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# Application value of surgical navigation system based on deep learning and mixed reality for guiding puncture in percutaneous nephrolithotomy: a retrospective study

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## Abstract

**Background** This study was conducted to investigate the clinical value of a navigation system based on deep learning and mixed reality for the treatment of kidney stones with percutaneous nephrolithotomy (PNL), and to improve its theoretical basis for the treatment of kidney stones.

**Methods** The data of 136 patients with kidney stones from October 2021 to December 2023 were retrospectively analyzed. All patients underwent PNL, and were categorized into a control group (Group 1) and a surgical navigation group (Group 2) according to puncture positioning method. Preoperative computed tomography (CT) was performed in both groups. In group 1, procedures were performed under standard ultrasound guidance. PNL was performed with navigation system fused with ultrasound to guide percutaneous puncture in group 2. The baseline information and procedural characteristics of both groups were compared.

**Results** PNL was successfully performed in both groups. No significant difference was found in the baseline date between the two groups. In group 2, real-time ultrasound images could be accurately matched with CT images with the aid of navigation system. The success rate of single puncture, puncture time, and decrease in hemoglobin were significantly improved in group 2 compared to group 1. ($p < 0.05$).

**Conclusions** The application of navigation system based on deep learning and mixed reality in PNL for kidney stones allows for real-time intraoperative navigation, with acceptable accuracy and safety. Most importantly, this technique is easily mastered, particularly by novice surgeons in the field of PNL.

**Keywords** Kidney, Urolithiasis, Puncture, Mixed reality, Navigation, Percutaneous nephrolithotomy

## Introduction

Renal calculi are a common disease of the urinary system, regardless of gender, race or age [1]. Percutaneous nephrolithotomy (PNL) is the primary method for treating kidney stones, especially large or complex kidney stones. However, percutaneous nephrolithotomy remains a significant challenge for urologists, primarily due to its steep learning curve and the potential risks of damaging blood vessels and adjacent organs [2, 3].

Percutaneous puncture is the most critical step in percutaneous nephrolithotomy, and greatly influences surgical outcome. Currently, surgeons primarily perform percutaneous punctures under fluoroscopy and ultrasound guidance. However, mastering these techniques

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requires a lengthy learning curve, typically involving approximately 60 surgeries [4]. Emerging puncture positioning technologies, such as iPad-assisted navigation, electromagnetic navigation and laser positioning navigation, attempt to simplify this step and reduce complications [5, 6]. Nevertheless, these methods have not yet been applied in routine practice owing to their technical complexity or extensive equipment requirements. This study aimed to evaluate the viability of a navigation system based on deep learning and mixed reality for percutaneous nephrolithotomy to overcome these issues.

## Materials and methods

The study was authorization by the Ethics Committee of Dongguan People's Hospital (number: KYKT2022-040). Participants were required to sign a detailed informed consent form.

From October 2021 to December 2023, the data of 136 patients with kidney stones were retrospectively analyzed. All patients underwent percutaneous nephrolithotomy, and were divided into a control group (Group 1) and a surgical navigation group (Group 2) according to the puncture positioning method. Preoperative computed tomography (CT) was performed in both groups (Fig. 1). In the control group, procedures were performed under standard ultrasound guidance. Percutaneous nephrolithotomy was performed with a navigation system fused with ultrasound in the surgical navigation group, and a urologist performed percutaneous puncture according to the selected puncture site. The preoperative baseline information of both groups, including age, hydronephrosis, stone size, gender, body mass index (BMI), and stone laterality, is shown in Table 1.

All procedures were carried out by a single surgeon, who had ten years of experience. Intravenous urography,

**Table 1** Preoperative baseline information in the two groups

| Variables | Group 1 | Group 2 | *P* value |
|---|---|---|---|
| Patients (n) | 66 | 70 | [@]NA |
| Age (years) | 46.9 ± 10.7 | 47.7 ± 10.3 | 0.664 |
| Gender (n) | | | 0.603 |
| Male | 31 (47) | 36 (51.4) | |
| Female | 35 (53) | 34 (48.6) | |
| BMI (kg/m$^2$)[a] | 23.9 ± 2.1 | 23.6 ± 2.2 | 0.425 |
| Stone laterality(n) | | | 0.883 |
| Right | 35 (53) | 38 (54.3) | |
| Left | 31 (47) | 32 (45.7) | |
| Multiple stone (n) | 49 (74.2) | 55 (78.6) | 0.336 |
| Hydronephrosis (n) | | | 0.068 |
| Nil | 25 (44.6) | 45 (64.3) | |
| Mild | 28 (50) | 21(30) | |
| Severe | 3 (5.4) | 4 (5.7) | |
| Stone size (cm)[b] | 5.2 ± 0.9 | 5.0 ± 1.0 | 0.149 |

The data are presented as the means ± standard deviations or counts (percentages)

[@] NA indicates not applicable

[a] *BMI* Body mass index

[b] Stone size = the diameter of the stones was measured by preoperative CT

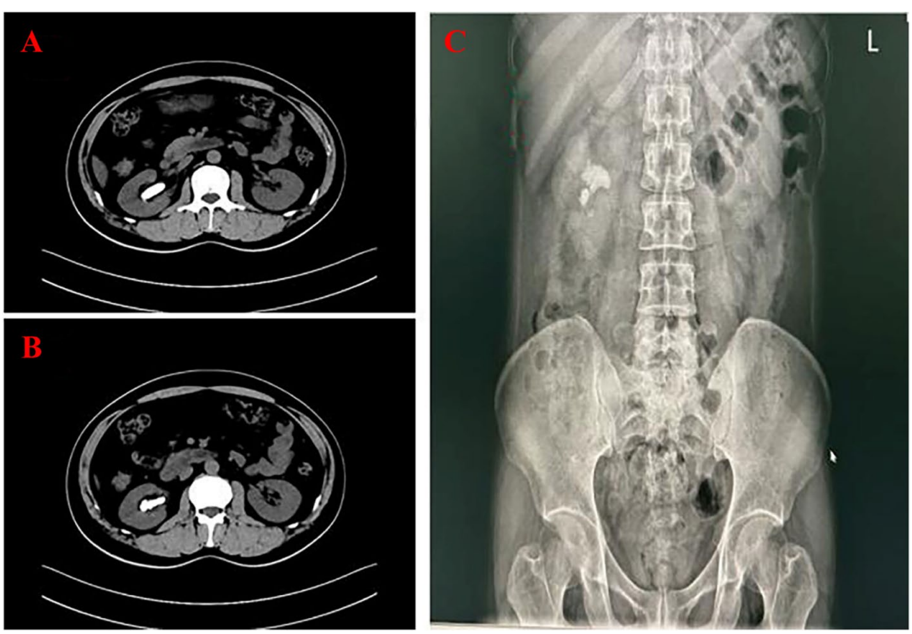


**Fig. 1** A 38–years–old man with multiple stones in right kidney. Noncontrast computed tomography **A** and **B**. Abdominal plain film image **C**

ultrasound and CT scans were performed preoperatively in both groups. Patients underwent urine analysis and midstream urine culture before surgery. Stone free refers to the absence of residual debris or particles less than 4 mm in length. An abdominal plain film and CT scan were performed the day following the procedure.

### Surgical protocol

Before surgery, radiologists reviewed CT angiographic images to select puncture sites away from blood vessels.

In the surgical navigation group, Digital Imaging and Communications in Medicine (DICOM) data from CT images were imported into the software platform of the navigation system. Patients underwent procedures under general anesthesia. Initially, the patient underwent the placement of a ureteral catheter via a cystoscope in the lithotomy position, and the patient was then turned to the prone position. The urologist utilized navigation system fused with ultrasound (Carben (Shenzhen) Medical Equipment Co., LTD) to perform the puncture at the selected site(s). Through the navigation probe bundled on the ultrasonic probe, the spatial position coordinates (X, Y, Z) of the probe were precisely calculated, so that the relative spatial positions of the two probes were consistent, and the ultrasonic image and CT image were fused. Percutaneous puncture was performed under the guidance of fusion ultrasound navigation system, dilation was performed with serial fascial dilators step by step, and a 20-Fr Amplatz sheath was utilized. A rigid nephroscope and a holmium laser lithotripsy system were utilized for stone fragmentation. Upon completion of the procedure, it is standard practice to insert a ureteral stent and a nephrostomy tube.

In the control group, the surgeon performed the puncture with standard ultrasound guidance. Patients underwent procedures under general anesthesia. The patient underwent the placement of a ureteral catheter via a cystoscope in the lithotomy position, and the patient was then turned to the prone position. Percutaneous puncture was performed under standard ultrasound guidance, dilation was performed with serial fascial dilators step by step, and a 20-Fr Amplatz sheath was utilized. A rigid nephroscope and a holmium laser lithotripsy system were utilized for stone fragmentation. Upon completion of the procedure, it is standard practice to insert a ureteral stent and a nephrostomy tube.

### Statistical analysis

SPSS 25.0 statistical software was used for statistical analysis. The data were presented as the means ± standard deviations or counts (percentages). Continuous variables were analyzed using the Student's test or the Mann–Whitney U test. Categorical variables were compared with the chi-square test or Fisher's exact test. $P < 0.05$ indicated statistical significance.

## Results

A total of 136 patients participated in the study. The preoperative baseline information is shown in Table 1. No significant difference in age was found between the two groups (46.9 ± 10.7 versus 47.7 ± 10.3 years, respectively, $p = 0.664$). The BMI of the control group was 23.9 ± 2.1 kg/m$^2$ and that of the surgical navigation group was 23.6 ± 2.2 kg/m$^2$ ($p = 0.425$). No significant differences were observed in stone size, stone laterality, gender, and hydronephrosis between the two groups.

PNL was successfully performed on all 136 patients. The procedural characteristics are described in Table 2. In the surgical navigation group, the CT source images were imported into the navigation system software platform, and the surgeon performed percutaneous puncture with navigation system (Fig. 2). Real-time ultrasound images can be accurately matched with CT images with the aid of a navigation system. This system allowed accurate visualization of the needle on CT images, providing surgeons with the exact location of the needle in the kidney, and allowing surgeons to precisely penetrate the target calyces (Fig. 3). Compared with the control group, the surgical navigation group demonstrated a shorter puncture time (4.8 ± 0.8 min versus 4.4 ± 0.7 min, $P = 0.003$). A statistically significant difference was also noted in the success rate of single punctures (68.2% versus 88.6%, $P = 0.004$). No significant difference was found in the surgery duration between the two groups (82.4 ± 14.7 min versus 83.8 ± 16.7 min, $P = 0.604$).

Guided by the navigation system, surgeons in the surgical navigation group, accurately penetrated target calyces through the renal papilla, reducing the risk of bleeding. A significant difference in the decrease in hemoglobin was found (17.6 ± 3.1 versus 16.4 ± 2.6, $P = 0.013$). No differences were observed in access number, stone-free rate, and length of hospitalization time between the two groups. Similarly, no significant difference in complications was noted (5 versus 6, $P = 0.831$).

## Discussion

Percutaneous nephrolithotomy, a minimally invasive procedure, is widely used for the management of kidney stones [7]. The key point of this procedure is to establish a safe percutaneous access, which could influence the subsequent operation.

Residual stones and renal hemorrhage still occur due to inaccurate puncture [8]. In particular, massive renal hemorrhage may require renal artery embolization or even nephrectomy, which seriously endangers patient safety [9]. Percutaneous puncture is the most critical

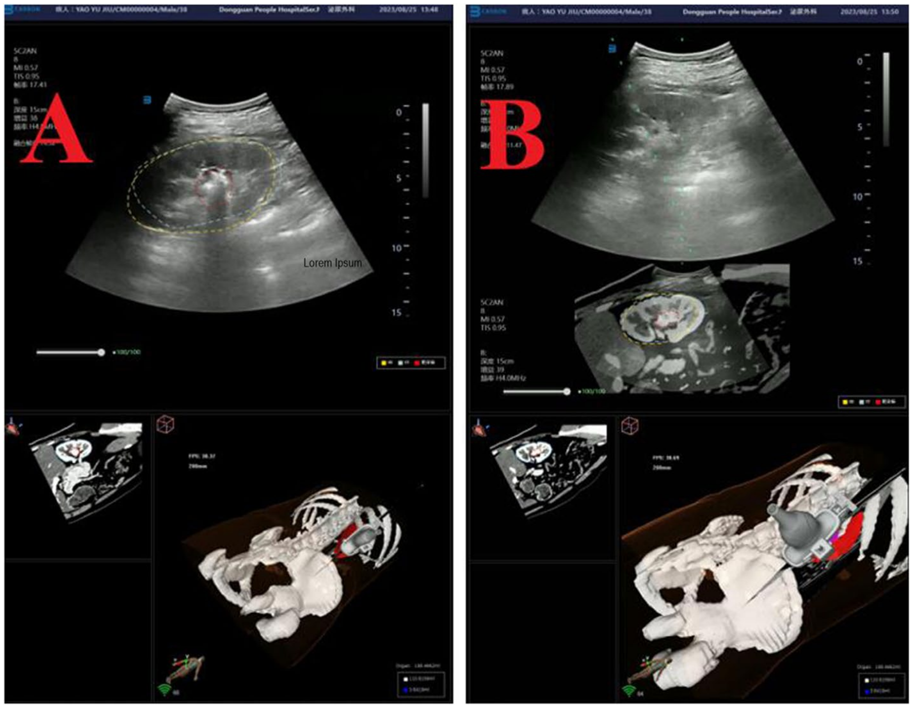


**Fig. 2** Percutaneous nephrolithotomy was performed with a navigation system based on deep learning and mixed reality. Image fusion provided a reference for selecting target calyces and establishing the renal tract **A**. Percutaneous puncture was precisely guided by the navigation system **B**


**Fig. 3** The surgeon successfully performed percutaneous puncture with navigation system (**A**, **B**)

step when performing percutaneous nephrolithotomy. Currently, fluoroscopy and ultrasound guidance are the preferred methods for percutaneous puncture. However, proficiency in these techniques involves a steep learning curve, often necessitating approximately 60 surgeries [4].

Currently, urologists are trying to improve puncture accuracy through the use of advanced guidance devices and puncture needles. Wu et al. introduced a visual navigation system to aid puncture, which could successfully assist the puncture of calices, thereby reducing the puncture time and radiation dose [10]. In a retrospective study, Francesco et al. reported that three-dimensional mixed reality hologram guidance for percutaneous puncture was safe, that the procedure was highly effective in

**Table 2** Comparison of procedural details between the two groups

| Variables | Group 1 | Group 2 | *P* value |
|---|---|---|---|
| Puncture time (minutes) | 4.8 ± 0.8 | 4.4 ± 0.7 | 0.003 |
| Surgery duration (minutes) | 82.4 ± 14.7 | 83.8 ± 16.7 | 0.604 |
| Access number (n) | | | 0.653 |
| 1 | 53 (80.3) | 54 (77.1) | |
| 2 | 13 (19.3) | 16 (22.9) | |
| Success rate of single puncture (%) | 68.2 | 88.6 | 0.004 |
| Decrease in hemoglobin (g/l) | 17.6 ± 3.1 | 16.4 ± 2.6 | 0.013 |
| Stone free rate (%) | 84.8 | 87.1 | 0.336 |
| Length of hospitalization (days) | 8.1 ± 1.5 | 8.5 ± 1.5 | 0.133 |
| Clavien Dindo < II complications (n) | 5 | 6 | 0.831 |

The data are presented as the means ± standard deviations or counts (percentages)

clinical practice, and that it was associated with a low intraoperative radiation exposure [11]. New imaging techniques, such as three-dimensional printing, visual needles, and electromagnetic navigation system, aim to simplify percutaneous puncture and reduce complications [12–14]. In our study, the navigation system based on deep learning and mixed reality, which could achieve real-time navigation, was applied for the treatment of kidney stones during percutaneous nephrolithotomy.

Accurate puncture of ideal calices is crucial step in percutaneous nephrolithotomy. Through ideal calycles, it is possible to reach as many kidney collection systems as possible and improve the stone-free rate. M. Rassweiler et al. postulated that iPad-assisted navigation could ensure accurate positioning, and assisted surgeon in establishing kidney access [15]. In a controlled study, computer assisted percutaneous nephrolithotomy demonstrated obvious advantages in terms of puncture success rates compared with standard percutaneous nephrolithotomy [16]. The percutaneous nephrolithotomy three-dimensional model, as reported by Wang et al., demonstrated notable accuracy and provided valuable guidance for puncture [17]. In our study, while the stone-free rate remained unchanged, the puncture time was reduced in the surgical navigation group (4.8 ± 0.8 min vs. 4.4 ± 0.7 min, $P = 0.003$).

Traditionally, fluoroscopy or ultrasound is typically used for guiding percutaneous puncture in percutaneous nephrolithotomy. However, radiation exposure inevitably occurs when fluoroscopic guidance is used. In a single academic center study, the optimal target calyces were identified using a flexible ureteroscope and punctured with a needle tip sensor guided by a real-time navigation system, and radiation exposure was significantly different between the two methods ($p < 0.01$) [18]. To reduce radiation exposure, we employed a navigation system based on deep learning and mixed reality to assist ultrasound-guiding percutaneous puncture, which achieved radiation-free.

To date, ultrasound guidance has garnered increased attention and is used to perform percutaneous puncture because there is no radiation. However, there are limitations in poor observation of the needle, and it is crucial for surgeons to closely monitor the position of the needle in the kidney in real time. John et al. revealed that a computerized needle navigation training system could accurately identify needles in ultrasound images [19]. Chau et al. demonstrated that magnetic field-based navigation ultrasound could visualize the position of the puncture needle relative to the target calyces during puncture [20]. In the surgical navigation group, the navigation system accurately identified the puncture needle in CT images. The difference in the success rate of a single puncture between the two groups was found to be statistically significant.

Although the risk of trauma is significantly lower than that of traditional surgical lithotomy, percutaneous nephrolithotomy can still cause complications, and bleeding is a prevalent and serious complications. Yamaguchi et al. reported that the incidence of bleeding during percutaneous nephrolithotomy was as high as 9.4% [21]. While the majority of bleeding can be managed conservatively, severe bleeding may require selective renal artery embolization, which occurs in approximately 1% of patients [3]. Therefore, it is more important to prevent bleeding than to take remedial measures after bleeding. Meng et al. analyzed computed tomography angiography before surgery to select puncture sites away from large vessels to reduce the risk of bleeding. This approach ensured a greater safety during the procedure [22]. To reduce bleeding, we selected puncture sites with fewer vessels according to computed tomography angiography. The percutaneous puncture was guided by the navigation system in the surgical navigation group, and the surgeon accurately penetrated the target calyces, minimizing the risk of bleeding.

Despite advances in technology and equipment, percutaneous puncture remains the most crucial step in percutaneous nephrolithotomy and necessitates extensive surgical procedures to achieve proficiency. In the last decade, urology has adopted three-dimensional printing technology for training [23, 24]. Electromagnetic guided puncture has a high success rate and a short learning curve for beginners [14]. To simplify and enhance puncture success, especially for novices, we attempted to perform percutaneous puncture with a navigation system based on deep learning and mixed reality. Compared with the control group, the surgical navigation group demonstrated a shorter puncture time. The difference in the success rate of single punctures was also found to be statistically significant.

However, several limitations should be noted in the current study, which we plan to address in future studies. First, the small sample size of our study necessitates further research with larger samples across multiple centers. Second, the retrospective nature of our study introduces selection bias, and a prospective cohort study is warranted for more definitive conclusions. Third, we performed all procedures under ultrasound guidance, limiting the applicability of our findings to fluoroscopy guidance. Nevertheless, both fluoroscopy and ultrasound guidance are primary methods used in urology.

## Conclusions

In the present study, preliminary data from a navigation system based on deep learning and mixed reality indicated that this new technique is feasible and effective. The navigation system is designed to assist surgeons in performing percutaneous nephrolithotomy in real time, enabling precise punctures with acceptable accuracy and safety. Most importantly, it is easily mastered especially by novices in the field of percutaneous nephrolithotomy.

### Abbreviations

| | |
|---|---|
| CT | Computed tomography |
| PNL | Percutaneous nephrolithotomy |
| BMI | Body mass index |
| DICOM | Digital Imaging and Communications in Medicine |

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### Authors' contributions

Xiangjun Meng: project development, manuscript writing, critical revision. Daosheng Luo: critical revision, data analysis,. Rujun Mo: data collection. All authors reviewed the manuscript.

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### Availability of data and materials

The data set generated during the current study are available upon request. Data requests can be made via email to the corresponding author.

## Declarations

### Ethics approval and consent to participate

The study received authorization from the Ethics Committee of Dongguan People's Hospital (number: KYKT2022-040), adhering to the International Conference on Harmonization Good Clinical Practice standards. Participants were required to sign a detailed informed consent form. The procedure was conducted in compliance with the Declaration of Helsinki.

### Consent for publication

Not applicable.

### Competing interests

The authors declare no competing interests.

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