patients where retrograde access is possible can also facilitate greater renal access success. Retrograde instillation of fluid can facilitate induction of artificial hydronephrosis. Similarly, selecting patients in whom there is already moderate hydronephrosis can facilitate greater success with renal access as accessing a non-dilated system is challenging. In addition, the presence of staghorn stone configurations has been associated with greater renal access challenge. While there are no contraindications exclusive to ultrasound guided access when compared to fluoroscopic access, selecting patients with favorable anatomy can facilitate greater success for the operator, particularly when they have less experience in renal imaging.

10 Pre-operative Considerations and Patient Positioning

Prophylactic antibiotics are tailored the patients' pre-operative urine culture (or prior cultures if a recurrent stone former) and local antibiogram as recommended by American and European Urological Association guidelines (Turk et al. 2016; Assimos et al. 2016). Computed tomography imaging should be obtained in order to review renal anatomy in addition to surrounding vasculature and viscera in addition to stone characteristics. We typically prefer general anesthesia as this allows for minimization of movement leading to higher accuracy.

Patient positioning will depend on surgeon preference and comfort, patient body habitus, comorbidities, and renal anatomy. Options include supine, Galdakao-modified Valdivia or prone. Each position can provide different tradeoffs that can be advantageous depending on the clinical need. For example, the Galdakao-modified Valdivia preserves retrograde access with rigid instrumentation while allowing for adequate percutaneous access to the kidney and avoids the ventilatory issues sometimes associated with the prone position.

After positioning, there are several options to obtain upper urinary tract access. An externalized ureteral catheter can be placed via a flexible or rigid cystoscope. This is useful to induce hydronephrosis by retrograde injection of saline. Other options for upper tract access include placement of a ureteral access sheath both for instillation of saline and for the option to visualize the puncture site with a flexible ureteroscope and perform the dilation under direct vision, commonly referred to endoscopic combined intrarenal surgery, or ECIRS.

11 Procedural Steps

(1) Renal ultrasonography

The first step in obtaining access is adequately visualizing the kidney and its surrounding structures. Any portable ultrasound unit is viable. While the preferred option for a transducer is a curved array in the 3.5 MHz range, a linear transducer is also usable (Table 2). While ultrasound gel is typically utilized in ultrasound imaging as a coupling agent, we have found that this can result in slippery hands intraoperatively which is unfavorable for instrument handling. Instead, sterile water or saline is periodically applied to the patient's body as a reasonable alternative coupling agent.

11.1 Adjusting User Dependent Imaging Variables

Figure 3 Ultrasound machine settings

Frequency and depth (Fig. 3C).

Table 2 List of recommended equipment for ultrasound guided access

Reusable
• Ultrasound with transducer in the 3.5 MHz range
• Needle guide (optional)
• Nephroscope and lithotripter device
• C-arm with contrast (if preferred for tract dilation)
Disposable
• 18 to 24-gauge needle with an echogenic tip
• Fascial dilators (recommend 10Fr or 12Fr)
• Safety wire introducer (optional)
• Access tract dilation equipment (serial dilation kit or balloon set)
• Guidewire per surgeon preference (recommend J-tipped coaxial, hybrid or super stiff)
• Sterile ultrasound console cover
• Sterile ultrasound probe cover (if probe is not sterilized)
• Ultrasound contrast agent solution (optional, useful in non-dilated systems)

One should select the highest possible frequency that allows for adequate depth of penetration. Frequency and depth are inversely related. The higher the frequency, the better the quality of the image, however the lower the depth of penetration. Usually, renal imaging is done between 2.5 and 6 MHz to allow for adequate tissue penetration (in contrast for testicular imaging, a linear probe at 12 MHz is commonly used).

Setting the ultrasound to approximately 8–12 cm depth is usually adequate for the average patient however this should be adjusted to maximize the size of the kidney on the ultrasound screen.

Gain (Fig. 3D).

Gain determines how much a returning sound wave will be amplified when it strikes the transducer. When gain is increased, the image is brighter or hyperechoic. Too much gain leads to an image that appears "washed out." In contrast when gain is decreased, the image is darkened. With too little gain, it is difficult to distinguish between structures.

Gain should be adjusted so that the stone and renal parenchyma are clearly visible and there is adequate contrast between the access needle and the collecting system.

Time-gain compensation (Fig. 3E).

Unlike overall gain, time-gain compensation (TGC) adjusts imaging brightness for specific regions of the scanned field to be individually amplified. This function is used to increase amplification in regions where there is high attenuation or decrease amplification where attenuation is low. A common example in the kidney when TGC can be used to optimize imaging includes renal cysts. TGC for the region below the cyst can be decreased to accurately image this area.

Field of view (Fig. 3F).

Decreasing the field of view will limit the width of the image so that only a portion of ultrasound information is displayed. This may improve the refresh rate as it decreases the amount of data processing needed for returning ultrasound data. It can also be used to exclude distracting tissue or artifact for the surgeon to focus on the organ of interest.

(2) Renal ultrasonography: identification of renal anatomy and vital structures

For patients undergoing PCNL, important landmarks include the midaxillary line, costal margin, the 11th and 12th ribs and the iliac crest. In the prone position, the paraspinous muscle is an important additional landmark. After identifying the 11th and 12th ribs, to optimize renal imaging, we recommend that the probe initially be placed along the midaxillary line just under the 11th rib. By convention, the probe should be oriented to the patient's body such that the cranial structures (i.e. the upper pole) should be to the left of the screen. Depending on the initial orientation, there will typically be post-acoustic shadowing by the ribs (Fig. 2A). This can be eliminated by rotating the probe to be parallel to the 11th rib (usually an adjustment of 30–45 degrees). The ideal initial view should be a longitudinal view that allows for identification of the renal cortex, collecting system and the target urinary stone(s).

Important surrounding structures that should be identified include bowel, pleura, vascular structures, and solid organs (Fig. 1B). Doppler flow can be used to facilitate vascular structure identification. To improve visualization of the collecting system, hydronephrosis may also be induced via manual or passive retrograde injection of saline via an externalized ureteral catheter, access sheath or flexible ureteroscope (Fig. 1A). Renal pyramids may be confused for calices so orienting to sinus fat and the collecting system and inducing hydronephrosis may help to differentiate these structures. In other cases where the stone occupies the collecting system or in minimally or mildly dilated systems, visualizing the stone post acoustic shadowing or a rim of darker black around the stone, representing urine next to the calyx, can confirm the target is in the collecting system (Fig. 2C).

(3) Choosing the ideal calyx

When choosing the appropriate calyx under ultrasound guidance, identifying the calyx closest to the top of the screen will provide the shortest tract from the skin to the target and enable successful access. Ultrasound facilitates caliceal selection without the need to focus on the concept of posterior versus anterior caliceal positioning. In many cases, particularly with supine positioning, an anterior calyx may be the optimal target if it provides direct access to the target stone and collecting system. Ultrasound can also facilitate flexibility in selecting patient positioning. Compared to fluoroscopy, ultrasound guidance in renal access may lend itself to different skin entry points. For example, accessing horseshoe kidneys in the prone position will often result in a more medial skin entry compared to fluoroscopy due to the lie of the horseshoe kidney.

(4) Renal puncture

The most technically challenging step to the case is the renal puncture. The surgeon must combine their kidney imaging interpretation with the technical skill of inserting the access needle. For needle insertion, we prefer to teach the renal puncture via the freehand approach which allows for more flexibility in needle adjustment. There are, however, several options for commercially available needle guides as described previously which attach to the ultrasound probe. These may facilitate learning as they decrease the challenge of coordinating the imaging with needle insertion and may be useful earlier in the surgeon's learning curve.

An 18-to-24-gauge needle with an echogenic tip should be used for access as these needles are more readily visible under ultrasound (Fig. 2D). We tend to favor the 18-gauge size for its stiffness, as the needle is less likely to deflect from its intended path during insertion. There are two options for needle insertion location in relationship to the probe, longitudinal and transverse. Both have their advantages. In the longitudinal approach, done by performing the puncture in line with the long axis of the probe, one can see the entire length of the needle as it traverses from the skin to the target calyx. In the transverse approach, the needle enters the skin from the side of the probe, providing a cross sectional view of the needle in any given imaging plane. This requires one to actively image the needle tip as it moves toward its target. While the transverse approach can allow one to navigate around ribs for example, we tend to favor the longitudinal approach for its safety profile.

Seeing the entire needle as it traverses the layers of body toward the target allows the operator confidence in avoiding peri-renal structures. For a lower pole puncture in the longitudinal approach, the needle is typically inserted approximately 1 cm from the caudal end of the probe and for an upper pole and mid kidney puncture, it enters the skin 1 cm from the cephalad end of the probe. Notably, if the probe is oriented correctly and the needle is inserted on the appropriate side of the probe, an upper pole and mid kidney puncture will be seen from the left of the screen whereas a lower pole puncture will be seen from the right. The needle should be visualized as it enters the skin and then passes the subcutaneous tissue including fat, fascia, and muscle (Fig. 2D). One critical principle is to visualize the target calyx, hold the image steady, and bring the needle into the target, rather than chase the needle.

For a transverse insertion, the access needle punctures the skin orthogonal to the long axis of the probe. Unlike the longitudinal approach where it is critical to hold the probe steady, with the transverse approach, the probe should be swept back and forth continuously to visualize the needle tip and trajectory to guide the needle to the calyx of interest. This active imaging movement with the ultrasound probe requires the operator to be moving both hands in concert with one another. The benefit of this approach however is that the needle can be inserted into the skin at any distance from the side of the ultrasound probe which allows for more flexibility in the angle and location of needle entry relative to the probe.

Learning to make real time adjustments to the needle can be challenging initially. If the needle tip is lost during insertion, two techniques can be of value. First, fanning the ultrasound probe back and forth to identify the needle location and adjusting the needle can bring it into the desired imaging plane. Second, with the ultrasound probe fixed in one position, the needle can be gently bounced in and out of the imaging plane to identify which direction it must be moved to enter the target imaging plane. One should be mindful not to enter the skin at too oblique of an angle which can not only make dilation more challenging but also cause the nephroscope to abut the patient's iliac crest. One advantage of ultrasound imaging is its live view imaging nature, compared to fluoroscopy that mostly entails spot imaging. The ability to monitor kidney movement during live imaging allows accurate coordination between the movement of the ultrasound probe and needle to ensure these remain in the same plane and approach the kidney as it moves. This can negate the need for temporary pause in ventilation commonly done with fluoroscopy to fix the kidney position in space during renal access.

(5) Guidewire access, tract dilation and sheath placement

Once the access needle is successfully inserted into the target calyx, the inner stylet should be removed. If the collecting system is hydronephrotic (whether through natural or induced means) there is often brisk return of urine through the needle. Depending on surgeon preference and comfort, at this point, the rest of the procedure can be completed under ultrasound or fluoroscopic guidance. If a ureteroscope has been inserted retrograde, direct vision guidance for dilation is also another option. For the purposes of this chapter, we will describe the rest of the procedure under ultrasound guidance, though endoscopic direct vision guidance can bring surgeons to an X-ray free state for tract dilation with a potentially shorter learning curve compared to ultrasound guidance.

Under ultrasound guidance, any wrapped or lined guidewire should appear as linear and hyperechoic and can readily be seen traversing the renal parenchyma into the collection system. The exception are hydrophilic wires which may be so smooth that they are not visible under ultrasound. If there are issues with seeing the wire, a gentle in and out "jiggle" of the wire may facilitate identification.

After the wire has been inserted into the collecting system through the needle and the needle removed, a small skin incision is made to the size of the planned sheath. We commonly use fascial or serial dilators to facilitate tract dilation. Since these instruments in their disposable form are often made of polypropylene or other synthetic polymers, and while they are opaque and visible under fluoroscopic imaging, with ultrasound they are non-echogenic. As the dilator is advanced, the loss of signal of the wire signifies the tip of fascial dilator. Instead of looking for the dilator to appear, we look for the wire to disappear to know where the dilator tip is located. Critically when performing this step, it is important to first have a reliable ultrasound image of the wire. If there are concerns regarding depth of the fascial dilator, backing it out while keeping the wire in place should reveal the wire once more. Frequently active fanning of the ultrasound prob may be required to confirm visualization of the wire. When utilizing reusable serial dilators, such as Alken dilators, these metallic instruments can be seen as bright linear echos that cast a shadow.

In contrast, balloon dilation devices are more readily visible under ultrasound and most have a tip that is slightly more echogenic than the wire which facilitates locating them within the collecting system for accurate positioning. Again, with balloon dilation, it is important to keep a view of the wire to watch the balloon as it is advanced into the calyx. Once dilated, the contours of the balloon appear as a column of liquid and can be readily seen under ultrasound.

The percutaneous access sheath, whether advanced over a balloon or a serial dilator, is often difficult to visualize under ultrasound guidance thus it is often advanced keeping an eye on the back end of the sheath and stopping its advancement when it is matched with a known landmark of the dilator. For example, during balloon dilation, we typically advance this sheath until the back end of the balloon can just be seen through the sheath which approximates the correct depth matching the front of the sheath to the distal end of the balloon.

(6) After renal access and tract dilation are completed, nephroscopy and stone treatment is then performed. Please see detailed descriptions of these steps in the relevant chapters in this book
(7) Renal drainage

If an ultrasound-only procedure is sought, it is notable that nephrostomy tube placement can also be performed under ultrasound guidance. We routinely place 10 french cope pigtail nephrostomy tubes or 4.8/6 french internalized ureteral stents (in the supine position) under ultrasound guidance. While sometimes difficult to visualize, especially if there has been bleeding resulting in blood clot in the renal pelvis, the tube coils will appear as circular echogenic structures in the renal pelvis or bladder. To confirm accurate positioning of a stent, if the bladder cannot be visualized via ultrasound (such as in prone positioning) the proximal curl can be visualized using the nephroscope and the distal curl using a cystoscope or ureteroscope.

Complications with access

The most common reported complications of ultrasound guided access for nephrostomy tube placement by urologists includes urinary tract infection (1.1%), hemorrhage (1.9%), sepsis (0.76%), inferior vena cava injury (0.15%) and death (0.3%) (Fulgham and Gilbert 2013). Overall major complications have been reported in 3.3–6.7% of patients and minor complications in 5–38% of patients. Several meta-analyses have been performed comparing ultrasound versus fluoroscopic access percutaneous for PCNL. One found that the overall lower pooled odds ratio favored a significantly lower complication rate (OR 0.56, 95% CI 0.36–0.86) however the authors note that this was likely driven by impact of a single study of 8 that were included (Yang et al. 2019).

12 Summary

Ultrasound guided renal access has many different characteristics compared to fluoroscopic guided access including reduction or elimination of radiation exposure, real-time visualization of renal anatomy and surrounding structures and ergonomic improvements for the surgeon and OR staff. This is a safe method to access the kidney and has been shown in randomized data to have a comparable complication profile to fluoroscopic access. In obtaining renal access, the initial challenge lies in coordinating renal imaging with advancement of the access needle into the target calyx. Ultrasound can then be used to guide the remainder of the procedure including tract dilation and drainage tube placement effectively eliminating any radiation exposure.

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