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Original Research

Tracked Ultrasonography Snapshots Enhance Needle Guidance for Percutaneous Renal Access: A Pilot Study

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Abstract

Background and Purpose: Although ultrasonography-guided percutaneous nephrostomy is relatively safe, a number of factors make it challenging for inexperienced operators. A computerized needle navigation technique using tracked ultrasonography snapshots was investigated to determine whether performance of percutaneous nephrostomy by inexperienced users could be improved.

Methods: Ten operators performed the procedure on a phantom model with alternating needle guidance between conventional ultrasonography and tracked ultrasonography snapshots. The needle was reinserted until fluid backflow confirmed calyceal access. Needle trajectories were recorded using the real time needle navigation system for offline evaluation of operator performance. Recorded needle trajectories were used to measure needle motion path length inside the phantom tissue, number of reinsertions, total procedure time, and needle insertion time as end points of this study.

Results: Needle path length measured inside the phantom tissue was significantly lower with ultrasonography snapshots guidance (295.0 ± 23.1 mm, average ± standard error of the mean) compared with control procedures (977.9 ± 144.4 mm, $P < 0.01$). This was associated with a significantly lower number of needle insertion attempts with ultrasonography snapshots (average 1.27 ± 0.10 *vs* 2.83 ± 0.31, $P < 0.01$). The total procedure time and the needle insertion time were also significantly lower with ultrasonography snapshots guidance.

Conclusion: Tracked ultrasonography snapshots appear to improve the performance of percutaneous nephrostomy in these preliminary investigations, justifying further validation studies. The presented navigation system is reproducible because of commercially available hardware and open-source software components, facilitating its potential role in clinical practice.

Introduction

Percutaneous nephrostomy (PCN) is commonly used to establish renal drainage in the setting of urosepsis or acute obstructive renal failure, and results in a reduced mortality rate.[1] Although this is a relatively safe procedure with a success rate of more than 90%,[2] it needs significant experience, and the successful puncture may take multiple attempts.

PCN is commonly performed under fluoroscopic guidance by the double-stick technique, or under ultrasonography and fluoroscopy guidance by the single-stick technique. Although a comparative study did not identify a difference in complications between the two techniques, the single-stick technique is recommended, because of the benefits of ultrasonography over fluoroscopy.[3] Ultrasonography has been shown to enable radiation-free PCN in children from the neonate age.[4] First pass accurate needle placement in PCN is especially important when the urine is infected. Manipulation with the catheter and guidewire may result in sepsis when the infected urine decompresses into the vascular bed.[5]

A recent randomized controlled study showed decreased postoperative fever when ultrasonography was used rather than fluoroscopy for needle guidance in percutaneous nephrolithotomy.[6] Ultrasonography-only needle guidance in PCN is favorable, but needs significant experience and generally not a skill developed during urologic training. The challenging procedural proficiency is to maintain a clear view of the target anatomy and the needle in the ultrasonography by simultaneously manipulating the ultrasound transducer and the needle.

The challenges in image-guided interventions have been addressed by the recent technology of electromagnetic position

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tracking. It enables needle navigation, which improves accuracy and extends possibilities in minimally invasive interventions.[7] The position of the needle tip can be directly tracked inside the body, which makes this technology suitable for navigation of various interventions including aortic stent-graft placement,[8] biopsies in liver and prostate,[9,10] and spinal needle placement.[11] Electromagnetic tracking has been used to show the needle path projection relative to the ultrasonography image in a commercial device specifically designed for kidney punctures.[12] Recently, tracked ultrasonography snapshot (TUSS) guidance was shown to improve the success rate and reduce the procedure time in ultrasonography-guided spinal facet joint injections compared with freehand ultrasonography guidance as performed by residents.[13] TUSS improves the procedural performance of novice operators by decoupling ultrasound scanning and needle insertion; therefore, the operators can focus their attention on one task at a time.

We investigated the possible benefit of the TUSS technology in PCN in a synthetic phantom model compared with conventional ultrasonography guidance.

Materials and Methods

Study protocol

Ten novice trainees who participated in this study as operators had no previous experience in ultrasonography-guided nephrostomy. They received a brief introductory presentation of ultrasonography-guided PCN and a live demonstration of the technique by an instructor. Then each operator performed two procedures with conventional ultrasonography guidance, and two procedures with TUSS guidance, in an alternating pattern (Fig. 1). The conventional ultrasonography guidance served as the control method in our comparative study. Five operators started with ultrasonography-only guidance and five started with TUSS to balance the experience gained during the study. Alternating guidance methods ensured that previous experience and skills of participants are equal in both groups, because all participants were tested with both methods.

Experiment materials

We modified a commercially available ultrasound-compatible kidney phantom (Renal Biopsy Ultrasound Training Model, Blue Phantom, Sarasota, FL) by placing a cannula in the kidney model to refill the calices with water between procedures. An electromagnetic position sensor was fixed to the phantom torso to serve as a coordinate reference for tracking the ultrasonography and the needle relative to the kidney model. This reference position sensor would be attached to the patient back in clinical procedures.

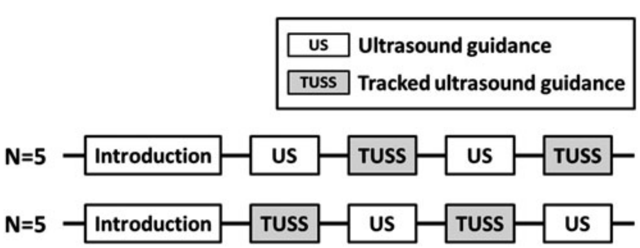

FIG. 1. Study protocol showing alternate guidance methods during needle insertions.

Procedural work flow

Our experimental procedures were confined to ultrasound scanning and needle insertion only, to study needle navigation. Timing of the procedure was commenced when the ultrasound was placed on the surface of the phantom model.

In the control group, operators scanned the kidney with ultrasound to find an appropriate target calix and a needle entry point so the needle path was close to the long axis of the calix, avoiding any ribs. The needle was then introduced to the target calix under continuous in-plane ultrasonography visualization. Successful puncture was tested by removing the stylet from the needle to check water drainage. In case of unsuccessful attempts, the operators were instructed to retract the needle partially or completely and try the insertion in a different angle.

The work flow for TUSS needle navigation was broken down into three distinct steps: (1) ultrasonography snapshot; (2) insertion planning; and (3) needle insertion.

Step 1. During the initial ultrasound scan, the operator identified a suitable scanning plane for needle insertion, and an ultrasonography snapshot was recorded with that transducer position. The ultrasonography snapshot included the prospective needle path leading to the calix, avoiding ribs.

Step 2. The snapshot was used to define needle entry and target points by clicking at the respective positions on the ultrasonography display. The navigation view was set up according to the insertion plan. The bulls-eye view looks down on the needle path, while the side view shows the remaining distance from the target point.

Step 3. Needle insertion was performed by looking at the three-dimensional (3D) view on the navigation display showing the real-time computer-generated models. During insertion, the ultrasound transducer was placed on the back of the mannequin to give a live image orthogonal to the ultrasonography snapshot (Fig. 2). This live ultrasonogrphy would confirm that the kidney has not moved because of breathing in a patient, and it shows needle echo when the needle arrives at the target.

Navigation hardware and software system

Our experimental system consisted of a conventional ultrasound machine integrated with an electromagnetic position

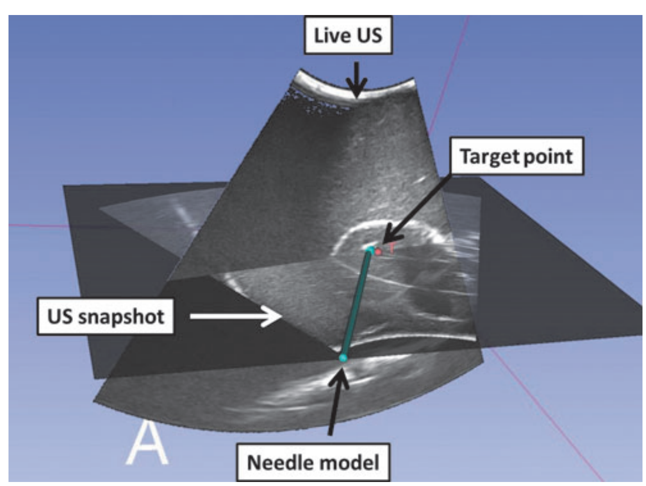

FIG. 2. Screenshot of the needle navigation software during needle insertion. US = ultrasonography.

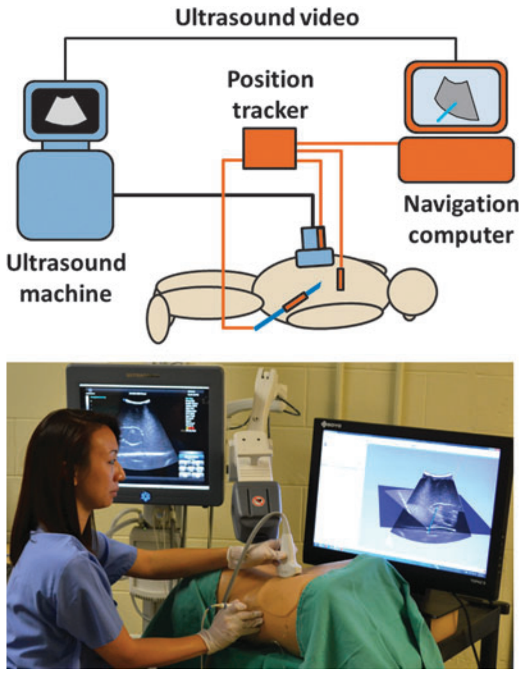

FIG. 3. Nephrostomy on a simulation model using tracked ultrasonography snapshot guidance.

tracker (Sonix Tablet with GPS extension, Ultrasonix, Richmond, BC, Canada), and a navigation computer with its display facing the operator (Fig. 3). The electromagnetic field generator of the position tracker is positioned near the needle insertion site with an adjustable arm. Tracking sensors are attached to the ultrasound transducer and the needle, and an additional reference sensor is fixed to the phantom model to serve as the reference coordinate system for tracking.

Two free, open-source software applications were used in the experimental setup (Fig. 4). The PLUS[*] server application (Queen's University, Kingston, ON, Canada) was running on the ultrasound machine to acquire the tracked ultrasound data and stream it over a network connection to the navigation computer. PLUS also provides the necessary calibration and synchronization methods for setting up the hardware the first time.[14] The second application that provided the needle navigation display was 3D Slicer (Harvard Medical School, Boston, MA), and its extension for image-guided interventions, SlicerIGT[†]. 3D Slicer is an image processing and analysis application with configurable user interface[15] that allowed us to visualize the needle and the ultrasonography images in a 3D virtual scene.

All software used in this study is freely available for research or commercial use without restrictions. In addition, PLUS can be configured to interface with most existing ultrasound machines and position trackers to allow the presented system to be replicated on a wide range of existing hardware. Software components communicate through the OpenIGTLink network protocol, which allows the navigation application to run on a separate computer and not overload the ultrasound machine.[16] An existing ultrasound machine can be extended with the presented navigation system at a cost below $10,000.

[*]www.plustoolkit.org
[†]www.slicerigt.org

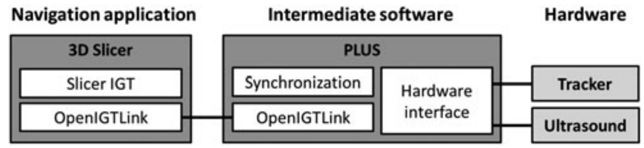

FIG. 4. Software components of the navigation system.

Evaluation of recorded procedures

All recorded procedures were reviewed by a radiologist blinded to the operators' identity or the guidance method in each needle insertion. The review was performed using a posteroanterior and a lateral 3D view with semitransparent models of the phantom skin, kidney, and calices, and a needle model following the recorded trajectory at real speed. The number of needle insertion attempts was counted, and the procedure time was measured (Fig. 5). Automatic needle motion analysis was performed by the PerkEvaluator software, which is part of the Perk Tutor[‡] extension for 3D Slicer.[17] Needle path length was measured as the sum of recorded trajectory elements with needle tip inside the phantom model. The PerkEvaluator software automatically generated three measurement outcomes—total needle path length inside tissue, total procedure time, and needle insertion time.

Results

All nephrostomy procedures were successfully performed by the operators, as confirmed by water backflow after removal of the stylet from the needle. The maximum number of needle insertion attempts in one procedure was five using conventional ultrasonography guidance, and two using TUSS guidance.

Needle path length measured in the phantom tissue was significantly lower in the TUSS group (295.0 ± 23.1 mm, average ± standard error of the mean) compared with the control group (977.9 ± 144.4 mm, $P < 0.01$) (Fig. 6). This was associated with a significantly lower number of needle insertion attempts in the TUSS group (average 1.27 ± 0.10 *vs* 2.83 ± 0.31, $P < 0.01$). Total procedure time was also significantly lower in the TUSS group (average 107.2 ± 46.4 seconds *vs* 222.4 ± 32.6 seconds, $P = 0.01$), as well as needle insertion time (average 48.2 ± 6.1 seconds *vs* 83.9 ± 10.6 seconds, $P = 0.04$).

Discussion

To the authors' best knowledge, this is the first report on TUSS used in computer navigated PCN. In a small cohort of inexperienced learners, we have shown that TUSS guidance significantly decreased the amount of needle motion in the tissue, total procedure and needle insertion times, as well as the number of attempts to successful urine drainage in simulation models. Our results suggest that TUSS may contribute to more accurate and efficient PCN procedures, facilitating procedural proficiency in learners as well as technical aid in routine clinical practice.

A limitation of our study is that our phantom model did not have breathing motion and represented average anatomy, making the procedure relatively easy to complete. This

[‡]www.perktutor.org

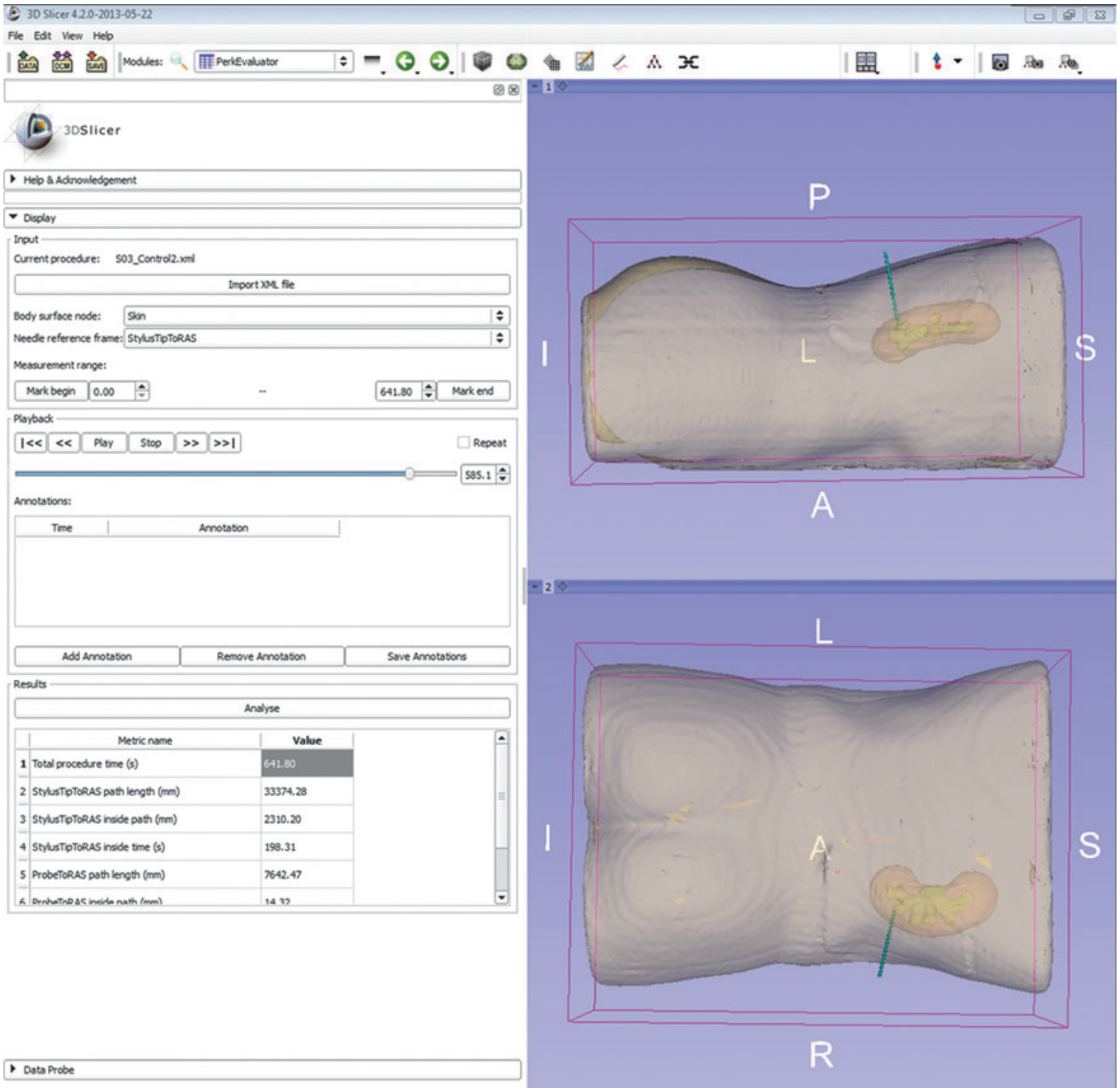

FIG. 5. PerkEvaluator software module for review of recorded procedures and measurement of needle trajectory parameters.

probably contributed to a successful procedure after the maximum five attempts by all participants. In patients, the kidney moves relative to the reference tracking sensor. Breathing motion in our prospective live animal and patient studies will be compensated by recording the ultrasonography snapshot in breath-hold, and inserting the needle while the patient holds the same breath phase. In case the kidney is not at the same place between these two work flow steps, the live ultrasonography shows the position offset, and the operator can wait for a suitable breath-hold.

Our operator sample size was relatively low, and we limited the operator population to novices who did not have previous experience in ultrasonography-guided kidney punctures. This ensured a fair comparison of our new tool against conventional ultrasonography guidance, because the participants have not learned any of the methods before their performance was analyzed. To fully evaluate the potential of TUSS guidance, future validation studies should involve expert operators and other centers with more participants. Another limitation of our study is that general needle motion economy parameters do not reflect all aspects of an ideal puncture. Recorded needle trajectories may be used to calculate metrics that are more specific to the procedure, such as needle orientation relative to the calix branch angle.

TUSS is only one of several tools developed in the past years to augment percutaneous renal access. Mechanical needle guides keep the needle in the ultrasonography imaging plane, but they restrict the needle motion range, limiting their use.[18] In some cases, this may not provide the operator sufficient freedom of motion to perform PCN at an optimal insertion angle. Simple stabilization of the needle under fluoroscopic guidance significantly reduces the procedure time,[19] and laser cross marker allows fast and successful needle placements, but this technique comes with higher radiation exposure.[20] Electromagnetic tracking can be used to guide the tracked needle to another position sensor that is positioned in the renal pelvis through retrograde catheterization.[21] This form of electromagnetic navigation is reported to allow simpler and quicker punctures at high accuracy,[22] although the navigation display shows only the position of the needle tracker sensor relative to the catheter introduced in a calix during ureterorenoscopy. The optimal navigation may

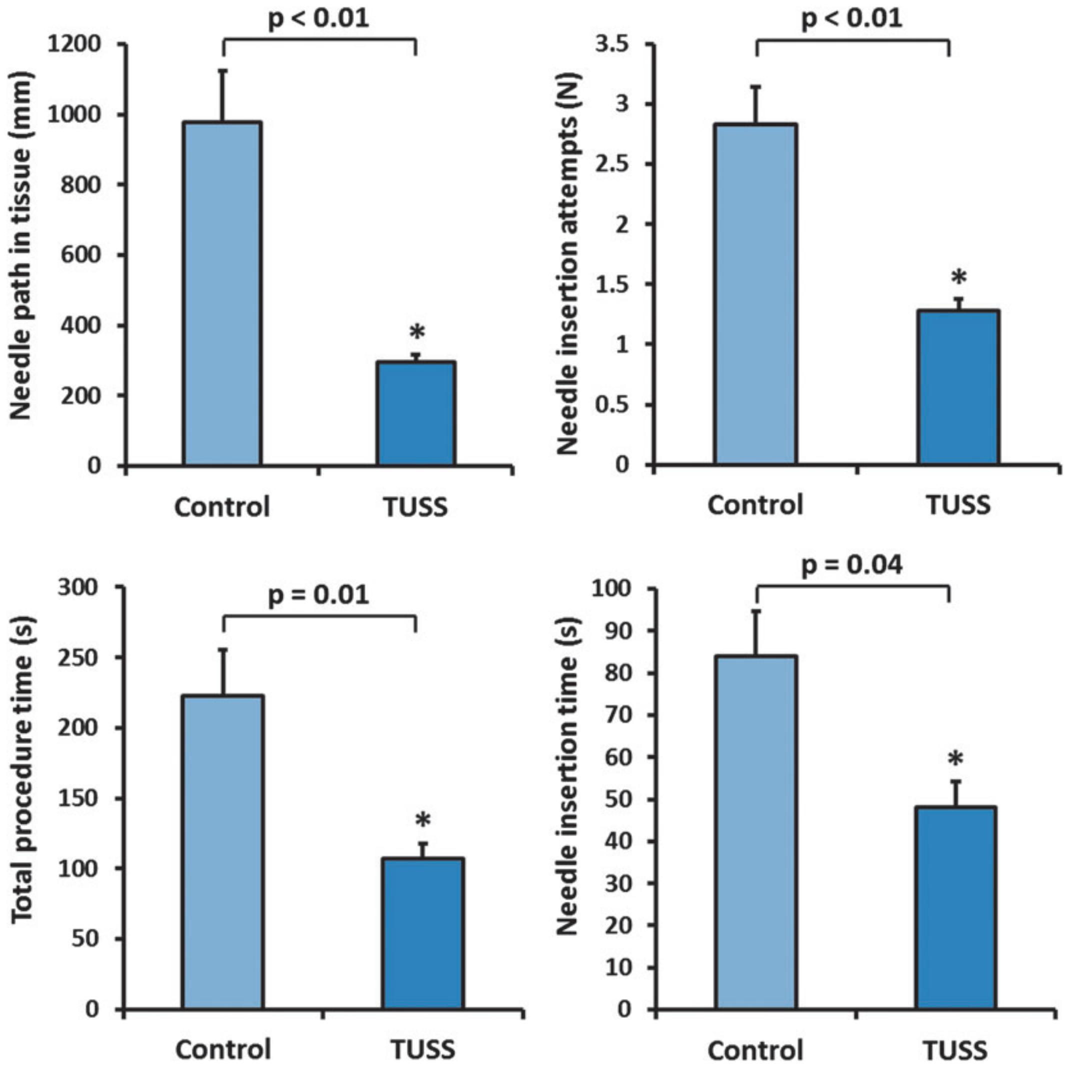

FIG. 6. Comparison of needle trajectory parameters between recorded tracked ultrasonography snapshot (TUSS)-guided and ultrasonography-guided (control) procedures. $N = 20$ procedures in each group. Data are expressed as average + standard error of the means. $^{*}P < 0.05$ at 95% confidence interval.

be performed in the future by a combination of this two-sensor method with TUSS.

Another potential application of the presented method is that it may be combined with image fusion of CT and ultrasonography.[23] This would add significant visual aid to any of the single-modality methods and solve the breathing motion compensation problem of CT-only based navigation. TUSS is the only tool that obviates fluoroscopic guidance and retrograde electromagnetic sensor placement at the target point. TUSS may be combined with other augmentation techniques in the future to provide a more straightforward navigation view for the operator and further increase accuracy and ease of use. TUSS may never become the guidance tool of choice for all nephrostomy cases, but will likely have a role in the clinical routine for cases that need accurate first-pass insertion to a smaller target calix.

The presented tool may improve percutaneous renal punctures in an array of different clinical situations. Ultrasonography snapshots allow careful planning of the needle path and navigation within a few millimeters of the target radius, which may be beneficial in biopsies of focal lesions. In urgent infected cases, TUSS may help establish percutaneous access when experienced operators or fluoroscopic guidance is not immediately accessible. This potentially reduces complications, because delay of renal drainage is the most common contributor to sepsis in these patients.[24] It is recommended for the same reason to avoid prolonged procedures in an infected, obstructed collecting system.[25] It was recently found that bacteremia and sepsis after percutaneous nephrolithotomy can be lowered by decompressing the renal pelvis before the procedure.[26] TUSS may simplify these procedures by accurate needle navigation that reduces procedure time and number of puncture attempts. Ultrasonography directly visualizes the needle path; therefore, TUSS-guided insertions may also have a lower risk of colon injury. The position of the colon varies among persons and, in rare cases, the retrorenal position of the colon should also be considered.[27]

Conclusions

TUSS may make PCN a safer and more accessible procedure. The presented navigation system is reproducible from commercially available hardware and open-source software components. Future animal and human subject studies are required in order to further validate this novel tool for percutaneous renal access.

Acknowledgement

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Disclosure Statement

No competing financial interests exist.

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Abbreviations Used

CT = computed tomography
PCN = percutaneous nephrostomy
3D = three dimensional
TUSS = tracked ultrasonography snapshot