Optically tracked needle for ultrasound guided percutaneous nephrolithotomy (PCNL) puncture: A preliminary report.

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We declare that all material in this assignment is our own work and does not involve plagiarism.

The paper or portion thereof have not been previously published and are not under consideration by another Journal.

Background and aim

Precise needle puncture of the renal collecting system is an essential step for successful percutaneous nephrolithotomy (PCNL). The use of ultrasound for puncture is receiving increased attention. Ultrasound has recognised limitations related to poor visualisation of the needle tip.

We aimed to assess if an affordable open source computerized needle navigation training system, using optically tracked ultrasonography, could improve performance of simulated PCNL puncture by urological trainees, compared to conventional free hand manual sonographic puncture.

Methods

This study describes a PCNL navigation system which can be recreated with any standard ultrasound machine using relatively inexpensive components.

The system allows the needle tip to be precisely appreciated in the ultrasound image, its trajectory planned, and the appreciation of needle tip to target calyx proximity aided by sound.

Eight urology trainees participated in assessment of the PCNL training model. Alternating freehand (control) and tracked needle (experimental) punctures were performed on a phantom kidney. Total procedure and the number of reinsertions required were recorded.

Results

The mean time for freehand puncture was 89 seconds (range 13 – 173), while that of the optically tracked needle was 36 seconds (range 12 – 72). Thus, puncture time was significantly reduced by an average of 53 seconds (p=0.045) in the experimental arm.
The mean number of needle reinsertions was 3,3 with freehand compared to 1,3 in the optically tracked puncture (p = 0.005).
The mean square root error (MSRE) of the optical tracking system was 1,8 mm (4 calibrations averaged).

Conclusion

This study demonstrates that affordable hardware and open source software can be used to construct an optically tracked ultrasound navigation system for PCNL training. Statistically significant reduced puncture time and number of passes required for successful puncture was demonstrated. We feel that computerised needle tracking during PCNL puncture deserves further evaluation in a training, and potentially, a clinical setting.

Keywords: PCNL, image guided surgery, nephrolithiasis.

Introduction

Percutaneous nephrolithotomy (PCNL) is the favoured endourology procedure for renal calculi >20mm. Renal collecting system puncture is the key step to achieving surgical success. Traditionally, fluoroscopy has been the puncture technique of choice. It remains the most widely used method. (1) Ultrasound was first introduced to PCNL in the 1970s and has received growing attention in the literature. Some authors have asserted that sonar offers several advantages over fluoroscopy, including reduced / no radiation exposure hazard, greater appreciation of the anatomy and thus prevention of inadvertent organ (lung/bowel) injury, easier appreciation of the posterior calyx, reduced operating time, reduced cost with similar stone free rates, and even reduced blood loss through being able to avoid the vasculature seen on doppler. (2)

Despite the apparent benefits of ultrasound puncture, it has not been universally embraced. This is in part due to some limitations of sonographic puncture. Some authors have described difficulty in puncturing of a non-dilated collecting system. (2)

In obese patients signal attenuation may result in poor visualisation of the anatomy. (1) Endourologists may also be less familiar with ultrasound for PCNL puncture. Lastly, the lack of echogenicity of the needle can make determining the exact location of the needle tip in the ultrasound view a challenge, particularly if the needle is not “in plane”. These limitations could be overcome by precise computerised tracking of the needle in the ultrasound image.

Commercially available navigation systems are expensive. They have found routine use in Neuro- ENT and orthopaedic surgery. Their use in urology has largely been limited to prostate fusion biopsy. Various image-guided methods to track the precise location of a needle are now described. These technologies should promote the growth of a “slow revolution” in navigated minimally invasive therapies in endourology. (5) These technologies include electromagnetic, optical and positional device (accelerometer / gyroscope) tracking.

This study aims to investigate if a computerised needle navigation technique using optically tracked ultrasonography could improve performance of PCNL puncture in a training model.

Materials and Methods

1) Hardware systems

In creating the system under study here we used off the shelf devices which are robust and compared to commercial systems, relatively cheap. Excluding the computer and the ultrasound machine, the total hardware cost for this system is ~$2000 US.

Optical tracking of the needle and ultrasound image was performed by fiducial detection using an Optitrack V120:Duo stereoscopic infrared camera (OptiTrack, Natural Point, Oregon, USA). The camera’s tracked images were relayed to a standard desktop computer.

A Sonoscape A6 ultrasound machine (Sonoscape Medical Corp., Shenzen, China) with a C351 curvilinear 2-6 MHz probe was used. Real-time ultrasound images were captured by the computer using a standard HDMI to USB 3.0 frame grabber. See Figure 1.

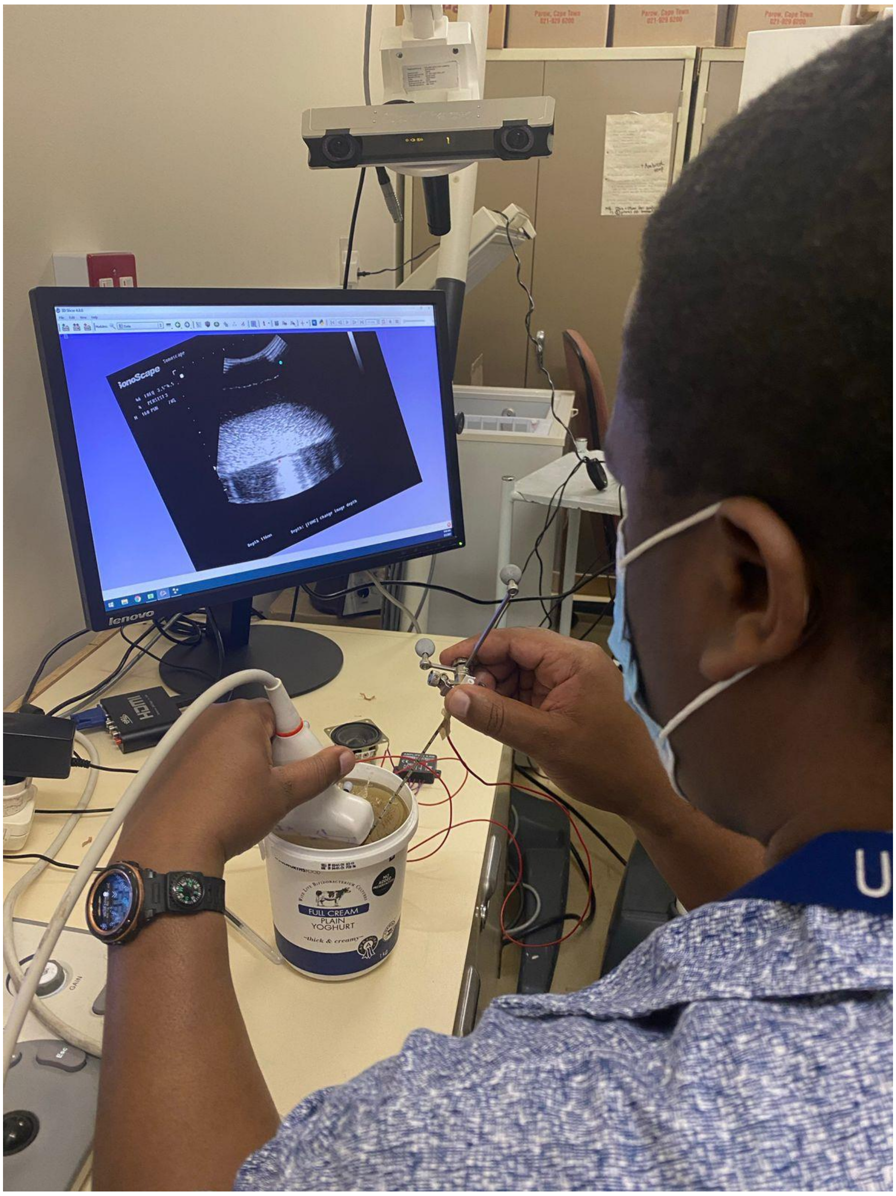

Figure 1: Illustration of the experimental setup. The red arrow shows the tracking camera. The green arrow shows the image of the tracked ultrasound and needle. The blue arrow shows the tracked fiducials attached to the puncture needle and the sonar probe with the gelatine kidney phantom.

2) Software setup

Tracking of the needle in the ultrasound image is a software function. There are three free, open source components to the optical tracking system:

a) The first application, providing the needle navigation display, is *3D Slicer* (www.slicer.org, Harvard Medical School, Boston, MA). It has an extension for image-guided interventions, *SlicerIGT* (4,5). See Figure 2 for an example of the 3D view of the tracked needle.

A further 3D Slicer extension – *SoundNav* - was used to aid puncture by aiding trajectory planning. *SoundNav* emits a variable sound to indicate nearness to the target – akin to a motor vehicle reverse warning indicator beeping alarm. (6)

b) Secondly, the *PLUS toolkit* application (Queen's University, Kingston, ON, Canada) is used to interface between the hardware (tracking camera and ultrasound) and the *3D Slicer* software. (7,8)

c) The actual fiducial tracking of the needle tip is facilitated by *Motive*, the propriety software of the *OptiTrack* camera.

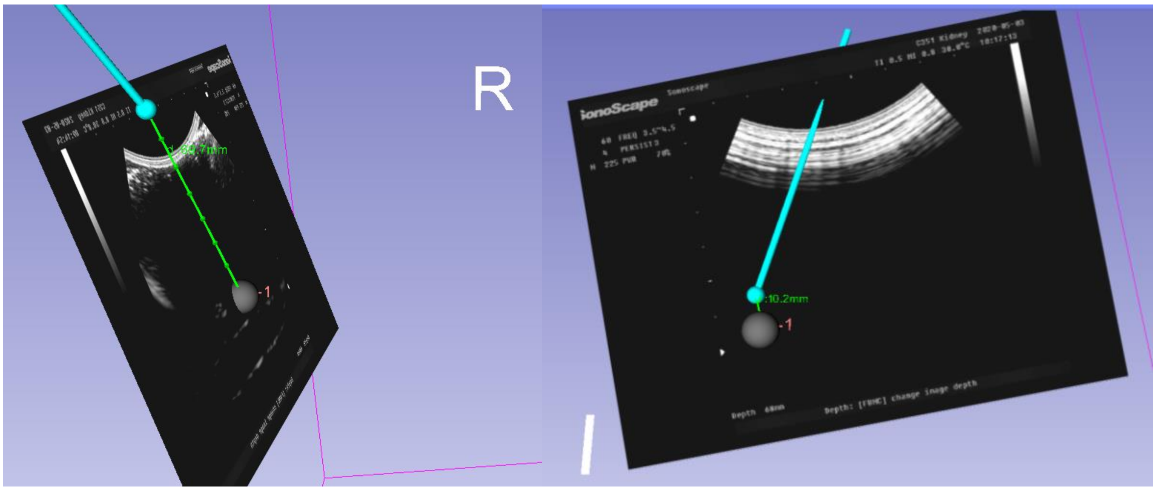

Figure 2: Real-time display of the tracked needle (blue) with the round sphere as the target (grey) in the ultrasound view of the kidney phantom in 3D Slicer software. The ideal trajectory is shown in green.

3) System design and sonar calibration

Figure 3 illustrates the experimental design. A critical step in building an optical tracked ultrasound system is to calibrate the US image with respect to the puncture needle tip. Within the *SlicerIGT* software are methods to achieve this calibration. (4) In summary, this process involves a pivot calibration to determine the needle tip position relative to the fiducials on the needle. A second process calculates the position of the ultrasound image relative to the fiducials on the probe. Lastly, the software derives a calculated the position of the needle tip relative to the ultrasound image. The ultrasound calibration accuracy is measured by *SlicerIGT*. The accuracy is conventionally recorded as the mean square root error (MSRE).

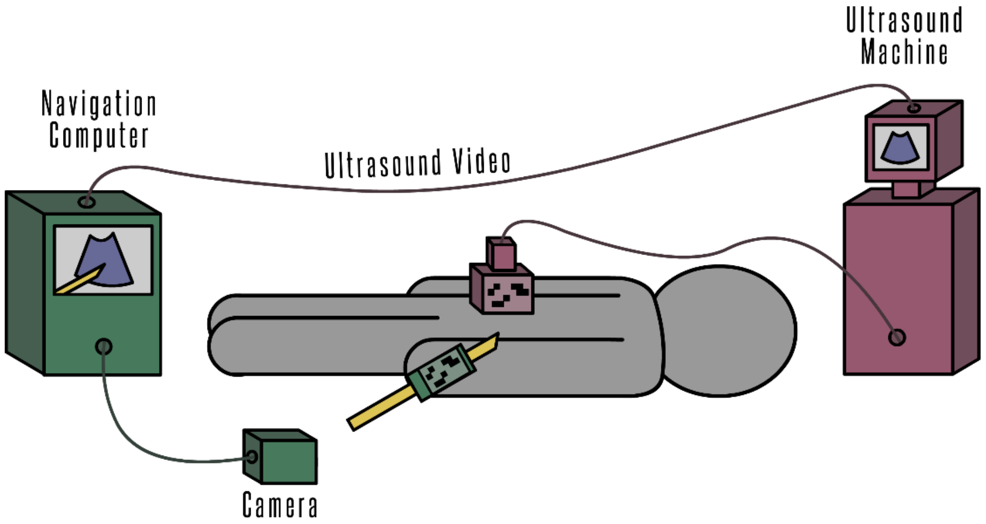

Figure 3: Illustration of the experimental setup for simulated PCNL puncture using optically tracked ultrasound.

4) Study Protocol

Eight urological trainees and four urological surgeons participated in the study. All had observed PCNL procedures previously, while only two perform PCNL independently in their clinical practice.

All were introduced to the phantom kidney and the target alarm, indicating successful puncture simulation. Comparison was then made between the manual freehand technique (control) followed by the tracked needle puncture (experimental). The method of timed assessment and number of passes / reinsertions was explained.

5) Experiment materials

A kidney phantom was constructed using gelatin as previously described (15). Gelatin is sonographically clear and once set allows simulated puncture, albeit with tensile strength which is less than human tissue. Metamucil (Psyllium husk powder) was added to achieve opacity and echotexture like human tissue, for a more realistic puncture.

The depth of the target for puncture in the phantom was 10 cm. The target was easily seen as hyperechoic on ultrasound. The target which was intended to simulate a renal calyx was 1cm in length and width. The target was a metal electrode which closed an electric circuit on contact with the needle, to make a sound to indicate successful puncture. A 14-gauge puncture needle was used.

6) Statistical analysis

We compared participants’ time to successful puncture, and number of reinsertions, with freehand (control) and tracked (experimental) puncture methods. Analysis was performed using Graphpad Prism statistical software package, version 5.03. The student’s t-test was used to compare the paired results. A p value of <0.05 was regarded as significant.

Results

All simulated PCNL punctures of the kidney phantom were successfully completed by all participants (n=8). Successful puncture was confirmed by closing the electric circuit from needle to target and a causing an alarm sound. Additionally, in the tracked needle puncture, the sound and colour of the target changed, indicating success.

Using the freehand conventional manual technique, the mean time to puncture was 89 seconds (13 - 173), while that of the optically tracked needle was 36 seconds (12 – 72). Thus, puncture time was significantly reduced by an average of 53 seconds (p=0.045) in the experimental arm. See Figure 4.
The mean number of needle reinsertions was 3,3 with freehand compared to 1,3 in the optically tracked puncture (p = 0.005).

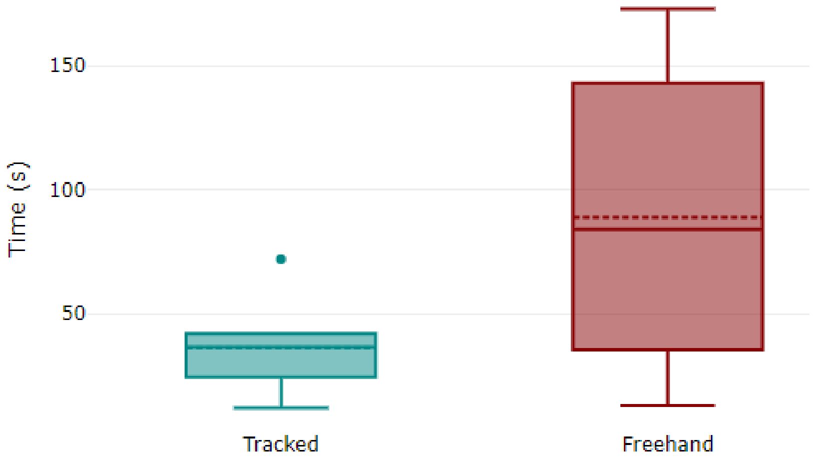

Figure 4: Comparison of mean simulated tracked ultrasound PCNL puncture (36 seconds) vs manual freehand PCNL puncture time (89 seconds), p=0.045.

We assessed the accuracy of the ultrasound tracking using the SlicerIGT software. This was done using the mean square root error (MSRE). We obtained an average MSRE of 1,8 mm from 4 separate calibrations.

Discussion

Renal collecting system puncture during PCNL is recognised as an advanced index endourological procedure. In our own clinical practice ultrasound guided puncture has, in the last few years, grown to be the dominant puncture method used. A recent randomised trial of supine PCNL demonstrated that totally ultrasonic puncture had the same outcomes as fluoroscopy. (10) Ultrasound offers the advantage of reduced / no radiation hazard for surgeon and patient. However, ultrasound has noted limitations including, for example, the puncture of a non-dilated collecting system, reduced appreciation of the anatomy in the obese, and the lack of echogenicity of the needle resulting in poor visualisation. (1,2) These limitations may decrease puncture success rates and potentially lead to accidental damage to surrounding organs.

Many innovative attempts to overcome the limitations of ultrasound puncture are described. An instructive review by Scholten et al documents these attempts which include echogenic needles, needle guides, 3D/4D ultrasound and various forms of image-based computer tracking. (11)

Our study initially explored the possibility of using affordable off the shelf hardware and open source software to develop an optical tracking method for training purposes. We first used ArUco paper-based tracking markers. These markers were able to be tracked to the calibrated ultrasound image in three dimensions in the software. (3) Unfortunately, this initial setup was not sufficiently accurate for clinical purposes although it made for a useful training system. We migrated to using the far more accurate OptiTrack stereoscopic infrared camara for this study.

Open source software allowed the puncture needle to be precisely appreciated superimposed on the sonar image. The target “calyx” in the phantom kidney is easily identified. The trajectory can also be clearly assessed prior to puncture and adjusted during puncture. The built-in sound navigation extension in SlicerIGT helps to indicate proximity. These features assist in overcoming the limitations inherent in freehand ultrasound puncture.

This study showed a significantly reduced puncture time (89 vs 36s) with a significantly reduced number of passes required for success (3,3 vs 1,3) in favour of optically tracked navigation in this training model.

The mean time for freehand puncture was 89 seconds (range 13 – 173), while that of the optically tracked needle was 36 seconds (range 12 – 72). Thus, puncture time was significantly reduced by an average of 53 seconds ($p=0.045$) in the experimental arm.
The mean number of needle reinsertions was 3,3 with freehand compared to 1,3 in the optically tracked puncture ($p = 0.005$).

Image tracking holds important future potential in endourology. Rassweiler et al have explored navigated PCNL puncture. They have demonstrated an iPad assisted puncture method. Here CT images are overlaid via optical tracking onto the patient and a laser guide exploits the bull’s eye puncture technique. (12) Mozer et al used an optical tracking system and demonstrated its feasibility in the PCNL setting. (18) Commercial optically tracked systems for medical use have recently emerged. (13)

Electromagnetic tracking has also been explored in simulated PCNL puncture. (14) It has the advantage of remaining accurate despite needle bending. Li et al have documented their experience using the *SonixGPS*, a commercial electromagnetic system. They concluded that the novel technology makes puncturing more accuracy and can significantly decrease the incidence of haemorrhage. (16)

Other examples of navigated PCNL puncture include the ability to perform a 3D reconstruction of tracked ultrasound images – creating an image like a reconstructed

CT volume. (4) Additionally, there is the ability to fuse CT with tracked ultrasound images which could further aid procedures like PCNL. Rodrigues et al validated a renal access technique using tracked reconstructed ultrasound images. (17)

There are several limitations in our study. Firstly, optical tracking, unlike electromagnetic tracking, requires line of sight which may be difficult in a cluttered operating theatre. Additionally, optical tracking methods are known to be inaccurate if the needle bends. 18-21 gauge needles are popular in PCNL. We needed to use a stiffer 14-gauge needle to avoid this problem, which would not be ideal in a clinical setting. A larger 14-gauge co-axial needle with an inner 18 gauge tracked needle could be a workaround for this problem.

Secondly, our study was limited by the small number of trainees and the small number of puncture attempts. Our renal phantom also lacked the real-world difficulty of respiratory movement and the tensile strength of human tissue.

Conclusion

This study has demonstrated that affordable hardware and open source software can be used to construct an optically tracked ultrasound navigation system for PCNL training. The system has shown significantly improved performance of trainees attempting simulated PCNL puncture. This line of research, we feel, deserves further efforts to fulfil the “slow revolution” towards greater integration of image guided minimally invasive interventions into endourology.

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