Ultrasound-Based Image Guidance for Robot-Assisted Laparoscopic Radical Prostatectomy: Initial *in-vivo* Results

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Abstract. This paper describes the initial clinical evaluation of a real-time ultrasound-based guidance system for robot-assisted laparoscopic radical prostatectomy (RALRP). The surgical procedure was performed on a live anaesthetized canine with a da Vinci SI robot. Intraoperative imaging was performed using a robotic transrectal ultrasound (TRUS) manipulator and a bi-plane TRUS transducer. Two registration methods were implemented and tested: (i)using specialized fiducials placed at the air-tissue boundary, 3D TRUS data were registered to the da Vinci stereo endoscope with an average TRE of 2.37 $\pm$ 1.06 mm, (ii)using localizations of the da Vinci manipulator tips in 3D TRUS images, 3D TRUS data were registered to the kinematic frame of the da Vinci manipulators with average TRE of 1.88 $\pm$ 0.88 mm using manual tool tip localization, and average TRE of 2.68 $\pm$ 0.98 mm using an automatic tool tip localization algorithm. Registration time was consistently less than 2 minutes when performed by two experienced surgeons after limited learning. The location of the TRUS probe was remotely controlled through part of the procedure by a da Vinci tool, with the corresponding ultrasound images being displayed on the surgeon console using TilePro. Automatic tool tracking was achieved with angular accuracy of 1.65 $\pm$ 1.24 deg. This work demonstrates, for the first time, the *in-vivo* use of a robotically controlled TRUS probe calibrated to the da Vinci robot, and will allow the da Vinci tools to be tracked for safety and to be used as pointers for regions of interest to be imaged by ultrasound.

Keywords: Image guided surgery, Robot-assisted prostate surgery, da Vinci surgical robot, 3D ultrasound.

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1 Introduction

Robot-assisted laparoscopic radical prostatectomy (RALRP) using the da Vinci system (Intuitive Surgical Inc., Sunnyvale, CA) has become widely accepted and is now used to perform up to 80% of radical prostatectomy (RP) procedures in the United States [1]. While robot assistance has enhanced the visualization of the surgical site and has improved dexterity over standard laparoscopic instruments, achievement of the three main RP outcomes - cancer control, urinary control and sexual function - is still highly dependent on the expert understanding of the prostate and periprostatic anatomy [10]. It can be challenging to localize critical structures such as the bladder neck, the neuro-vascular bundles (NVB), the urethral sphincter muscle, and to define accurate dissection planes solely using visual cues [9]. Intraoperative imaging may aid the surgeons in localizing these structures. Trans-rectal ultrasound (TRUS) is the most commonly applied modality for imaging the prostate and the only approach implementable in a standard operating room (OR). To be useful, the TRUS transducer must be positioned and controlled by the surgeon in an intuitive way. Furthermore, the TRUS images should be displayed at a correct location relative to the da Vinci vision system and the da Vinci instruments.

Recently, robotic TRUS manipulators have been used for real-time guidance during RALRP procedures [10,9,8]. Hung *et al.* used a robotic TRUS manipulator (ViKY system, EndoControl medical, Grenoble, France) for real-time monitoring of the prostate and periprostatic anatomy. They showed that using robotic TRUS is feasible and safe, and it provided the surgeon with valuable anatomic information [9]. Long *et al.* used the same TRUS robot to visualize real-time bladder neck dissection, NVB release and apical dissection [10]. They showed that using robotic TRUS resulted in no positive surgical margins in five patients. Han *et al.* used their custom-made robotic TRUS manipulator for improved visualization of the NVB. This study demonstrated that the prostate can be safely scanned using the TRUS robot, to reconstruct the 3D images of the prostate gland and adjacent NVB, and the intra-abdominal da Vinci instruments can be clearly visualized in the TRUS images [8].

In previous *in-vivo* studies, the TRUS manipulators have not been registered to the da Vinci robot or camera, and therefore the ultrasound image could not be presented at the correct location in space relative to the console view or the da Vinci instruments. The control of the TRUS image location from within the da Vinci console has also not been demonstrated before in *in-vivo* studies. The work presented in this paper describes the evaluation of a robotic TRUS guidance system, performed *in-vivo* on a canine model. The contributions of this study include showing that registered robotic TRUS imaging can be deployed and used easily during surgery with high accuracy in a short time, and that TRUS imaging can be controlled in the registered coordinate system directly from within the surgeon console. We used a live anaesthetized animal before engaging in human studies in order to verify the feasibility and the safety of our approach, which requires some additional steps to conventional RALRP. The canine model is the most often used for various urologic procedures in the kidney, urethra, bladder, prostate and bowel [5].

Similarly to [2], the robotic system used in this work for real-time TRUS imaging has two degrees of freedom (translation along the TRUS axis and rotation about the TRUS axis) and is mounted on a brachytherapy stabilizer. In order to determine the location of the TRUS probe with respect to the da Vinci coordinate system, we follow the approach from [11] to localize the da Vinci instruments tips in the TRUS volume at multiple locations. After registration, the TRUS imaging plane can track the da Vinci tool tips in order to display their location relative to the internal structures seen in ultrasound. The method for direct registration of 3D TRUS to da Vinci stereo-camera system [3] was also implemented in order to overlay TRUS images to the surgeon's camera view at the correct spatial location for improved guidance.

2 Material and Methods

Experimental Setup and Clinical Setting: A 10-month-old male hound weighing 27 kg was used in this IACUC-approved study (Institutional Animal Care and Use Committee). Following a lower bowel prep, the anaesthetized animal was placed on the OR table in a 40-degree Trendelenburg position. Before docking the da Vinci surgical robot, the TRUS robot was attached to the OR table using the MicroTouch Brachytherapy stabilizer passive arm (CIVCO Medical Solutions, Kalona, IA), which was adjusted for the TRUS to provide optimal transversal and sagittal images of the animal's prostate as done in standard brachytherapy procedures (Figure 1). A Sonix TABLET ultrasound machine

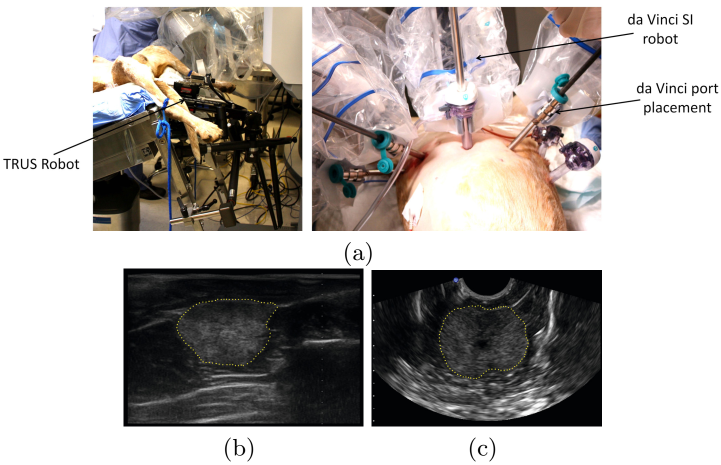
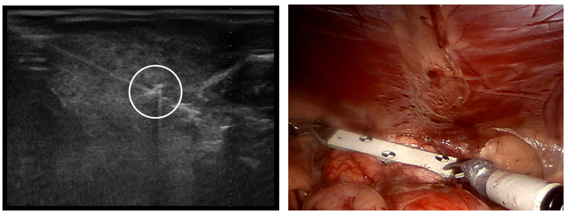


Fig. 1. The clinical setup and TRUS images of the canine's prostate: (a)TRUS robot attached to the OR table in Trendelenburg position with the da Vinci robot docked to the table and da Vinci ports are placed as in RALRP. (b)Sagittal plane TRUS image of the prostate at elevational depth of 4 cm. (c)Transverse plane TRUS image.

(Ultrasonix Medical Corp., Richmond, BC) with a bi-plane TRUS transducer was used for imaging. All TRUS volumes were captured using the 128-element 55 mm long linear BPL9-5/55 array with transmit frequency of 6.6 MHz and imaging depth of 4.0 cm. They were acquired using an 80-degree rotary sweep about the probe axis, and contained 220 images at increments of 0.36 degrees. Image capture time was 8.8 seconds per volume. The surgeons placed the da Vinci ports in the recommended pattern for RALRP, taking into consideration the smaller size of the canine model. Three arms were used for the procedure, with a Large Needle Driver, Prograsp and Maryland Bi-polar forceps in the right, left and third arm respectively. A 12 mm 0-degree stereo endoscope (3.8 mm disparity) was used throughout the procedure. TilePro was used in order for the surgeon to see the ultrasound image in the da Vinci console while performing the surgery. The surgeon continued with the RALRP procedure, with the TRUS transducer in position, until the anterior surface of the prostate was visible in the stereo camera.

3D TRUS to da Vinci Stereo-Camera Registration: Because the air-tissue boundary is the only region that can be visualized in both the camera and ultrasound image, a direct registration method as described in [3] was performed using a drop-in registration tool consisting of a machined stainless steel plate, with angled handles designed for easy grasping by the da Vinci needle driver instruments. The tool has three camera markers on one face, and three ball-bearing ball fiducials on the other face (Figure 2). The registration tool was inserted in the abdominal cavity through one of the ports, and placed on the prostate surface, where all three camera markers and the ultrasound fiducials were visible in the camera and US images, respectively. The coordinates of the three camera markers in the camera frame were detected by the stereo triangulation. The spherical fiducial corresponding to each marker was localized manually in the TRUS volumes by clicking on the appropriate B-Mode images. A homogeneous transformation between the two frames was found using least squares [3]. In order to accurately localize the markers on the registration tool, a standard camera calibration [4] was completed before capturing the camera images. The registration tool was repositioned four times in order to acquire 12 paired ultrasound fiducial and camera marker locations. In order to validate



(a) (b)

Fig. 2. (a)US image of the registration tool pressed on the anterior surface of the prostate, where the figucial in the US image is circled. (b)Camera image of the surgical site through the da Vinci console.

the registration method and to determine its accuracy, three pairs (representing one registration tool position) or six pairs (representing two registration tool positions) of ultrasound fiducials and camera markers were used to find the homogeneous transformation. The remaining points were used as target points to calculate the target registration error (TRE), defined as the distance between the point in camera space and the ultrasound fiducial point *transformed* into camera space. Registration accuracy results are listed in Table 1.

TRUS to da Vinci Instrument Registration: The surgeon was asked to press the tool tip of a da Vinci instrument against the prostate surface while a full TRUS volume was being acquired. The tool tip is visible as a hyperechoic focal point in the B-Mode image. To manually find the tool tip, first the angle of the TRUS imaging plane is selected. Then the tool tip axial and lateral coordinates are selected in this plane. The tip location relative to the TRUS coordinate system is obtained by transforming these cylindrical coordinates to Cartesian ones. The tool tip location relative to the robot coordinate system is also known from the Research API provided by Intuitive Surgical [6], providing three constraint equations for the homogeneous transformation relating the da Vinci coordinate system to that of the TRUS. Multiple constraints are obtained by repeating the process. $N = 12$ different target locations and corresponding volumes were acquired. For $n = 100$ iterations, $N_f = 4$ point pairs were picked at random and a least squares problem was solved to find the registration homogeneous transformation. The remaining $N_t = N - N_f = 8$ target locations were used to calculate the TRE, defined as the error between the location of the tool tips and the transformed points from the ultrasound volumes. To determine the inter-subject variation (ISV) in fiducial localization and analyze its effect on TRE, four different ultrasound users were asked to localize the tool tip in each of the $N = 12$ B-mode TRUS volumes we acquired. The TRE and Fiducial Registration Errors (FRE) in all three anatomical directions and RMS values for each user, as well as the mean over all users, are reported in Table 2.

3D TRUS to da Vinci Instrument Registration Using Automatic Tool Localization: In addition to the manual localization, the 3D automatic tool tip localization algorithm developed in [11], was also used on these $N = 12$ volumes. In this method the tool tip is found by looking for the tool tip signature on the surface (Figure 3) in the volume. The automatic detection results were compared to those obtained manually by four observers. The results can be found in Table 3.

Registration Timing: To determine the ease with which the above registrations can be performed, we asked the surgeon to perform four timed registrations using four registration points each. For each registration point, the tool tip location was found manually in the ultrasound volume. Often the surgeon would gently move the tool tip to confirm the correct tool tip location. After each registration, the automatic tracking was activated and the surgeon was asked to

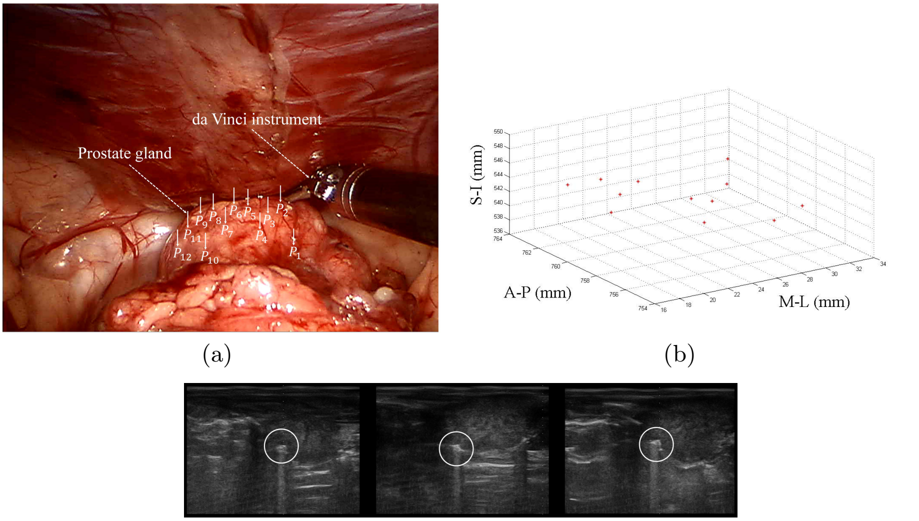


Fig. 3. (a) Camera image of the surgical site through the da Vinci console and spatial locations of the instrument tips scattered on the surface of the prostate. (b) The da Vinci intrument tip locations were spread on the surface of the prostate to achieve an accurate registration across the entire prostate gland. (c) US images of the da Vinci instrument tip pressed on the anterior prostate surface at different points.

move the tool tip to an additional 10 points on the surface of the prostate. For each location, the corresponding TRUS angle was recorded, then the tracking was temporarily deactivated and the points were located manually by adjusting the TRUS angle. The error in this measurement is shown in Table 4.

3 Results

3D TRUS to da Vinci Stereo-Camera Registration: Table 1 lists mean TRE and FRE when one or two registration tool positions are used for registering the TRUS to the camera. Since 12 point-pairs in the camera and US frames were collected and could be used for registration; the results are averaged over all combinations of 3 fiducials out of 12 points (one tool position), and all combinations of 6 out of 12 points (two tool positions).

Table 1. 3D TRUS to da Vinci stereo-camera registration accuracy

Tool positions	Number of fiducials (N_f)	Number of targets (N_t)	Mean FRE (mm)	Mean TRE (mm)
1	3	9	0.68 ± 0.42	3.91 ± 1.23
2	6	6	0.95 ± 0.38	2.73 ± 1.06

Table 2. 3D TRUS to da Vinci surgical tool registration accuracy (Manual tool tip localization in 3D TRUS). TRE and FRE are calculated for (n = 100) iterations, ($N_f = 4$) tool tip points and ($N_t = 8$) target points with 4 manual tool tip localization trials perfomed by 4 different users.

	$TRE_{AP}(mm)$	$TRE_{SI}(mm)$	$TRE_{ML}(mm)$	Mean TRE (mm)	Mean FRE (mm)
Subject 1	1.96 ± 1.04	1.66 ± 0.54	1.78 ± 0.85	1.86 ± 0.80	0.86 ± 0.44
Subject 2	1.93 ± 0.52	1.62 ± 0.58	1.72 ± 0.70	1.76 ± 0.61	0.97 ± 0.97
Subject 3	1.94 ± 1.09	1.67 ± 0.99	1.80 ± 0.92	1.81 ± 0.99	0.91 ± 0.35
Subject 4	2.19 ± 1.31	2.07 ± 1.17	2.07 ± 0.97	2.11 ± 1.15	1.02 ± 0.38
Average	2.01 ± 0.99	1.75 ± 0.82	1.84 ± 0.86	1.88 ± 0.88	0.94 ± 0.54

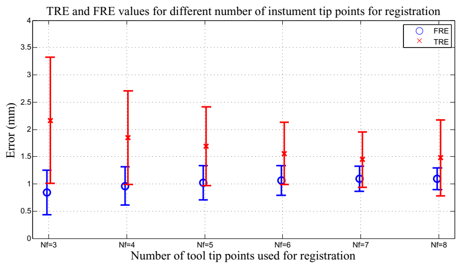


Fig. 4. TRE and FRE values for different number of tool tip points used for registration. As the number of fiducials increase, TRE decreases. We suggest using 6 fiducials in clinical applications.

TRUS to da Vinci Instrument Registration with Manual Fiducial Localization: Table 2 lists the mean values for TRE and FRE during TRUS robot to da Vinci instrument registration. A total of 12 TRUS volumes and da Vinci API point-pairs were collected. Errors are represented in the anatomical frame of the patient (Anterior-Posterior (AP), Superior-Inferior (SI), Medial-Lateral (ML)). Mean values of FRE and TRE and their standard deviations were calculated for each combination of (N_t,N_f) for 100 iterations and the results are plotted in Figure 4. As can be seen from this figure, as N_f increases, both the mean and the standard deviation of the TRE decreases. Based on this analysis, the number of fiducials suggested for this registration is $N_f = 6$.

Table 3. 3D TRUS to da Vinci surgical tool registration accuracy (Automatic tool tip localization in 3D TRUS). Mean TRE and FRE for (n = 100) iterations, with ($N_f = 4$) tool tip points and ($N_t = 8$) target points, FLE in (x, y) and (θ) and inter-subject variations calculated for 4 users.

FRE (mm)	TRE (mm)	$\text{FLE}_{(x,y)}$ (mm)	FLE_{θ} (deg)	$\text{ISV}_{(x,y)}$ (mm)	ISV_{θ} (deg)
1.56 ± 0.57	2.68 ± 0.98	2.91 ± 0.90	1.48 ± 0.70	3.55 ± 0.34	1.62 ± 0.39

Table 4. Automatic da Vinic tool tip tracking accuracy

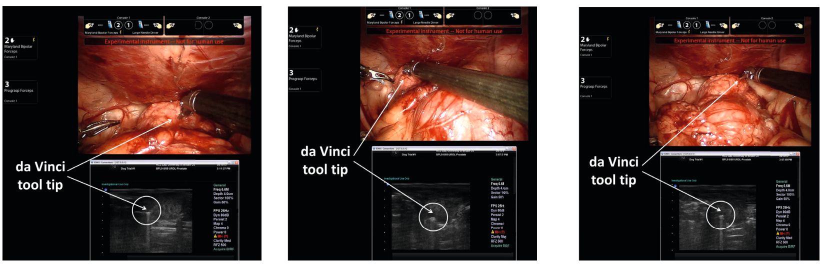
	Tracking error (deg)	Mean TRE (mm)	Time
Registration Trial 1	1.47 ± 0.83	1.78 ± 0.65	120s
Registration Trial 2	1.63 ± 1.22	2.00 ± 1.04	90s
Registration Trial 3	1.95 ± 1.28	2.11 ± 1.17	111s
Registration Trial 4	1.58 ± 1.63	1.83 ± 0.76	64s
Average	1.65 ± 1.24	1.93 ± 0.90	96s

TRUS to da Vinci Instrument Registration Using Automatic Tool Localization: The TRE and FRE obtained with automatic fiducial localization technique compared to manual localization are listed in Table 3. The table includes the TRUS imaging plane angle (θ) localization error, and the localization error ($(x, y)(\theta)$=lateral, axial) in the plane at θ. The fiducial localization error of the algorithm and the inter-subject variations (ISV) seen during manual localization are also reported.

Registration Timing: The tracking accuracy for the four timed registration trials are reported in Table 4. TRE values were also calculated for each registration. All registrations were completed in under 2 minutes with an average registration time of 96 seconds. Throughout the registration experiments and the surgery, TRUS images were streamed into the da Vinci console for real-time guidance. Figure 5 shows the TilePro and camera images inside the da Vinci console, when the automatic tool tracking is activated and the TRUS image follows the da Vinci tool tip.

4 Discussion

In this set of experiments, we tested and validated the intraoperative use of a robotic TRUS manipulator for RALRP procedures. The TRUS robot is based on a small modification to a standard brachytherapy stabilizer which is available in almost any hospital where brachytherapy is performed. Hospital staff are familiar



(a) (b) (c)

Fig. 5. TilePro images inside the surgeon console while the automatic tool tracking is activated. The da Vinci instrument tip is visible in both camera and ultrasound images.

with the set-up and positioning of the transducer on the stabilizer with respect to the patient.

Registration of the TRUS robot to the da Vinci camera showed a mean TRE of 2.73 mm when using two tool positions. This is about 1mm larger than the error reported using the system in phantoms [3]. Unlike [3], which used a cross-wire phantom to compute TRE, the current approach uses point-pairs of camera markers/ultrasound fiducials at different locations of the registration tool. This approach is more clinically practical but may lead to higher registration errors. The tight space within the pelvic cavity limited the registration tool placements that we could use. To avoid this problem, a more compact registration tool should be designed in the future.

During the TRUS to da Vinci tool registration, a TRE of 1.88 ± 0.88 mm was achieved. This is on par with the results from [3] when using a PVC prostate phantom. It is pointed out by Ukimura *et al.* [13] that the mean distance between the NVB and the lateral edge of the prostate ranged from 1.9 ± 0.8 mm at the prostate apex, to 2.5 ± 0.8 mm at the base. This is suggestive of the required accuracy of a guidance system since one major aspect of the system is to accurately localize the NVB. Currently the error in our TRUS to camera registration is slightly larger, but the error between the da Vinci tools and the TRUS is within the range reported in [13].

We believe that a large part of the error in the camera to TRUS registration was due to the difficulty of accurate camera calibration, which presently requires that the camera be taken off the robot. The da Vinci stereo camera has a disparity of 3.8 mm, meaning that the depth measurement calculated from the differences between the left and right images is very sensitive to calibration. For both registration approaches (to camera and to tool), some of the registration error may also be due to the limited localization accuracy of the fiducials within the US images. While subjects were instructed on the best way of picking the fiducial edges as described in [7], they had higher variance in localizing the fiducials than the automatic method. The use of an automated algorithm would also mean that no additional personnel would be needed in the OR in order for the tracking to be activated. For the TRUS to da Vinci tool registration error, another contributing factor is the tool tip localization error from the da Vinci API, which has been reported to be within 2mm. Another source of error is instrument shaft deflection, as pointed out in [12].

Timing results have shown that the da Vinci instrument to TRUS registration could be completed very quickly and would be valid throughout the surgery since neither the TRUS nor the da Vinci coordinate systems will be moving. We determined that using six tool tip positions gives the best TRE with minimal added benefit derived from further measurements. This would increase registration time by approximately 20 seconds. Camera to TRUS registration tools should be similar, not counting the time required for camera calibration.

Although the canine model was chosen, there are key differences from humans which actually made the study somewhat more difficult. Positioning with a human patient does not usually put extensive pressure on the distal end of the transducer, but in the canine case, there was a larger amount of force on the transducer which could cause errors in TRUS rotation during TRUS volume acquisition and also in fiducial lozalization in TRUS images.

5 Conclusions

We have presented the validation of two intraoperative registration methods that can be used during RALRP for image guidance and surgical navigation. Both methods use the air-tissue boundary as a common interface for the da Vinci robot and the ultrasound images. The da Vinci camera to TRUS registration is the first step in creating an augmented reality navigation system for da Vinci surgery (3D image overlays in the surgeon's console). Using the kinematics of the robot, we were able to register the da Vinci coordinate system with that of the TRUS robot. This was achieved quickly and efficiently with surgeons new to this concept. All registration errors were within the scope of the clinical setting and the constraints of the ultrasound imaging system. Surgeons even suggested approaches on how to distribute the registration points (2 points at the prostate base, 2 points at mid-gland and 2 points at the apex) to make the process more efficient and maintain registration accuracy across the prostate. We have demonstrated that these registration methods work effectively in an *in-vivo* environment. The camera registration tool would need to be modified specifically for a clinical environment, while the da Vinci kinematic registration is ready for clinical testing. We have submitted our application to human ethics and we plan to begin patient studies soon.

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