Toward Image Guided Robotic Surgery: System Validation

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Purpose: Navigation for current robotic assisted surgical techniques is primarily accomplished through a stereo pair of laparoscopic camera images. These images provide standard optical visualization of the surface but provide no subsurface information. Image guidance methods allow the visualization of subsurface information to determine the current position in relationship to that of tracked tools.

Materials and Methods: A robotic image guided surgical system was designed and implemented based on our previous laboratory studies. A series of experiments using tissue mimicking phantoms with injected target lesions was performed. The surgeon was asked to resect "tumor" tissue with and without the augmentation of image guidance using the da Vinci® robotic surgical system. Resections were performed and compared to an ideal resection based on the radius of the tumor measured from preoperative computerized tomography. A quantity called the resection ratio, that is the ratio of resected tissue compared to the ideal resection, was calculated for each of 13 trials and compared.

Results: The mean ± SD resection ratio of procedures augmented with image guidance was smaller than that of procedures without image guidance (3.26 ± 1.38 vs 9.01 ± 1.81, $p < 0.01$). Additionally, procedures using image guidance were shorter (average 8 vs 13 minutes).

Conclusions: It was demonstrated that there is a benefit from the augmentation of laparoscopic video with updated preoperative images. Incorporating our image guided system into the da Vinci robotic system improved overall tissue resection, as measured by our metric. Adding image guidance to the da Vinci robotic surgery system may result in the potential for improvements such as the decreased removal of benign tissue while maintaining an appropriate surgical margin.

Key Words: robotics; surgery, computer-assisted; validation studies; phantoms, imaging; urology

Abbreviations and Acronyms

CT = computerized tomography

IGS = image guided surgery

PVA = polyvinyl alcohol

RIGS = robotic IGS

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The use of robotics in various urological and other surgical procedures has been increasing rapidly. This popularity has been driven by the expansion of available minimally invasive surgical applications as well as the improved dexterity and decreased tremor provided by robotic assisted surgery. Similar to standard open and laparoscopic surgery, guidance and navigation are provided strictly via a visual route using a laparoscopic camera, which does not provide subsurface information. In various minimally invasive surgical procedures subsurface information, such as the position of tumor margins or vascular structures, is crucial to the appropriate application of surgical therapy. The availability of intraoperative IGS has the potential

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to provide significant benefit to the operating surgeon and patient.

Robotic assisted surgery has been particularly well received in urological surgery.[1–3] The primary application of robotic assisted urological surgery has been in laparoscopic radical prostatectomy.[1,4–10] The robotic surgical system decreases the learning curve associated with complex laparoscopic tasks such as suturing, while placing camera control and various arm manipulators under the control of the primary surgeon. At our institution robotic assistance provides benefit in the form of decreased blood loss and a reduction in positive surgical margins during radical prostatectomy.[11,12] Recently several investigators have also reported using the robotic surgical system to aid in laparoscopic partial nephrectomy for renal masses.[13–16]

IGS has become the standard of care in providing navigational assistance during neurosurgery because it can provide subsurface and functional information to the surgeon.[17] In IGS preoperative cross-sectional images are co-registered with a tracked device in the surgical field. A display provides the surgeon with images marked with the current location of the tracked device updated in real time. This display allows the surgeon to visualize an interactive map of the subsurface structures based on the preoperative imaging, including the position of neural structures, vasculature and pathological tissues, before surface incision.

The da Vinci classic and da Vinci S robotic surgical systems are commonly used for minimally invasive, robot assisted surgery. Each arm or manipulator is composed of a series of passive setup joints and an active robot. The setup joints and robot consist of a series of revolute and linear joints, allowing the system flexibility in its reach. The setup joints define the work volume, within which the robot can move intraoperatively.

An image guided surgery system consists of a method of localization along with a software application to register, update and display images. Our initial study focused on assessing the accuracy of the da Vinci system as a localizer. As previously demonstrated in our series, the da Vinci robotic surgical system robot section can be used as a localizer system with the exclusion of the setup joints (fig. 1).[18,19] The setup joints have been shown to have a high level of positional uncertainty, which is amplified through the lever arm of the robot. To mitigate the inherent error of the setup joints a hybrid localization scheme and design were developed using a secondary optical localizer (fig. 2).[20] This hybrid system allows the use of the entire da Vinci surgical system as a single localizer as well as the tracking of all instrument arms in the same coordinate space.

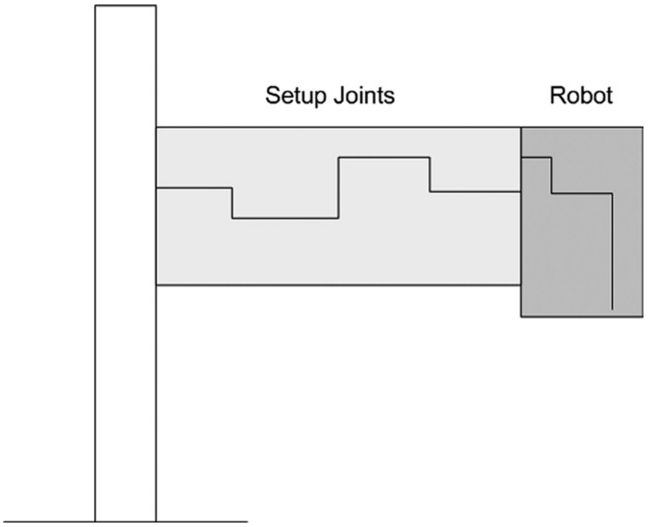

Figure 1. Diagram of da Vinci patient side manipulator, composed of series of passive setup joints and active robot joints.

Registration between the image and physical space can be performed by surface or point based methods. In surface based methods digitization of the surface of the anatomy is accomplished through a stylus or a range scanner. This extracted surface is then fit to a surface segmented from preoperative images. In point based methods a series of fiducial points are chosen from the anatomy or from attached markers. These points must be visible on preoperative images and accessible to the localizer. The locations of these fiducial points are found in each space and aligned using least squares methodology. The transformation between fiducial points in imager space and localizer space is considered the registration. These 2 techniques assume rigid transformation between image and localizer spaces.

Registered preoperative images are displayed using the IGS software application as multiplanar reformatted slices or as a rendered volume. These visualizations allow surgeons to see their current surgical position, in addition to visualizing a predicted map based on preoperative imaging of what is beneath the surface. It is also possible to use images from multiple modalities that allow the visualization of different structures or even of function.

While system accuracy and precision can be tested using a series of rigid phantoms, validating a RIGS system is best performed by applying the system in surgical scenarios. These scenarios can be a mock surgical task or an actual surgical task. As previously demonstrated, materials can be manufactured that mimic tissues for use in mock surgical experiments. These materials enable a large number of experiments to be performed without the complications involved in animal or human studies.