ULTRASOUND-BASED SURGICAL NAVIGATION FOR PERCUTANEOUS RENAL INTERVENTION: IN VIVO MEASUREMENTS AND IN VITRO ASSESSMENT

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ABSTRACT
This paper evaluates the feasibility of a proposed ultrasound-based surgical navigation system for percutaneous renal intervention via in vivo measurements and in vitro assessment. The system integrates preoperative computer tomography (CT) planning with intraoperative ultrasonography (US) by means of a proposed semi-automatic US to CT rigid registration. The interventional procedure is performed with a visualized guidance interface. The navigation system is evaluated at two levels. Level I evaluation comprises measurements of the accuracy, precision, and processing time of our registration method on in vivo data provided by volunteers. For Level II, expert urologists are asked to rate the perceptual quality of the system via in vitro tests on a kidney phantom. Both objective and subjective evaluations validate the proposed surgical navigation system.

Index Terms—Surgical navigation, ultrasound, CT to US registration, evaluation, percutaneous renal intervention.

1. INTRODUCTION

Computer-assisted surgical navigation aims to provide surgeons with anatomical target localization and critical structure observation, where medical image processing methods such as segmentation, registration and visualization play a critical role. One promising application of surgical navigation is percutaneous renal intervention, which refers to a surgical procedure where access to a target inside the kidney is achieved via a needle puncture of the skin. This procedure is of vital importance in several minimally-invasive surgeries of the kidney, such as Percutaneous Nephrolithotomy (PCNL) and radiofrequency ablation (RFA) of kidney tumors [1].

Intraoperative navigation is critical for percutaneous renal intervention, because the accuracy of the puncture without navigation cannot be guaranteed and injury to vital structure could occur. It has been shown that ultrasonography (US) is a good alternative to traditional fluoroscopy as intraoperative guidance for renal puncture, since it is radiation-free, portable, and economical [2]. Current computer-assisted navigation often incorporates a preoperative surgical planning. The purpose of surgical planning for percutaneous renal intervention is to compute an optimal needle trajectory using 3D reconstructed preoperative images such as computer tomography (CT) or magnetic resonance (MR). A major challenge of renal intervention navigation is to realize the surgical plan on the patient in the operating room [1]. The US-based renal navigation is difficult because of more soft-tissue deformation and poorer quality of abdominal US images.

To address this problem, registration between the preoperative CT or MR volume and the intraoperative abdominal US has been studied. After the registration, the spatial transformation between pre- and intraoperative modalities can be known, such that the preoperative planning can be transferred onto the patient in situ. The existing registration approaches can be categorized into voxel intensity- and feature-based methods. The main advantage of intensity-based methods is the property of automatic registration, i.e., no manual operation is required. However, the similarity measure is a big problem as the intensity correlation between different modalities is not that explicit [3]. Multi-modality registration can be facilitated by means of anatomical features such as vascular structures or organ surface. However, the intraoperative feature selection is often time-consuming and less reliable [4]. Furthermore, most of the existing methods need densely-sampled intraoperative US volume, leading to extensive processing time and substantial workflow variations that prevent them from clinical use.

In this paper, we evaluate the feasibility of a proposed ultrasound-based surgical navigation system for percutaneous renal intervention via in vivo and in vitro tests. A semi-automatic CT to US rigid registration transfers the preoperative planning onto the intraoperative context. A visualized guidance interface aids the correct execution of the planning. The system is evaluated at two levels. At Level I, the accuracy, precision and processing time of our registration method are measured on in vivo data. At Level II, four urologists with expertise in renal interventions are asked to rate the perceptual quality of the navigation system according
to a custom scoring method via in vitro tests on a kidney phantom. Both objective and subjective evaluations validate the proposed navigation techniques.

The rest of the paper is organized as follows. Section 2 describes the navigation system in more detail, including preoperative planning and intraoperative navigation. In Section 3, we describe the experimental data and the related evaluation results. Section 4 concludes the paper.

2. SYSTEM AND METHODS

2.1. System Description

An overview of our surgical navigation system is given in Fig. 1. The devices used include diagnostic ultrasound device, optical tracker and main computer. The medical image processing methods employed are shown in gray rectangles in Fig. 1. The navigated surgery workflow consists of preoperative surgical planning and intraoperative surgical navigation.

First, the patient is scanned by CT and the kidney, vessels and tumors are then segmented from the CT volume as a 3D model, such that a surgeon can make an optimal surgical plan preoperatively. During the surgery, the tracker reads the positions of markers fixed on the needle and the US probe, while the preoperative data and the surgical plan are registered to the calibrated intraoperative US images. Then, the preoperative plan can be transferred into the operating room. With an image-guidance interface, the interventional puncture can then be performed in accordance with the surgical planning, based on the hand-eye coordination of the treating surgeon. Next, we will describe in detail the image processing methods involved in each stage of the navigated surgery workflow.

2.2. CT-based Preoperative Planning

In percutaneous renal interventions, needles have to be inserted from skin to accurately reach an intrarenal target. During the insertion, extra accuracy is required to avoid any damage of large vessels and kidney calices which in turn may lead to serious complications. With a surgical planning based on preoperative CT, surgeons can preoperatively design a needle trajectory that is optimal for the insertion. The prerequisite of a surgical planning is the segmentation of kidney parenchyma and vascular structures from contrast enhanced CT. First, we manually choose a cube that mainly contains kidney voxels and apply the semi-automatic algorithm from [5] to segment the kidney parenchyma and abnormal tissue. The vessels and skeleton can be segmented via a threshold algorithm. All segmented models are then visualized via 3D rendering, as shown in Fig. 2. A 3D planning can then be defined.

2.3. Ultrasound-based Intraoperative Navigation

We expect to provide intraoperative navigation by transferring the preoperative planning to the intraoperative conditions and guiding the puncture with a visualized user interface. The important consideration is the acceptability and feasibility of the proposed navigated intervention in clinical context.

The intraoperative medical processing starts with the calibration of the US probe. In particular, we determine a homogeneous transformation $T_{C}$ that maps pixel positions from 2D US plane to 3D space $S_{US}$ defined by the optically tracked markers mounted on the US probe, as shown in Fig. 1. We use the method described in [6] to achieve a rapid calibration. After a further transformation $T_{T}$ from local space $S_{US}$ to the coordinate system $S_{tra}$ defined by the tracker, all US images can be localized in the same space $S_{tra}$. On the other hand, we want to acquire the US slices at the same stages of the respiration cycles, in order to account for the breathing motion and ensure consistency of all used US slices. This can be achieved by optically tracking the positions of the US probe and recording the US slices acquired at the maximum exhalation positions of each respiration cycle.

Next, we aim to transfer the preoperative planning onto the patient in situ by means of CT to US registration. Presently, surgeons need an effective image guidance that optimizes the surgeon’s hand-eye coordination, but are often reluctant to accept over complicated navigated intervention workflow. To this end, we do not use the CT to dense US volume 3D-3D registration studied by some groups, which requires overlong intraoperative processing time. Instead, we propose a more practical approach on top of a semi-automatic rigid registration based on orthogonal US images.
First, the US probe is swept near the 11th intercostal space. A few US images are acquired at the maximum exhalation positions. Two pairs of almost orthogonal images, \( U_1, U_2, U_3 \) and \( U_4 \) are selected, where \( U_1, U_2 \) are approximately parallel to the transverse section of the human body and \( U_3, U_4 \) are acquired with the probe along the midaxillary line. \( U_1, U_2 \) should contain clearly visible hilum vein, inferior vena cava (IVC), and a transverse kidney contour while \( U_3, U_4 \) a longitudinal kidney contour.

Next, a semi-automatic rigid registration is performed for the alignment of the US slices and the CT volume, using kidney surface and large vessel surface as registration features. The target feature consists of kidney surface, hilum vein surface and IVC surface preoperatively segmented from CT. The source feature is a set of manually-picked points on kidney contour in all US slices, and on hilum vein surface and IVC surface in \( U_1, U_2 \). Because we only use two pairs of orthogonal slices, the point picking will be completed within reasonable time. The feature data are categorized into kidney, hilum vein and IVC to aid the alignment. The iterate closest point (ICP) algorithm proposed in [7] is used to estimate the transformation \( T_R \) that minimizes the root mean square (RMS) error between the target and source feature sets. The estimate starts with manually aligning \( U_1, U_2 \) to an axial CT slice and \( U_3, U_4 \) to a coronal one based on the kidney surface under the multiplane reformatted (MPR) mode display of the CT data. The orthogonal geometry of the US slices can effectively facilitate the manual alignment. This manual preprocessing allows quick algorithm convergence without falling into local minima, thus reducing the computing time while improving the reliability. The translation and rotation parameters are then optimized using ICP within \( \pm 32 \text{mm} \) and \( \pm 24^\circ \) to minimize the RMS error. With the final estimate of \( T_R \), the transformation from the US plane to the CT image space \( S_{CT} \) can be given by \( T = T_C T_T T_R \). Fig. 3 shows the corresponding US and CT slices from a patient with renal cell cancer, where the tumor is labeled in both images.

Based on \( T_R \), the planned puncture path can be transferred from the preoperative space \( S_{CT} \) into intraoperative space \( S_{tra} \). The needle position can be precisely measured by the tracker in realtime. At the maximum exhalation, the needle is rapidly inserted into the intrarenal target under the navigated guidance. The navigation interface is shown in Fig. 4, based on which the puncture trajectory can be guided and guaranteed to be coincident with the planning.

### 3. EXPERIMENTAL EVALUATION

The feasibility of the proposed surgical navigation system is evaluated at two levels, including Level I accuracy measurements on \( in vivo \) data, and Level II \( in vitro \) perceptual quality assessment on a kidney phantom.

For the Level I evaluation, we aim to measure the registration accuracy in terms of the RMS target registration error (TRE) on \( in vivo \) CT and US data. Because no gold standard is available for kidney registration, we use the CT to dense US volume registration proposed in [4] as a bronze standard [8]. The CT data was acquired from three healthy volunteers (distinguished by A, B, C) on a BrightSpeed system from General Electric (GE) at 120kV, 54mA, with a 2.5mm thickness and 2.5mm reconstruction interval. The volunteers were asked to hold breath at the maximum exhalation when being scanned. Therefore we can assume that the kidney deformation between CT and US images is very small and can be neglected in this preliminary study. The US slices were acquired with a GE LOGIQ 5 machine and a 3.5MHz probe. For calculating the bronze standard, 110 US images were selected at the maximum exhalation from each volunteer, covering from transverse to longitudinal views of the kidney. Four urologists with expertise in US-guided renal intervention were asked to individually conduct the proposed registrations and the bronze standard for each volunteer (denoted as Test1-4).

The accuracy can then be measured as follows. All voxel positions within the segmented kidney were transformed from \( S_{CT} \) into \( S_{tra} \), using both the proposed registration and the bronze standard. The RMS error between the two result position sets was then calculated. Thus, the accuracy in terms of RMS TRE was given. To evaluate the precision, or repeatability of the proposed method, the RMS distance from the transformed positions to their average, i.e. the standard deviation, was calculated. The elapsed time including the manual alignment time and the algorithm computing time for the proposed registration was also recorded. All results are given in Table 1 and Table 2. The results in Table 1 show a good convergence to the bronze registration within reasonable processing time. No evident failures were found. We believe this has benefited from the manual initiation by the expert interventionists.

![Fig. 3. US slice (left) and corresponding CT slice (right).](image1)

![Fig. 4. Left: puncture plane. Right: 3D navigation interface.](image2)
where local minima was avoided. The Table 2 results prove the registration to be repeatable for the tested \textit{in vivo} data.

For the Level II evaluation, the same four interventionists were asked to rate the perceptual quality of the system via \textit{in vitro} tests on a kidney phantom. The perceptual quality of the navigation system for surgeons is very important, as their satisfaction relates to the therapeutic impact in selecting the system. First, a triple-modality 3D abdominal phantom model 057 from Computerized Imaging Reference Systems (CIRS) was scanned by CT. With the reconstruction of the segmented models, a planning trajectory was defined. A passive Polaris system from Northern Digital Incorporation (NDI) was used for position tracking. After CT to US registration, the needle punctures were performed by the four interventionists individually under the proposed visualized guidance. Then, the perceptual quality was rated in terms of three criteria according to a custom scoring system, as follows:

**Table 2.** \textit{In vivo} measurement of the precision (in millimeter-s).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Test1</th>
<th>Test2</th>
<th>Test3</th>
<th>Test4</th>
<th>Mean</th>
</tr>
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<tr>
<td>RMS TRE A</td>
<td>4.12</td>
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<td>4.72</td>
<td>4.56</td>
<td>4.76</td>
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<tr>
<td>Elapsed Time A</td>
<td>10</td>
<td>13</td>
<td>7</td>
<td>15</td>
<td>11.3</td>
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<tr>
<td>RMS TRE B</td>
<td>2.62</td>
<td>3.13</td>
<td>2.96</td>
<td>2.44</td>
<td>2.79</td>
</tr>
<tr>
<td>Elapsed Time B</td>
<td>12</td>
<td>16</td>
<td>8</td>
<td>10</td>
<td>11.5</td>
</tr>
<tr>
<td>RMS TRE C</td>
<td>3.23</td>
<td>3.60</td>
<td>4.10</td>
<td>2.97</td>
<td>3.48</td>
</tr>
<tr>
<td>Elapsed Time C</td>
<td>8</td>
<td>12</td>
<td>7</td>
<td>10</td>
<td>9.3</td>
</tr>
<tr>
<td>Grand Mean</td>
<td>RMS TRE: 3.68 Elapsed Time: 10.7</td>
<td></td>
<td></td>
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</table>

**Table 3.** \textit{In vitro} assessment of the perceptual quality.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Test1</th>
<th>Test2</th>
<th>Test3</th>
<th>Test4</th>
<th>Mean</th>
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<td>4</td>
<td>4.5</td>
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<td>3.1</td>
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<tr>
<td>Clin Relvce</td>
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<td>3.5</td>
<td>4</td>
<td>3.5</td>
<td>3.8</td>
</tr>
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</table>

4. CONCLUSION

We evaluated the feasibility of a proposed ultrasound-based surgical navigation system for percutaneous renal intervention via both \textit{in vivo} and \textit{in vitro} tests. The system provides a 3D preoperative planning, which can be transferred onto the patient in operating room by a proposed semi-automatic rigid CT to US registration. A 3D interface helps to perform the navigated needle puncture. Both \textit{in vivo} measurement of the accuracy, precision, and processing time and \textit{in vitro} assessment of the perceptual quality validate the proposed system.

5. REFERENCES


