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Aid to Percutaneous Renal Access by Virtual Projection of the Ultrasound Puncture Tract onto Fluoroscopic Images

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ABSTRACT

***Background and Purpose*: Percutaneous renal access in the context of percutaneous nephrolithotomy (PCNL) is a difficult technique, requiring rapid and precise access to a particular calix. We present a computerized system designed to improve percutaneous renal access by projecting the ultrasound puncture tract onto fluoroscopic images.**

***Materials and Methods*: The system consists of a computer and a localizer allowing spatial localization of the position of the various instruments. Without any human intervention, the ultrasound nephrostomy tract is superimposed in real time onto fluoroscopic images acquired in various views.**

***Results*: We tested our approach by laboratory experiments on a phantom. Also, after approval by our institution's Ethics Committee, we validated this technique in the operating room during PCNL in one patient.**

***Conclusion*: Our system is reliable, and the absence of image-processing procedures makes it robust. We have initiated a prospective study to validate this technique both for PCNL specialists and as a learning tool.**

INTRODUCTION

IN THE CONTEXT of percutaneous nephrolithotomy (PCNL), percutaneous renal access is a difficult technique, requiring rapid and precise alignment of the puncture needle with a particular calix along the optimized puncture tract through a renal papilla that will decrease the risk of bleeding.[1] In routine clinical practice, percutaneous renal access usually is performed with fluoroscopic or ultrasound guidance or both, with the help of a puncture guide in the latter case. The problems the surgeon has to face lie not only in the anatomic localization and orientation of the targeted kidney, but also in a number of drawbacks presented by those imaging modalities. Fluoroscopy provides mostly static projective images of opacified structures from various orientations; its handling often is cumbersome, and it exposes the patient and the medical staff to a non-negligible radiation dose. Ultrasound provides dynamic sectional images of the kidney and the target, but the speckled noise makes it difficult to delineate and interpret anything. To minimize those drawbacks, some teams have used CT for difficult cases,[2] but the procedure, apart from being time-consuming, remains difficult, as kidney movements cannot be taken into account in real time.

To our knowledge, only two innovative techniques are currently under development as an aid to percutaneous renal access. The first system, called PAKY,[3] is a joystick-controlled robotic arm: during a ventilatory pause, the operator directs the robot to a target identified on fluoroscopic images. Studies currently are under way to automate CT-guided puncture. The second system is an augmented reality tool[4] that projects the preoperative CT scan onto the patient's body. This system does not allow real-time monitoring of the procedure.

We believe that it is possible to improve the precision and safety of percutaneous renal access by using computerized methods to project the ultrasound puncture tract virtually onto preoperative fluoroscopic images. The surgeon can then perform the usual procedure guided by the three-dimensional information displayed on a screen.

The objective of this study was to establish a real-time correspondence between the ultrasound puncture tract and fluoro-

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scopic images acquired at the beginning of the procedure. Such a system would allow better planning of the puncture tract, guided simultaneously by two imaging modalities. The ultrasound puncture tract projected onto fluoroscopic images is only virtual and is visualized as the fluoroscope is no longer is in the operative field. We present the results of our laboratory experiments on a phantom designed to validate this approach, together with the preliminary results obtained in one patient.

MATERIALS AND METHODS

In order to dilate the pyelocaliceal cavities and make them visible on fluoroscopy, we initially place a ureteral catheter in the upper calix according to the usual PCNL procedure. The patient is then placed in the prone position, and the renal pelvis and calices are filled with contrast agent mixed with blue indigo carmine. The ultrasound needle guide we use allows the choice among three nephrostomy tracts.

The principle of image fusion is based on the possibility of spatially localizing the fluoroscope and the ultrasound transducer in the operating room (Fig. 1). We use a Polaris® infrared camera system (Northern Digital Inc, ____________, Ontario, Canada), which depicts reflective markers mounted on the various instruments. This type of localizer is already used routinely with surgical navigation systems (e.g., Surgetics® system, PRAXIM-Medivision, _____________, France), especially in orthopedic surgery.[5] It provides the spatial position of the surgical instruments in real time with submillimeter precision.

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We attach a localization target to the ultrasound transducer (Fig. 2, left) and onto the fluoroscope. A reference rigid body, fixed to the operating table, is used as a fix absolute frame, relative to which every other frame will be localized by the Polaris throughout the operation. Prior to surgical navigation, every reference-holding tool has to be calibrated. This step consists of presenting the localized tool and a mechanical calibrating device to the Polaris (Fig. 2, right), which records the actual shape of the surgical tool. After the calibration step, which takes less than a minute, the ultrasound needle guide and the fluoroscopic images may be localized in space relative to each other.

F2

The first step is the acquisition of fluoroscopic images. Images acquired from various orientations (e.g., −30° and +30°) are particularly useful to allow examination of every calix and determination of the axes of the caliceal stalks. As the kidney moves with breathing with good repeatability,[6] for each image

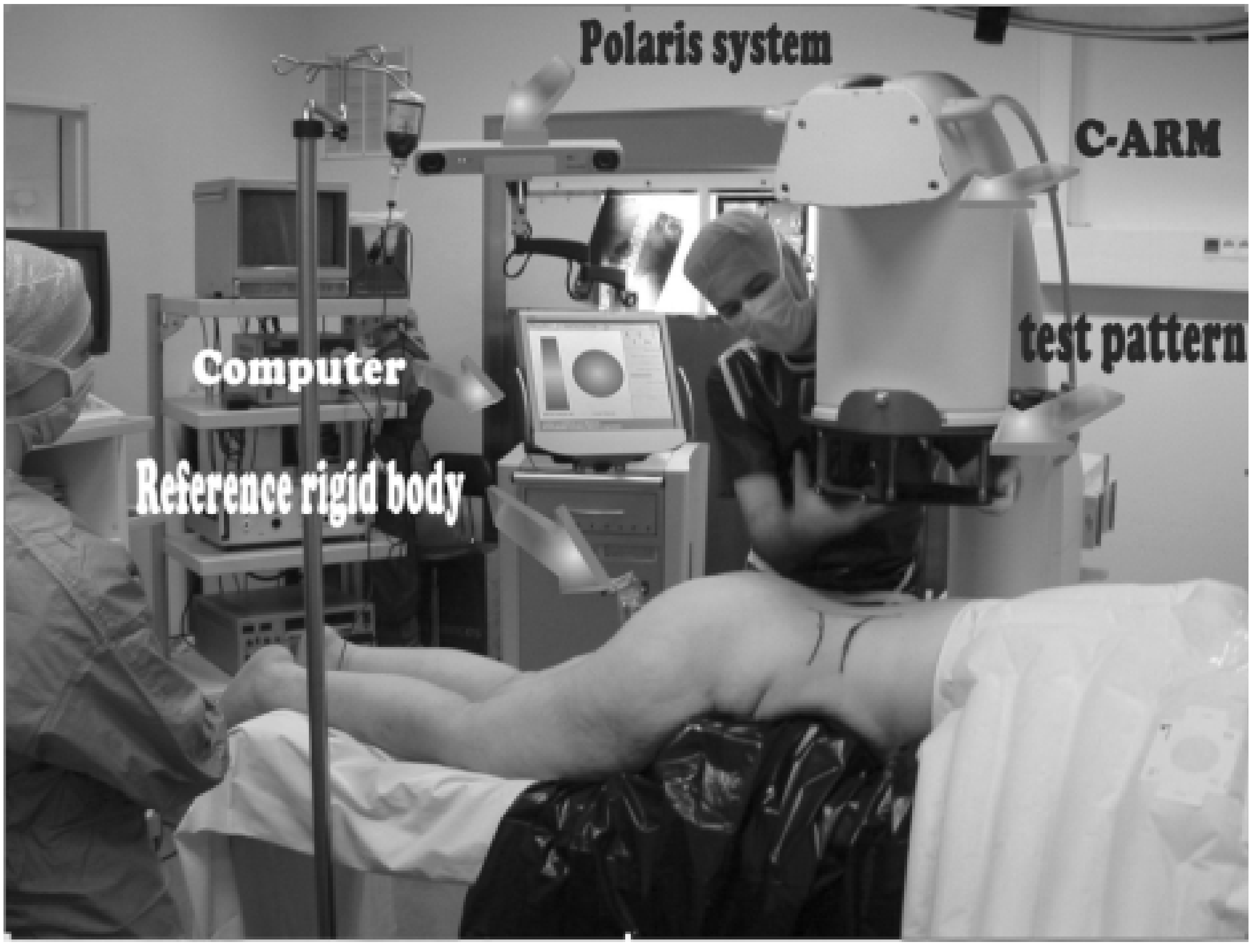

FIG. 1. Operative set-up

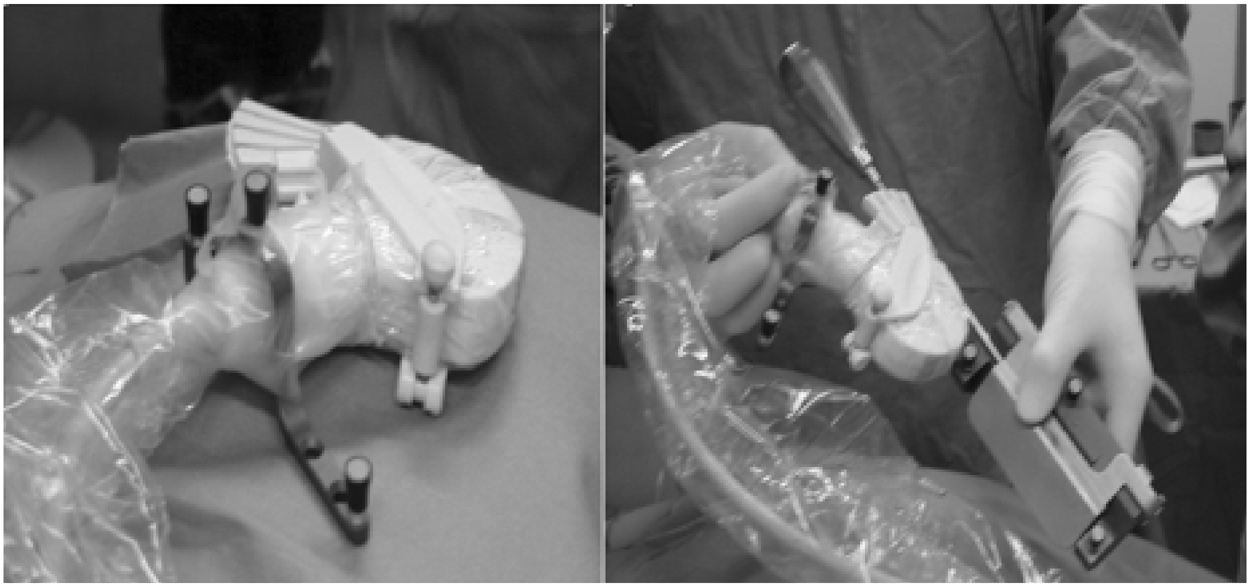

FIG. 2. Left: rigid-body ultrasound transducer. Right: Calibration of nephrostomy tract.

acquisition, the anesthetist is asked to stop ventilation for a few seconds at the end of expiration so that we can acquire a coherent set of images. The fluoroscope is then removed from the operative field to leave more room for the operator.

From this point on, only the ultrasound transducer fitted with its puncture guide is mobilized. The computer system, which has integrated the spatial position of the fluoroscopic images, is able to represent the calibrated nephrostomy tract on them virtually. The operator therefore sees, in real time, both the puncture tract on the ultrasound image and the virtual tract on every fluoroscopic view. In spite of kidney motion, a ventilatory pause with the same insufflated volume as during fluoroscopic acquisition ensures perfect image fusion. The operator is therefore able to determine the optimal puncture tract and can monitor the progression of the needle on the ultrasound monitor. The operator consequently utilizes the respective performances of each imaging system simultaneously. These two imaging systems therefore provide real synergy while leaving the surgeon completely free to perform the operative procedure.

RESULTS

We initially validated our approach using a phantom manufactured in the laboratory that is composed of agar gel containing two metal objects acting as targets that can be seen by both ultrasound and fluoroscopy (Fig. 3). We managed to navigate a calibrated puncture needle to them and verified that the virtual tract was precisely superimposed on the fluoroscopic targets on frontal and lateral views. In parallel, with the phantom immersed in water and as agar gel is transparent, we also measured on the ultrasound image the actual position of the needle tip in the metal objects. We estimated that the correspondence between the two imaging modalities was about 1 mm (Fig. 4).

After approval by our Ethics Committee, we used this system to access the pyelocaliceal cavities in one patient. Figure 5 represents the correspondence of the puncture tract on the ultrasound and fluoroscopic images. The operator, with considerable experience in ultrasonography, verified that the calices visible on the ultrasound puncture tract actually corresponded to the calices vis-

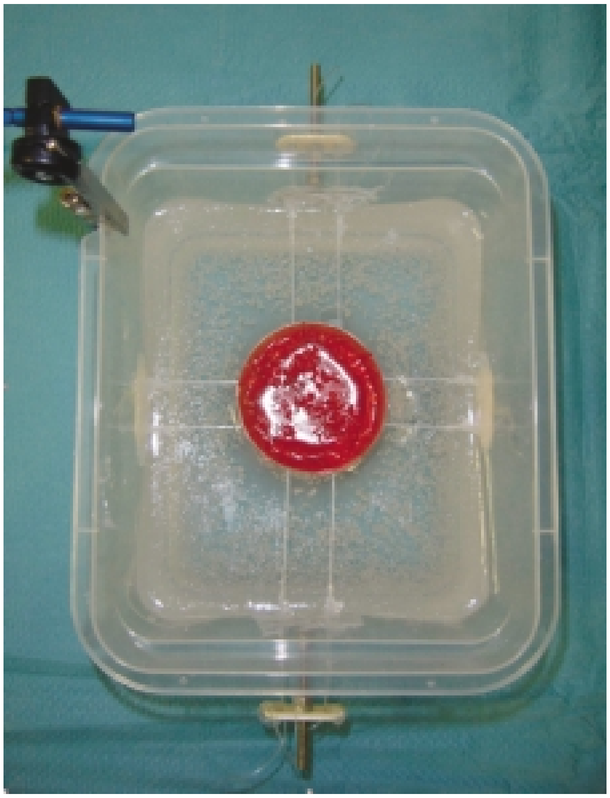

FIG. 3. Phantom with targets visible by fluoroscopy and ultrasonography.

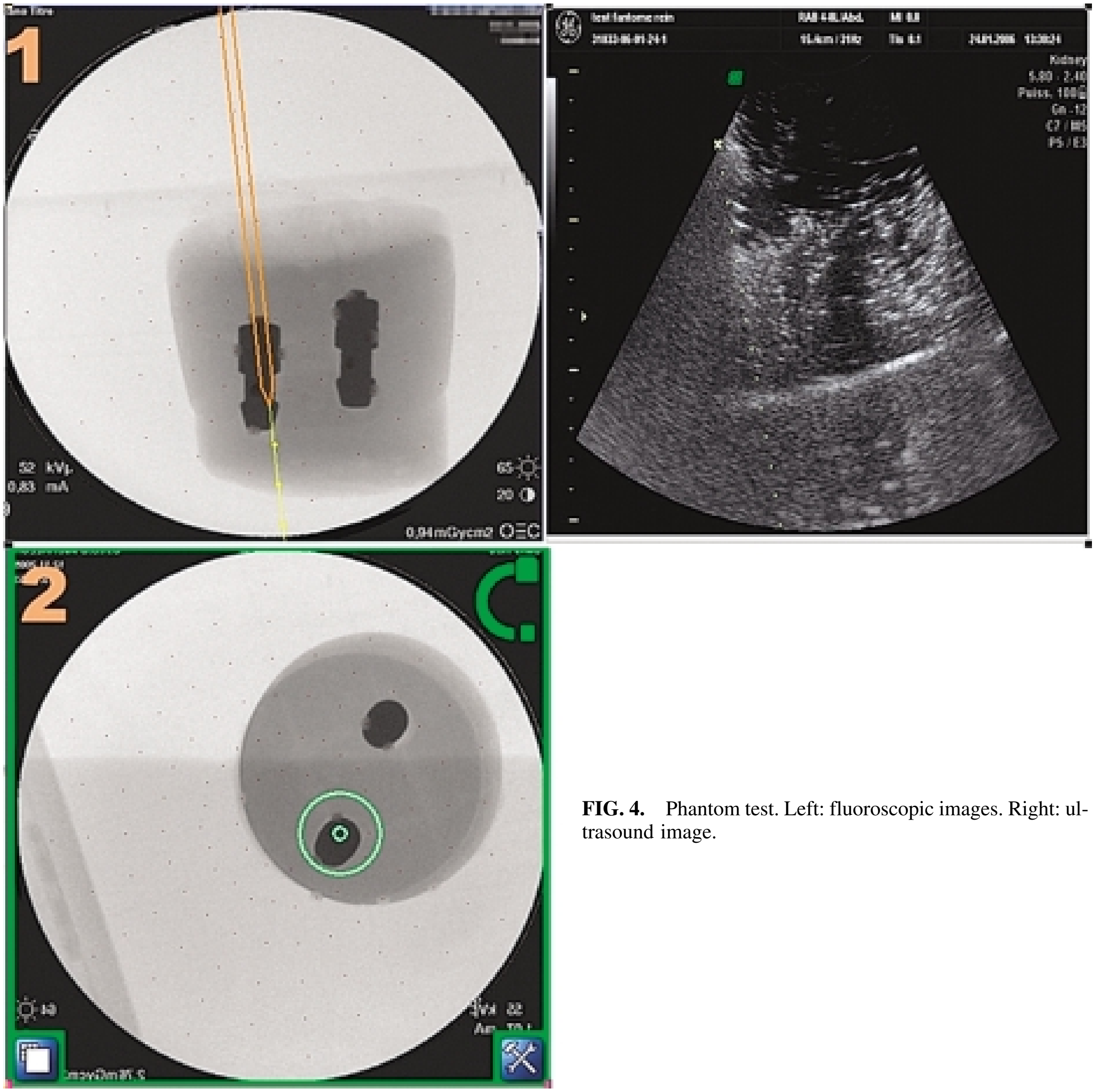

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FIG. 4. Phantom test. Left: fluoroscopic images. Right: ultrasound image.

ible on the virtual fluoroscopic puncture tract. A single puncture was necessary to reach the target, and the needle tract depicted by a fluoroscopic image of the needle corresponded to that chosen by the operator. No intraoperative difficulty or complication was observed, and the duration of X-ray exposure during the puncture phase reached only 0.8 minutes.

DISCUSSION

This idea of superimposing the ultrasound puncture tract onto fluoroscopic images is derived from preliminary studies on ultrasound and CT image fusion performed in our laboratory.[7] We have demonstrated the possibility of fusing images of the kidney derived from these two imaging modalities by delineating (call segmentation process) the renal capsule on CT and ultrasound images. However, although segmentation can be automated for CT images, it becomes more difficult for ultrasound images, for which the manual segmentation of the kidney contours would appear too difficult and time-consuming to perform routinely in the operating room. Our solution, consisting in acquiring a few localized images, can be performed in any operating room and appears to be efficient, as the simple superimposition of the ultrasound puncture tract overcomes the problems of correspondence between CT and ultrasound images.

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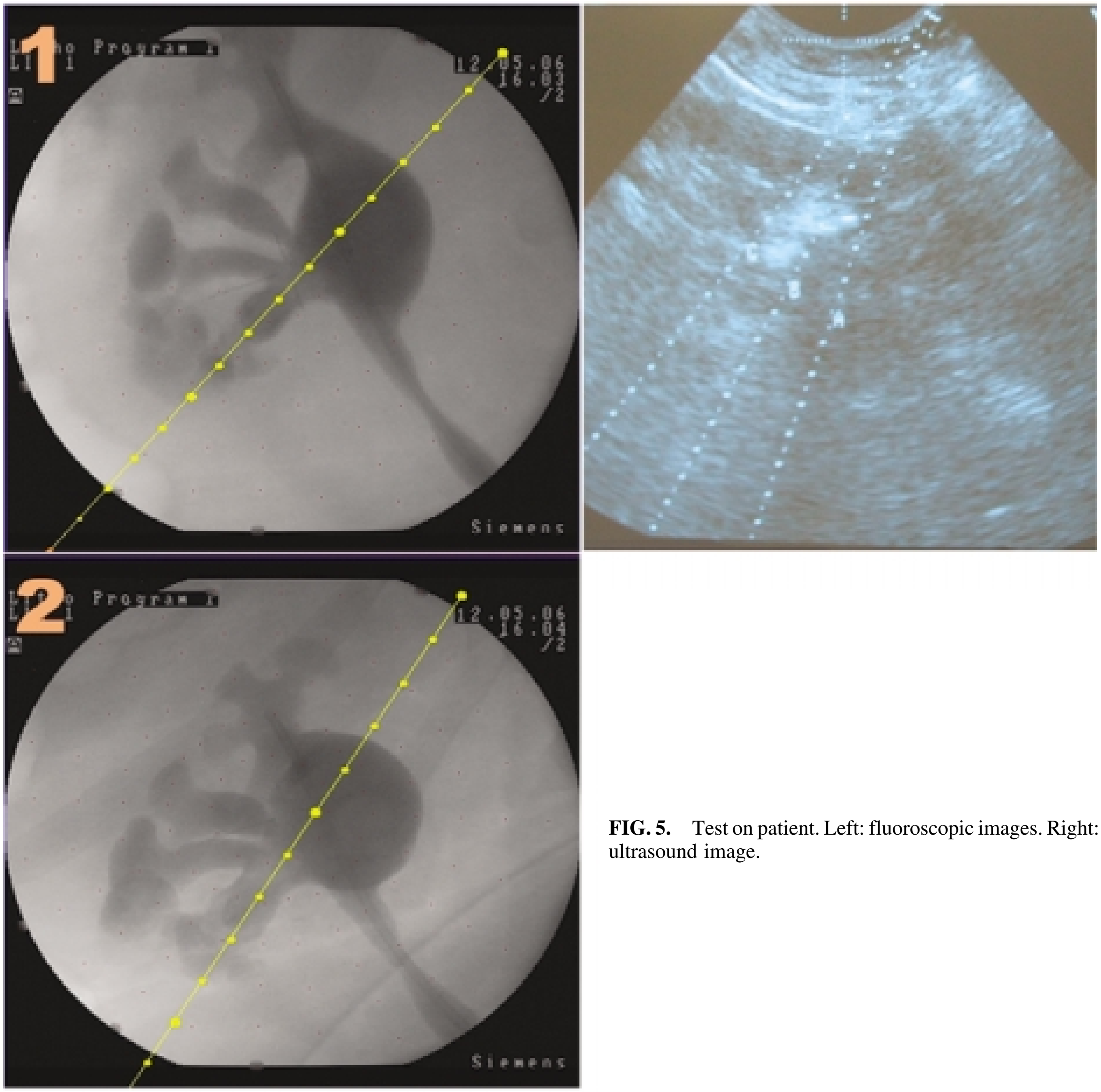

FIG. 5. Test on patient. Left: fluoroscopic images. Right: ultrasound image.

Kidney motion can be considered reproducible with breathing. This property allows the operator to request a short period of apnea at a precise point in the breathing cycle (e.g., deep expiration). That maneuver brings spatial coherence to the set of images and to the virtual navigation provided the patient does not move relative to the reference table. Given the patient setup in the operating room and the general anesthesia, so far, the patient has remained immobile, but one probably should track potential unpredictable motion, which could easily be compensated for by re-calibration of the system.

Regarding the benefit brought by the technique with respect to the introduction in the operating room of a navigation platform, we would argue that this type of device has proved efficient and well integrated in other surgical specialties for more than 10 years and that the potential benefit in time and safety probably justifies the associated cost (<100,000), although long-term economic studies should be carried out.

CONCLUSION

This system can be used to project the ultrasound nephrostomy tract onto fluoroscopic images virtually. This system obviously is generic and is not limited to percutaneous renal access but could also be used for all applications in which the target is visible on both imaging modalities.

The result obtained with the first patient has encouraged us to initiate a prospective study of the value of this system in routine clinical practice.

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ABBREVIATIONS USED

CT = computed tomography; PCNL = percutaneous nephrolithotomy.

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