# Computer-Assisted Percutaneous Renal Access Using Intraoperative Ultrasonography

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*Abstract*—**This paper develops an ultrasound-based surgical navigation system for percutaneous renal intervention. The proposed system integrates preoperative magnetic resonance (MR) planning with intraoperative ultrasonography (US) slices, where the MR imagery is registered to the calibrated US data. The interventional punctures can be performed under a visualized guidance interface. We describe this navigation system in details and evaluate the navigated intervention via a phantom model.**

***Keywords-image-guided; percutaneous renal interventions; ultrasound-based; practicability.***

## I. INTRODUCTION

With increasing deployment of image-guided computer-assisted technology in medical applications, the techniques have been gradually accepted by most people and achieved huge success in past decades. Image-guided computer-assisted surgery technology is very efficient that compromises computer science and biomedicine and brings us a new pattern of thinking that differs from conventional methods of operation. System based on this technique is always implemented by locating positions in space of surgical instruments, calculating the location of the instrument tip in relation to the patient, and reconstructing the models of instrument tip as well as the body anatomic structure of the patient. Preoperative MR images and intraoperative ultrasound images are employed for preoperative planning and intraoperative navigation.

There are several useful applications of image-guided technique available currently. Robot-assisted dental surgery proposed in [1] uses CT data to render a target region and a pathway associated with relative organs before operation and provides three-dimensional (3D) orientation of surgical instrument position and trajectory displayed on a monitor in real-time within patient's 3D imaging data. Another application is expressed in [2] that navigation technology viewed as a method to improve visualization during surgery and served as an adjunct to nasal endoscopy replaces the conventional technique for opening obstructed and diseased sinus outflow tracts. In [3], a system based on intraoperative 3D ultrasound volumes for image-guided navigation of surgical instruments for live surgery is put forward. All applications of image-guided techniques above have been showed its advantages over the same kind of surgery without using image-guided technique, and they are proved to be able to take place of traditional ways of surgery in near future.

All our work in this paper is aiming to apply image-guided technique into renal calculus surgery and work out an ultrasound-based navigation system for it.

## II. DESCRIPTION

Our proposed navigation system mainly consists of three parts: preoperative planning, intraoperative registration, and intraoperative visualization, which is shown in more detail in Fig. 1.

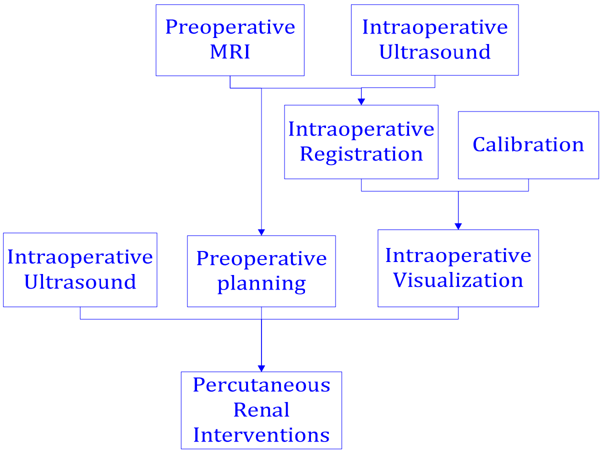


Figure 1. Procedures of Ultrasound-based Surgical Navigation for Percutaneous Renal Interventions

The particularly and scientifically designed system would provide us a precise judgment and scientific diagnosis all along the percutaneous renal interventions.

Before operation, we obtain several MR slices of patients' abdomen, and with which, the doctors can analyse the situation about the patient and get some information of renal calculus. The previous MR images are then utilized to register with the intraoperative ultrasound images to give out a precise relationship between them so as to let doctors find the corresponding position in the kidney from the patient. Therefore, with the information above, we can make out a preoperative planning which includes the best puncturing points and paths of the kidney. The Polaris optical tracking system used in our system plays an important part in the intraoperative visualization procedure for its tracking and locating functions, which provides us exact coordinates of the surgical instruments and ultrasound probe that are to be used to calibration and reconstruction, and we will illustrate this in details in the calibration and visualization parts.

## III. METHOD

### A. Preoperative Planning

Safety and accuracy are the most important characteristics that we are seeking for of our system. The procedure of preoperative planning is designed to make sure that surgery be done under safe and accurate condition. In this paper, we illustrate our theory based on experiments, and we make all our experiments on a phantom with processed stones manually placed inside the kidney of the phantom to make the “renal stones” easily be seen under MR.

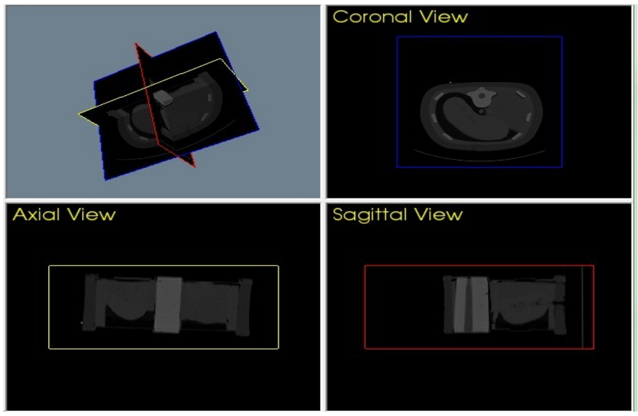
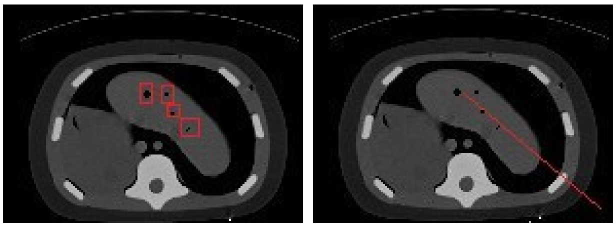


Figure 2. A unit of MR data displayed in coconal, axial, and sagittal planes, respectively.



(a) (b)

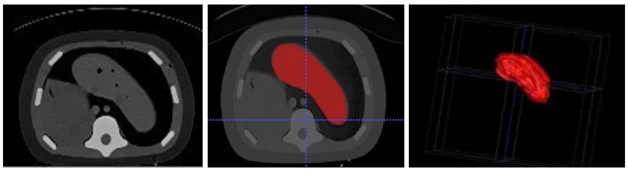
Figure 3. Find out renal stones and decide puncturing point and path. (a) Distribution of “renal stones” in kidney. (b) The best puncturing point and path.

Generally, in this step, we obtain a lot of MR images of the kidney from the patients, both inside and outside. As shown in Fig. 2, the MR images are a unit of cuboidal data and a detailed nephritic anatomy, which allow us to display them simultaneously in the coronal, axial, and sagittal planes, from which we can easily find the geometric distribution of the kidney.

We work with the MR slices aiming to get some information about the positions of kidney and renal stones of the patient on the whole. And then, we discuss and analyze this information and make various plans as for various situations.

In most cases, the renal calculus are always not in regular distribution or gathered together in spatiality, which makes it a big problem for the surgeon to decide the best position to puncture. So, what we can and need to do is making a careful plan to make sure that we clean up the calculus with a more precise point of puncturing and use the least amount of needle puncturing. As shown in Fig. 3, the renal stones have been marked in MR image, and the best puncturing point and the best puncturing path have been marked as well. So it’s not only convenient for surgeon to decide how to carry out the operation, but also safety and accurate for the whole surgery.

The next we need to do is segmenting kidney from the surrounding abdominal viscera. Firstly, we manually outline the contour of the kidney and present clear indication of the region. Then, we carry out 3D segmentation method by dealing with the feature of the contour. It doesn’t take much time to implement this procedure and the result is feasible for guidance. This is the procedure of preoperative planning, and it is really a progress over the operations with current methods.



(a) (b) (c)

Figure 4. Preoperative planning. (a) MR slices displayed simultaneously in the coconal, axial and sagittal planes. (b) An MR slice set as original data. (c) 3D segmentation of kidney.

### B. Ultrasound-based Navigation and Registration

Although, Ultrasonography is less accurate than MR, it can consistently provide us real-time images during operation and produces no radiation risks when being used, what’s more, ultrasound is economical and with a higher speed of imaging, which would be more useful and important in the course of operation than using MR and CT. With known positions of renal stones and exact path in the preoperative planning, we can find out the corresponding positions and path in the ultrasound image, as shown in Fig. 5.

The registration procedure is to establish a relationship between preoperative MR images coordinate system and intraoperative ultrasound images coordinate system, that is, we must give out a transformation matrix which is able to translate from any point in the MR images to the same point in the ultrasound images, so as to find the precise point on the intraoperative ultrasound images corresponding to the preoperative MR images [4]. We chose kidney surface as the feature for registration. The intraoperative surface data is obtained from ultrasound. With this data, we use iterative closest point (ICP) method for registration with the preoperative MR volume. Firstly, we identify anatomical landmarks on or near the kidney edges and use them to get a coarse registration. Then, we can identify the corresponding positions of these landmarks intraoperatively by touching them with the tracked probe whose position is located by the Polaris optical tracking system. When the positions of all anatomical landmarks have been obtained, a point-based registration is figured out that produces minimization of the root-mean-square distance between corresponding anatomical landmarks [5]. However, the result is not accurate enough due to the possibility of deformation and difficulty in localizing landmarks. It is still an acceptable result that is close enough to make ICP reach a suitable minimum. In addition, with registered images, we have no difficulty identifying the same position in both two image coordinate systems.

### *C. Coordinate Systems and Ultrasound Calibration*

This section is an important part in our navigation system, where we establish mathematic relationship among coordinate systems included in our navigation system.

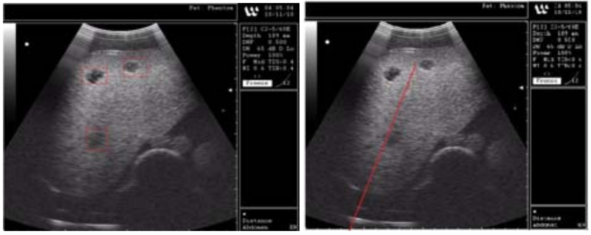

(a) (b)

Figure 5. Intraoperative ultrasound image. (a) Renal stones in the ultrasound slice. (b) Corresponding puncturing point and path in ultrasound slice.

Fig. 6 shows the coordinate systems here and simple relationship of them. Optical tracker tracks the positions of markers in its measurement volume, so we can precisely locate the reference tool and surgical instrument by the markers attached to them in coordinate system of the optical tracker. So, we can locate the ultrasound probe by the readings of the optical tracker, and we set reference tool as the world coordinate system, which all coordinates of any instrument need to be translated into as to unite. Ultrasound provides us body anatomy structure by its image, but we can not obtain positions of points on its image directly, which remains us a problem to be solved.

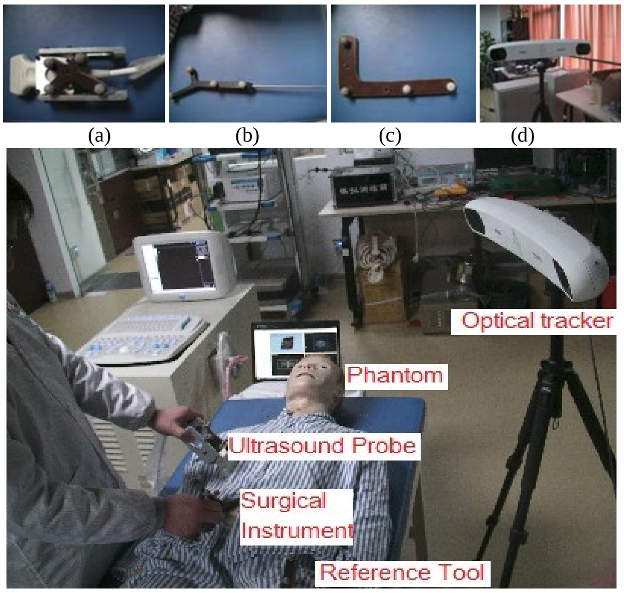
From Fig. 7, we can have a full understanding of the relations in our system. Each pixel in the ultrasound scan plane location is transformed first to the coordinate system of the ultrasound probe, then to the optical tracker coordinate system, and finally to the reference coordinate system, then we can get coordinate information of every pixel in the world coordinate system.

The overall transformation between coordinate system and world coordinate system can be expressed as the following multiplication of homogeneous transformation matrices:

$$X_{\mathrm{w}} = T_{o\to w}\cdot T_{p\to o}\cdot T_{u\to p}\cdot X_u \tag{1}$$

where

$$X_u = (s_x u, s_y v, 0, 1)^T \tag{2}$$


(a) (b) (c) (d)

(e)

Figure 6. Coordinate system of our system. (a) Ultrasound probe with optical markers and probe coordinate system. (b) Optical tool used as surgical instrument in our experiment and attached with optical markers and its instrument coordinate system. (c) Reference tool and world coordinate system. (d) The Polaris optical tracking system and optical tracker system. (e) All coordinate systems and their functions in our navigation system.

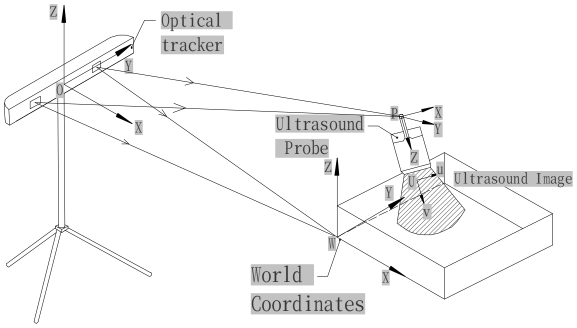


Figure 7. Relationship between coordinate systems in our navigation system and ultrasound calibration

For the sake of calculation, we set the top center of the ultrasound image as the origin. The *u* and *v* above are the column and row indices of the ultrasound image, and $S_x$ and $S_y$ are the scale factors with units of mm/pixel, respectively [6]. The point at position ($u$, $v$) in the ultrasound image is first scaled by $S_x$ and $S_y$ [7]. Then it is mapped to ultrasound probe coordinate system by transformation $T_{u\to p}$, then into the optical tracker coordinate system by $T_{p\to o}$, and finally into the world coordinate system by $T_{o\to w}$. After all these translation steps are achieved, we get the coordinates of the points on the image in the world coordinate system $X_{\mathrm{w}}$, and here

$$X_w = (x, y, z, 1)^T \quad (3)$$

So, (1) can be translated as:

$$\begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} = T_{o\to w} T_{p\to o} T_{u\to p} \begin{pmatrix} s_x u \\ s_y v \\ 0 \\ 1 \end{pmatrix} \quad (4)$$

In this equation, we can precisely know the coordinates of every point in the world coordinate system by its optical relationship between the optical tracker and markers in the reference tool, that is, the $T_{o\to w}$ is known. Similarly, the transformation $T_{\mathrm{p}\to o}$ between ultrasound probe and the optical tracker sensor coordinate system is not necessary to calculate for the acquisition of the passive markers attached to the ultrasound probe by our Polaris tracking system. That leaves just $T_{u\to p}$ , which needs to determined by calibration, and calibration for our navigation system involves determining the position and orientation of the ultrasound, which is performed by scanning a phantom with known geometric dimensions. We use “cross-wire phantom” method in our system to process calibration. The method uses two intersecting wires that are both mounted in a water bath and place the optical tracker at a fixed location with respect to the two wires, What’s more, the origin is set at the intersection of the two wires [8,9]. Another like “three-wire phantom” method [10] and “Cambridge phantom” method [11] are also useful for calibration.

### D. *Intraoperative Visualization*

In our navigation system, we focus on information of images of the kidney and stones via MR and ultrasound. From intraoperative ultrasound image, we can capture progress of surgery in real-time directly. Registration provides us clearly corresponding relations between intraoperative ultrasound images and preoperative MR images, with which we can easily and exactly find the points for needle puncturing and paths rather than using endoscope. Coordinate systems in our navigation system and ultrasound calibration help us reconstructed a navigation system by these relations. The position of surgical instruments can be dynamically obtained by optical tracker sensor, so we can monitor the surgery in real-time as to identify the potential risk and carry out the operation of renal calculus safely and smoothly. What is more, with segmentation and 3D reconstructed techniques, the kidney can be re-established through the unit of preoperative MR images. With these, the surgery will go smoothly with safety and accuracy. However, conventional surgery is operated under poor visualization, and doctors are always not able to get enough sight in this condition, which may result in potential danger during the operation and not clearing up renal stones absolutely.

## IV. CONCLUSION

In this paper, we have proposed our theory and made some investigation on the ultrasound-based surgical navigation for percutaneous renal interventions aiming to find a new way to take place of conventional methods for surgery of renal stones. We have made detailed explanations for each part of our navigation system and evaluated its practicability. To illustrate the convenience and advantages of our navigation system, we have made a lot of contracts with conventional surgery without navigation systems both by theories and experiments and evaluate its practicability. The goals of improving our proposed technique will continue to be vigorously pursued.

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