Patient-Specific, Touch-Based Registration during Robotic, Image-Guided Partial Nephrectomy

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Abstract:

Image-guidance during partial nephrectomy enables navigation within the operative field alongside a 3-dimensional roadmap of renal anatomy generated from patient-specific imaging. Once a process performed by the human mind, the technology will allow standardization of the task for the benefit of all patients undergoing robot-assisted partial nephrectomy. Any surgeon will be able to visualize the kidney and key subsurface landmarks in real-time within a 3-dimesional simulation, with the goals of improving operative efficiency, decreasing surgical complications, and improving oncologic outcomes. Toward similar purposes, image-guidance has already been adopted as standard of care in other surgical fields; we are now at the brink of this in urology. This review summarizes touch-based approaches to image-guidance during partial nephrectomy, as the technology begins to enter *in vivo* human evaluation. The processes of segmentation, localization, registration, and re-registration are all described with seamless integration into the da Vinci surgical system; this will facilitate clinical adoption sooner.

Keywords: partial nephrectomy, robot-assisted, image-guidance, registration, re-registration, touch-based

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Introduction:

The idea of image-guidance during partial nephrectomy (IGPN) arose as the field of urology adopted complex, nephron-sparing surgery as standard of care, while simultaneously shifting towards laparoscopy and robotic assistance. Minimally invasive surgery has many advantages; however, the tactile feedback used to identify pulsating arteries and tissue planes in open surgery remains limited. All the while, the challenge of distinguishing normal from pathologic tissue persists, in all forms of surgery. Circumventing these limitations in the current paradigm of partial nephrectomy relies heavily on a surgeon's mental coregistration – the brain's ability to 1) reconstruct the 2-dimensional spatial relationships of anatomic structures from pre-operative imaging (i.e. renal artery to renal vein, renal tumor from normal parenchyma, etc.) into a 3-dimensional mental model, and then 2) align that mental model to what is visualized intra-operatively. Today, computer algorithms can fully automate this process to enable real-time navigation around observed structures and, most importantly, the unseen subsurface structures beneath them.

IGPN can range in complexity from manually-aligned 3-dimensional renal imaging displayed next to the endoscope monitor to intra-operative CT used to align fiducials implanted in the kidney to endoscope video. The benefits of these approaches have now been shown in several human studies (1–3). However, the registration methods employed still have several drawbacks and/or limitations to widespread adoption. Most importantly, no group has achieved fully automated registration *in vivo* during robot-assisted partial nephrectomy that is non-invasive, fits within current surgical workflow, and where registration accuracy has been quantitatively accessed. Touch-based registration as reviewed here has the potential to address all of these challenges. By leveraging the da Vinci (Intuitive Surgical, Sunnyvale, CA, USA) robot's inherent knowledge of its instrument tip position in the workspace, it can be used as a localizer enabling accurate surface registration(s) with pre-operative imaging.

Clinical utility of IGPN:

Partial nephrectomy balances oncologic control with preservation of normal renal parenchyma. Doing so requires careful control of renal vasculature and careful resection of the renal mass(s). Image-guidance can facilitate all of these aims, with several examples in the literature. In 2009, the potential of image-guidance in urology was showcased when its use enabled "ideal" robot-assisted resections of lesions from cylindrical gel phantoms, where resection of "non-tumorous" gelatin was minimized (4). More recently, image-guidance allowed the identification of endophytic lesions in a kidney phantom covered by fat nearly as well as exposed, exophytic lesions (5).

The above findings have also been seen in human partial nephrectomy series where manually-aligned, 3-dimensional renal imaging was projected over endoscope video. IGPN enabled preservation of 90% of normal parenchyma compared to 83.5% in a propensity-matched historical cohort (3). Another group found IGPN to significantly lower the need for main arterial clamping, facilitate tumor enucleation, minimize collecting system entry, and reduce drops in renal plasma flow at 3 months after surgery, when compared to standard intra-operative ultrasound in robot-assisted partial nephrectomy of complex tumors (2).

Basics of image-guidance:

Image-guided surgery can be simplified into 4 steps: 1) image acquisition (+/- segmentation), 2) image-to-physical space registration, 3) three-dimensional location tracking, and 4) display of imaging data and tool tip location (6). Images can be obtained pre-operatively and/or intra-operatively, but in most situations, requires segmentation to reconstruct relevant anatomy from axial, coronal, and sagittal slices into 3-dimensional models. By far the most complex aspects of IGPN are registration and localization. In touch-based registration, location tracking is required not only for the display of surgical instrument locations relative to the anatomy in the image space, but also to collect surface data to generate the registration itself.

Registration refers to the process of determining the mathematical relationship between objects in the image space and the same objects in physical space (i.e. the operative field). After registration, a transformation can be performed to align the spaces enabling IGPN. Registration is often achieved by matching unique points or anatomic landmarks (i.e. "point-based registration"), or by matching the surface of structure(s) (i.e. "surface-based registration") in both spaces (6). The kidney poses inherent challenges for registration due to a lack of distinct anatomic landmarks. In addition, much of relevant renal anatomy is covered by fat and the surface of the kidney itself is rather amorphous.

One group has approached these challenges by surgically implanting fiducial markers in the kidney and obtaining intra-operative computed tomography (CT) imaging. Point-based registration is then established by aligning the marker locations in segmented imaging to the markers seen endoscopically (1). This process requires intra-operative imaging techniques not readily available, real-time segmentation, and is complicated by the invasiveness associated with marker placement. Laser range scanning of kidney surfaces in open partial nephrectomy has also been demonstrated (7). Unfortunately, such devices do not exist clinically for minimally invasive surgery as it requires direct line of site with tissue and further complicates the surgical workflow; however, industrial conoscopic holography has been applied in the engineering literature for this purpose (8).

Registration requires position data of the relevant anatomic points/features in the operative field which necessitates location tracking. Furthermore, registration quality depends on the accuracy of the localizer. Location tracking has traditionally been accomplished using optical or electromagnetic systems that track markers placed on a surgical instrument via triangulation. By default, optical trackers were favored due to the large number of conductive structures in the operating room (i.e. metal operating table, da Vinci robot, electrosurgical devices, etc.) that introduce electromagnetic noise (6). The error introduced from such noise can be up to ~5 cm (9). This preference is despite optical trackers requiring continuous line of site with emitters, which can be shadowed by the robot and other operating room equipment/personnel (6).

As an alternative to optical tracking, the da Vinci system itself can serve as a geometric localizer. Like other geometric localizers historically, early da Vinci versions were less accurate due to compromises between stiffness and lightness of articulated arms as well as limitations in the encoders built into the arms (6,10). Understandably, those versions were designed to prioritize movement accuracy corresponding to surgeon inputs rather than absolute accuracy.

da Vinci as an accurate localizer:

The da Vinci robot has 4 arms, each with several joints that slide in a fixed direction or rotate around an axis. Encoders within each joint measure the position or angle of the joint, which can be extracted using the da Vinci Application Programming Interface (API). Knowledge of these joint values can be used to compute the position of the tip of the surgical tool. Because the location of the tool can be computed, the tool's tip can be used to touch and localize anatomy.

Any localizer has some degree of localization error. For the da Vinci robot, the localization error of the tool tip originates from measurement errors in the encoders and can be amplified the further a joint is from the tool tip (11). Despite this, experiments comparing the da Vinci robot to other industry standards have proven the robot to be an accurate localizer. Fifteen years ago, the 1st generation da Vinci robot was shown to have a localization error of only 1.02 mm when using one arm, with fixed setup joints. Importantly, this error was found to be Gaussian in each direction and isotropic (error was similar in each of the three directions) and was comparable across the entire workspace (11). Subsequent study of the da Vinci S revealed a similar localization error of 1.05 mm (12).

Nonetheless, ideal IGPN requires localization of all arms in a common coordinate system, thus requiring consideration of da Vinci's setup joints to error contribution. Setup joints are the passive joints used for gross positioning of the robot arm's remote center and are proximal to the active joints used to control surgical instruments. Taken together, these joints amplified error to 10.6 +/- 22.9 mm on the da Vinci S when evaluated alongside an optical localizer. However, when the da Vinci arms were calibrated using optical tracking of each setup joint (a hybrid localization approach) and co-registered into the same coordinate system, the localization error resembled that seen in previous experiments (9).

The introduction of the da Vinci Xi was groundbreaking for instrument tip localization. Not advertised among its evolved features is the remarkable improvement in its setup joint encoders; obviating the need for hybrid localization using external trackers. For the older Si, the localization error (including the setup joints) decreased from 140.86 mm when un-calibrated to 4.94 mm when calibrated. Alternatively, with the newer Xi, calibration reduced errors from 2.09 mm to 0.97 mm—a substantial improvement over the Si (10). As a result, calibration with an optical tracker is no longer necessary at the beginning of every IGPN procedure. Setup joints can also be adjusted intra-operatively in the event of clashing without re-calibrating. Indeed, a one-time calibration procedure can account for manufacturing tolerances and other sources of error (13). However, this may not even be necessary for many applications with un-calibrated localization error approaching 2 mm (10).

Surface registration:

While using the da Vinci robot as a localizer makes this a "plug-and-play" technology, an IGPN system providing accurate, fully automated registration to preoperative imaging is more likely to gain rapid adoption. Registration using surface features detected from *in vivo* endoscope images has been described but was only semi-automated previously (14,15). More recently, an automated process has been published (16). Nonetheless, head-to-head comparison of registration accuracy in ideal circumstances using kidney phantoms and only the da Vinci robot favors touch-based registration to the triangulation of fiducials detected in stereo endoscope images or surface scanning from stereoscopic depth mapping algorithms (13). Endoscope-based methods must also segment camera images to differentiate the kidney from surrounding tissues prior to registration; the extraneous segmentation is unnecessary in touch-based registration.

In touch-based registration, a portion of the renal capsule is lightly traced via a da Vinci needle driver, creating a tracing comprised of many points called a point cloud, digitizing the exposed surface. An algorithm then translates and rotates the point cloud from the operative field to align with the point cloud from preoperatively-segmented imaging (Figure 1a). An iterative closest point (ICP) approach is one such algorithm used to align point clouds. It iteratively estimates the transformation necessary by associating points in each cloud to their nearest neighbor in the other cloud after an initial guess. It subsequently aligns the point clouds by minimizing the distance between paired points and uses that transformation to again associate new point pairs for further alignment. The process is repeated until convergence theoretically occurs or a threshold is reached. ICP in surface registration for IGPN was first used by Ong et al., in which the algorithm stopped when the mean distance between point clouds was 1×10^{-7} mm and/or 500 iterations were performed (7). Currently, the touch-based registration approach uses a globally optimal iterative closest point (GO-ICP) variation, which no longer requires an initial guess and is fully automatic to the user (17).

Registration quality has thus far been accessed *ex vivo* by measuring target registration error (TRE) – the difference in matching surface target locations in both spaces relative to known locations of "ground-truth" fiducials that are consistent in both spaces. Early work in IGPN surface registration via laser range scanning confirmed that registration accuracy varies with the amount of renal capsule recorded and the geometric descriptiveness of those areas (higher surface curvature enables more accurate registration). Recording and registering to both poles of laparoscopically-oriented kidney phantoms provided a TRE <1 mm but this is not acceptable when the goal of minimally invasive surgery is to disturb as little tissue as possible. However, recording 28% of the kidney surface provided TRE < 5 mm regardless of the specific kidney surface subset used for registration (Figure 2) (18). As a result, the current system analyzes tracing data to ensure that an adequate surface area is captured. This is facilitated by a ball-pivoting surface reconstruction algorithm that creates a mesh model from the collected surface data (19).

Without tactile feedback, one may argue the difficulty in tracing soft-tissue without compressing it or lifting off using a da Vinci needle driver. However, additional registration accuracy studies have demonstrated the above methods to be reliable and consistent. The root mean square (RMS) average of TRE across the entire kidney surface was 3.69 mm (standard deviation ± 0.61 mm) after performing 700 surface tracings over a compressible, soft-tissue kidney phantom (SynDaver Labs, Tampa, FL, USA) (5). Similar results were also achieved using validated partial nephrectomy phantoms made by Ghazi et al. (Figure 3) (20,21). In both of these experiments, registration accuracy did decrease as the distance from the surface tracing increased but this change was minimal (i.e. RMS TRE over the traced surface was 2 mm versus 2.75 mm over the entire kidney) (5).

Re-registration and its utility:

Thus far, rigid registration has been assumed (the distance between paired points does not change). During partial nephrectomy, however, rigidity of the kidney is not maintained and experiences topological changes/deformation (detachment from surrounding structures, position changes relative to aorta and vena cava, changes in turgidity during clamping and resection, etc.). For instance, surface displacement in the direction of gravity was seen after incising perfused and clamped porcine kidneys. Fiducials implanted throughout these kidneys displaced on average 3.4-6.7 mm (20). Likewise, when ink fiducials were placed on the kidney surface during open partial nephrectomy and scanned using a laser range scanner before, during arterial clamping, and after resection, the mean TRE of these ink fiducials corresponding to the subsequent two registrations were 0.95 and 7.33 mm, respectively indicating that significant deformation had occurred (7).

Fast, periodic re-registration is therefore necessary to maintain accurate registration of the renal tumor and hilum throughout the operation. To address this, touch-based registration now applies a, rapid point-based re-registration process as needed, a concept that was repurposed from the measurement methods involving open partial nephrectomy described earlier (7). After the initial registration, ink fiducials are tattooed on the renal capsule and localized relative to the initial surface registration using the da Vinci needle driver. During the remainder of the operation, the ink fiducials can be localized again to re-align the initial registration instantaneously without re-tracing the surface of the kidney (Figure 1b). The accuracy of re-registration has been tested in validated partial nephrectomy phantoms exposed to intra-procedural movement and after resection of exophytic as well as endophytic tumors. Minimal changes in TRE were seen pre and post resection (from 1.34 to 1.70 mm and from 1.60 to 2.10 mm, respectively) (21).

***In vivo* application and current workflow:**

Touch-based registration during IGPN is currently being evaluated in humans with the goal of quantifying registration accuracy by comparing vessel insertion locations, tumor locations, and resection contours. Prior to surgery, pre-operative CT scans are manually segmented by a urologist and engineer using 3D Slicer, an intuitive, open-source medical image computing and visualization software platform (23). Anecdotally, this process is more efficient with thin-cut CT timed in the arterial phase. During the surgery, minimal connections are required to an auxiliary computer, including an Ethernet data connection from the Vision cart to stream kinematic data from the da Vinci API and DVI input to TilePro^{TM} to display the image-guidance in the surgeon console.

After gaining intra-abdominal access, docking the da Vinci Xi, and mobilizing the colon per standard fashion, the anterior, lower pole renal capsule is exposed. Surface tracing is performed by lightly touching the da Vinci needle driver over >28% of the surface with inclusion of as much renal capsule curvature as possible for geometric detail (Figure 4). A point cloud is then generated and a registration is automatically performed to the previously segmented imaging using a custom-built submodule in 3D Slicer. Renders of each da Vinci instrument are localized from the endoscope point of view in relation to the 3-dimensionally reconstructed kidney, tumor and hilar structures and displayed in TilePro^{TM} in real-time as the robot moves.

Four or more marks are then made on the renal capsule and localized relative to the previous surface registration using the needle driver. The remainder of the operation is then carried out and when necessary, re-registration can be performed by localizing only the tattooed marks to re-align the surface registration.

Conclusions and future work:

The lessons learned from current human studies will guide further development of touch-based image-guidance using the da Vinci robot. As reviewed, the hardware and methodology are in place for IGPN to be readily available as a software upgrade. Further areas of study may include automated segmentation and incorporation of topological changes/tissue deformation. Modeling may be required to estimate the effects of imaging performed in the supine position versus surgery performed in the flank position; the kidney has been shown to shift up to 10 mm cephalad and 11 mm medially via intra-operative CT (1). Likewise, respiratory motion may require simulation, which has been quantitatively shown to move the kidney in left-right, anterior-posterior, and cephalad-caudad directions (24). It is worth noting that linear motions will not affect registration accuracy for internal kidney structures relevant to partial nephrectomy; only changes in the kidney's shape can introduce inaccuracies. A statistical understanding of registration error also holds the potential to provide the surgeon an optimal resection margin to consider (25). And to enhance accuracy still further, touch-based registration may be augmented with endoscope data and/or updated with intra-operative ultrasound; incorporation of ultrasound into IGPN is currently underway.

With an intuitive interface that provides arguably more useful data than mental coregistration and intra-operative ultrasound, we foresee touch-based image-guidance to become standard of care during robot-assisted IGPN. Indeed, it may become the standard of care even more broadly, since all of these principles are likely to be applicable to next generation robotic surgical devices, provided their encoders and tolerances are comparable to those of current surgical robots.

Author's Contribution:

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Fig. 1 Overview of the current touch-based approach to image guidance for the da Vinci robot: a, Surface tracing of the kidney capsule with the instrument tip allows for an initial registration to pre-operative CT imaging of the kidney

b, Markings placed on the renal capsule enable fast, point-based updates to the initial surface-based registration in case of gross kidney motion or changes in renal topography

Fig. 2 Quality of surface registration for different scanned regions of a phantom kidney model (the combination of numbers at various points in the graph refers to the combination of different scanned regions used for registration in the top right corner) (18)

Fig. 3 Resection of a lesion during robot-assisted partial nephrectomy performed on a validated kidney phantom using touch-based image-guidance (images are displayed chronologically from left to right)

Fig. 4 Top: In human tracing of the renal capsule using a da Vinci large needle driver, enabling touch-based image-guidance

Bottom: Corresponding tracing data (red dots) and robotic instruments visualized in TilePro™ prior to image alignment