Usefulness of real-time three-dimensional ultrasonography in percutaneous nephrostomy: an animal study

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Objectives
To evaluate the effect of real-time three-dimensional (3D) ultrasonography (US) in guiding percutaneous nephrostomy (PCN).

Materials and Methods
A hydronephrosis model was devised in which the ureters of 16 beagles were obstructed. The beagles were divided equally into groups 1 and 2. In group 1, the PCN was performed using real-time 3D US guidance, while in group 2 the PCN was guided using two-dimensional (2D) US. Visualization of the needle tract, length of puncture time and number of puncture times were recorded for the two groups.

Results
In group 1, score for visualization of the needle tract, length of puncture time and number of puncture times were 3, 7.3 ± 3.1 s and one time, respectively. In group 2, the respective results were 1.4 ± 0.5, 21.4 ± 5.8 s and 2.1 ± 0.6 times. The visualization of needle tract in group 1 was superior to that in group 2, and length of puncture time and number of puncture times were both lower in group 1 than in group 2.

Conclusions
Real-time 3D US-guided PCN is superior to 2D US-guided PCN in terms of visualization of needle tract and the targeted pelvicalyceal system, leading to quick puncture. Real-time 3D US-guided puncture of the kidney holds great promise for clinical implementation in PCN.

Keywords
percutaneous nephrostomy, three-dimensional ultrasonography, hydronephrosis

Introduction
Percutaneous nephrostomy (PCN) is commonly used in urology, mainly as a treatment for urinary obstruction or diversion, as well as a prelude to complex endoscopic surgery [1]. The crucial step in PCN is percutaneous puncture. At present, two-dimensional (2D) ultrasonography (US) and X-ray technologies are most often used to provide visualization during the percutaneous puncture step [2,3]. Compared with X-ray imaging, 2D US has several advantages: improved inner structure display, no ionizing radiation exposure and device portability. 2D US is preferred for use in children, patients with abnormal renal function and patients with renal stones negative in X-ray.

Unfortunately, 2D US can only provide 2D information in a single imaging plane, which is far from efficacious in guiding operations during which instruments are moved in three-dimensional (3D) space. During 2D US-guided puncture, needle visualization is limited by the sectional display of 2D US, which may result in inaccurate puncture and, in turn, severe complications [4,5]. In addition, 2D US is also ineffective for indicating the spatial relationship between the needle and pelvicalyceal system (PCS). An incomplete understanding of this spatial relationship may result in improper establishment of a percutaneous tract, which may complicate the subsequent stone removal procedure in percutaneous nephrolithotomy [6,7].

Recent studies indicate that the rapidly developing technique of real-time 3D US can accurately locate the instruments and show the 3D relationship between the instruments and the organs. This technique has been successfully used to guide operations such as ablation of hepatic carcinoma, cardiac interventional operation and neurosurgery operation [8–11].
Little is known, however, about the feasibility of PCN guidance using real-time 3D US. In the present study, we performed PCN under real-time 3D US guidance using a beagle hydronephrosis model. This study may provide evidence to justify the clinical use of real-time 3D US for guiding PCN.

Materials and Methods

For the present animal study, 16 beagles (age 15.2 ± 1.9 months, weight 12.9 ± 1.5 kg) were used. Our institutional ethics committee approved the experimental protocol. Hydronephrosis of the beagles was induced by ligating the right ureter partially to the psoas [12]. After 2–4 weeks, hydronephrosis grade was evaluated using a sonographic scanner (IU22; Phillips, Amsterdam, Netherlands) and a 2D US probe (C5-2). The hydronephrosis was classified using the Society for Fetal Urology grading system [13]. Since US-only guidance of PCN is clinically restricted to grade ≥2 hydronephrosis [14], only beagles with hydronephrosis grade 2 or grade 3 were used for PCN in this study. The 16 beagles were divided into two groups equally; group 1 underwent PCN with real-time 3D US guidance, and group 2 underwent PCN with 2D US guidance.

A urologist with 5 years’ experience in performing renal puncture performed each PCN. A sonographic scanner (IE33; Philips) and a real-time 3D probe (X5-1), which can be used either in 2D or real-time 3D mode, were used to perform guidance of PCN. Two sonographers were responsible for the parameter design, data processing and operation of the 3D US machine.

Prior to performing PCN in both groups, the whole kidney and adjacent tissue/organs were reviewed to establish the targeted calyx for puncture. The posterior calices were chosen in this study. To assess the conspicuity of the needle tract in the 2D and 3D US images, we scored clear visualization of the needle tract as 3, adequate visualization of the needle tract as 2, and poor visualization of the needle tract as 1. Clear visualization of the needle tract meant that the tract was clearly displayed and was simultaneously displayed with the targeted calyx in the same image for the whole duration of the puncture; adequate visualization meant that the needle tract was ambiguously displayed, but the needle and targeted calyx were in the same image for the whole duration of the puncture; and poor visualization meant that needle tract was lost when the image was used to display the targeted calyx.

Fig. 1 Two-dimensional display of needle tract and percutaneous nephrostomy. (A) Adequate display of needle tract. (B) Clear display of needle tract. White arrows indicate the needle, red arrows indicate the boundary of kidney, and green arrows indicate dilated pelvicalyceal system.

Fig. 2 Real-time three-dimensional (3D) display of needle. The needle was always clearly visualized in real-time 3D ultrasonography. (A) Needle in a case of grade 2 nephrosis. (B) Needle in a case of grade 3 nephrosis. White arrows indicate the needle, red arrows indicate the boundary of kidney, and green arrows indicate dilated pelvicalyceal system.
After puncture, the outflow of transparent or light reddish urine represented a successful puncture. The puncture duration was defined as the time from the entrance of needle into the skin to the time when puncture was judged to be successful/ unsuccessful.

The number of puncture times was defined as the number of times required for a successful puncture. If the first puncture was successful, the PCN was deemed successful and the number of puncture times was recorded as one. Otherwise, re-puncture was required. In each beagle, no more than five puncture times were allowed. If all five puncture attempts were unsuccessful, PCN in the beagle was deemed unsuccessful. The puncture duration and number of puncture times were recorded for each case.

A paired Student's t-test was used to evaluate the difference between 2D and real-time 3D US guidance, and P values <0.05 were taken to indicate statistical significance.

Results
Real-time 3D US clearly displayed the 3D needle for the whole duration of the puncture (Figs 1 and 2), which is key to successful puncture and to instilling confidence in the surgeon.

The conspicuity of the needle tract during puncture in the two groups (2D US and 3D US) was scored (Table 1). For group 1, the needle tract could be clearly visualized with the targeted calyx with the same ultrasound volume all the time in all beagles, therefore all needle visualization scores were 3 in this group. In group 2, 2D US could not always provide clear visualization. In two beagles there was clear visualization of the needle tract (score 3), and successful PCN was achieved with one puncture. In three beagles there was adequate visualization (score 2), and PCN was successful with one puncture. In two beagles, the first punctures failed and there was poor visualization. The second punctures were successful and the visualization was adequate (needle tract visualization mean score 1.5, two puncture times). For the last beagle, needle tract visualization was given a mean score of 2 because the first poor visualization was followed by a clear visualization, and the number of puncture times was two. The needle tract visualization score was thus higher in group 1 than in group 2: 3.0 vs 2.1 ± 0.6 (P < 0.05).

Both groups had PCN success rates of 100% and there were no severe complications, such as liver, bowel and pleural impairment, massive haemorrhage or sepsis, after surgery in either group. In the 2D US group, the mean puncture duration was 21.4 ± 5.8 s, and the number of puncture times was 1.4 ± 0.5. In the 3D US group, the puncture duration was shorter at 7.3 ± 3.1 s and the number of punctures was one in each beagle (Table 2); thus, the puncture time and number of punctures were both lower in the real-time 3D US group than in the 2D US group (P < 0.05; Table 2).

Discussion
Real-time 3D US has been applied in various surgical guidance procedures involving percutaneous puncture. In a case–control study of ablation in patients with hepatic tumours, absolute curative ablation was achieved in 60% and 95% of patients for 2D US guidance and real-time 3D US guidance, respectively [15]. In US guidance for biopsy, anaesthesia and cardiac interventional operations, real-time 3D US is also efficacious [4,16,17]. Little is known, however, about the feasibility of 3D US in guiding PCN. In the present study, we performed real-time 3D US-guided PCN in vivo for the first time.

Unclear visualization of the needle may hinder surgery and result in unexpected impairment. To highlight the fact that 3D US was superior to 2D US with regard to needle display, we used a subjective measure ‘visualization of the needle tract’ and gave this a score of 1–3. We confirmed that, during PCN, visualization of the needle tract in the real-time 3D US group was superior to that in the 2D US group (Figs 1 and 2) according to the visualization scores (Table 1).

We also used two objective measures, puncture duration and number of puncture times to evaluate the efficacy of real-time
3D US-guided PCN. Experimental results showed that the two measures in the real-time 3D US group were clearly superior to those in the 2D US group. The main reason for these results may relate to the spatial display facilitates for locating the needle. In the real-time 3D US group, the needle was clearly displayed in the volume, and easily tracked; therefore, during US guidance, accurate needle location ensured a safe and quick puncture. For the traditional 2D US guidance, the needle needed to be parallel to the image plane. If the needle was directed out of this plane, the needle track was lost and re-tracking had to be performed. Sometimes the re-tracking was not easy and took up much time.

Another important reason for the results was that we used volume-rendered (VR) imaging instead of multiplanar reformatted (MPR) imaging to display the 3D US data. The 3D US data could be displayed in either MPR or VR imaging. MPR imaging has been preferred in previous studies because of its high image quality, but it is difficult to manipulate. By contrast, VR imaging is easy to manipulate, although it provides unsatisfactory image quality in soft tissue [18,19]. The resolution of US imaging improves, however, when the elements of the matrix probe increase. We confirmed that the needle advancing was clearly displayed by VR imaging when using a X5-1 probe with 3 040 elements. The particular fluid-embedded conditions of hydronephrosis also benefit image quality when using VR imaging [18,20]. In beagles with hydronephrosis, we found that VR imaging was especially helpful to locate the needle tip in the PCS. Clear location of the needle tip is a prerequisite for measuring the length of needle in PCS and thus avoiding severe complications.

The matrix probe used in the present study also facilitated the puncture procedure because of its small size and quick imaging speed [20]. Although the matrix probe has been used clinically in the diagnosis of heart disease, it was appropriate for the present study as the beagle kidney is similar in volume to the human heart. Nevertheless, because the human kidney with hydrenephrosis is much larger than that of beagles, a special matrix probe should be designed for PCN in a clinical setting.

A limitation of the present study is that the number of surgeries carried out was relatively small. For both the real-time 3D US and the 2D US group, there was a 100% PCN success rate and no severe complications occurred. With a larger number of surgeries, success rates in each group would differ and would be lower than 100%. A different PCN success rate would be useful to demonstrate different safety results between real-time 3D US- and 2D US-guided PCN.

Another limitation is that no inexperienced surgeon was involved in performing the real-time 3D US-guided PCN. Although real-time 3D US improved the efficacy of PCN for the experienced surgeon, efficacy of real-time 3D US-guided PCN would differ between experienced and inexperienced surgeons. In particular, because the needle tract is always clearly visualized with the targeted PCS in the same ultrasound volume when using real-time 3D US, real-time 3D US would markedly improve safety results when performed by novice surgeons. The safety and efficacy of the two techniques should be examined in further studies.

The learning curve for real-time 3D US-guided PCN also needs further study with a larger number of surgeries and systematic evaluations. Because real-time 3D US provided clear visualization of the needle tract, targeted the PCS in the same ultrasound volume, and was associated with a shorter puncture duration and lower number of puncture times, it may be speculated that the learning curve for real-time 3D US-guided PCN is shorter than for 2D US-guided PCN.

In conclusion, in the present preliminary study, we confirmed that real-time 3D US-guided PCN was superior to 2D US-guided PCN in visualization of the needle tract and in providing the targeted PCS in one image, leading to quick puncture, for experienced surgeons.

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Conflict of Interest
None.

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Abbreviations: 2D, two-dimensional; 3D, three-dimensional; MPR, multiplanar reformatted; PCN, percutaneous nephrostomy; PCS, pelvicalyceal system; US, ultrasonography; VR, volume-rendered.