Toward Image Guided Robotic Surgery: System Validation

Stanley D. Herrell,* David Morgan Kwartowitz,† Paul M. Milhoua and Robert L. Galloway

From the Departments of Urology Surgery (SDH, DMK, PMM), Biomedical Engineering (DMK, RLG), Surgery (RLG) and Neurological Surgery (RLG), Vanderbilt University, Nashville, Tennessee

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

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

Abbreviations and Acronyms

CT = computerized tomography
IGS = image guided surgery
PVA = polyvinyl alcohol
RIGS = robotic IGS
to provide significant benefit to the operating surgeon and patient.

Robotic assisted surgery has been particularly well received in urological surgery.\textsuperscript{1–3} The primary application of robotic assisted urological surgery has been in laparoscopic radical prostatectomy.\textsuperscript{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.\textsuperscript{11,12} Recently several investigators have also reported using the robotic surgical system to aid in laparoscopic partial nephrectomy for renal masses.\textsuperscript{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.\textsuperscript{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).\textsuperscript{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).\textsuperscript{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.

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.
A RIGS system allows the surgeon to visualize previously unavailable subsurface information. This subsurface information acts to augment the already available surface information by providing the location of critical structures and margins. We hypothesized that additional information in the form of IGS might enable improvements in the resection task with the potential to achieve improved margins in the form of increased preservation of normal tissue.

METHODS

To validate the integrated RIGS system a mock surgical task experiment was designed. These mock surgical experiments allowed multiple trials with controls, repeatability and a decrease in potential surgeon bias. To validate the RIGS system a tissue mimicking material was chosen made of PVA. This material was used because it cuts and stretches without tearing, similar to tissue, enabling dissection and retraction to open the resection cavity.

A series of cylindrical PVA gel phantoms were manufactured. These phantoms were 101.6 mm (4 inches) in diameter with a height of 114.3 mm (4.5 inches). The phantoms were placed in containers that held them vertically with 1 surface exposed. The gel containers had standardized external fiducial markers at varying heights on the containers, which were visible on CT and allowed an orientation of the gel container in the working volume of the robot that was similar to the CT orientation. A standardized volume of diluted iodinated contrast medium mixed with visible dye was injected into a random subsurface location at least 1 cm from the container wall. Enough time was allowed to pass to enable the contrast medium to diffuse to a steady state, forming a “lesion” in the gel. After a steady state was achieved each phantom was preoperatively imaged using CT.

Phantoms were divided into a control and an experimental group. The control group would be operated on using currently available, standard visual navigational techniques and the experimental group would be operated on while augmenting these standard visual techniques with image guidance. The centers of the fiducial markers were localized for all phantoms in the experimental group to enable registration to preoperative CT images.

A phantom was randomly chosen, randomizing between the group designated for image guidance and the group designated for visual guidance. This randomization removed the potential for bias due to the grouping or ordering of control and image guided trials. In all experiments the surgeon was provided with preoperative images on the operating room picture archiving and communication system workstation (fig. 3). The surgeon was allowed to examine the images and make measurements, as would currently be done preoperatively. The surgeon was then asked to extract the “tumor,” which appeared bright in the images. Determining the location of the surface and subsurface incisions into the gel to remove the enhanced tumor was left to the surgeon. In the control group visual guidance was achieved by the surgeon using only the robotic camera system and the surgeon estimation of location, need for margin tissue and resection depth.

If a phantom was a member of the group designated for image guidance, the preoperative image set was co-registered with the da Vinci RIGS system. In phantoms designated for image guidance continually updated images were streamed into the surgeon console (fig. 4). The view could be toggled between a pure camera image and the split screen (fig. 4) by a tap on the camera pedal. This configuration allowed the surgeon to augment the current technique with the additional information provided by the image guidance system.

After the resections were complete the phantoms were imaged again to provide a postoperative CT set. These postoperative CT images allowed the measurement of the resection cavity as well as any tumor remnant (fig. 3). To do this the preoperative and postoperative image sets were first co-registered using point based rigid registration. This registration enabled the comparison of changes at any given spatial location. The registered image sets were processed to extract the original gel volume, the original tumor volume, resection cavity size and the tumor remnant after resection. A difference image was calculated by subtracting postoperative image intensity from preoperative image intensity at each voxel. This difference image showed the location and size of the resection cavity. Preoperative and postoperative images were thresholded at a 10% enhancement over water. A connected components algorithm was used to decrease the impact of injection tracks on the measured volume. Additionally, initial tumor depth was measured.
Based on the volume of the preoperative tumor an ideal resection was determined (fig. 5). The ideal resection was equal to the measured tumor and a cylindrical plug of tissue immediately above it. The tumor was modeled as a sphere because it was approximately spherical using the equation, tumor volume = \( \frac{4}{3}\pi R^3 \), where \( R \) represents

**Figure 3.** CT shows tissue mimicking phantom. \( A \), preoperative enhancement of seeming tumor site (arrow). \( B \), postoperative image reveals void of removed material.

**Figure 4.** Augmented display with image guidance (2) shows curved scissors tool (right) being tracked, represented by circle in image volumes (3).
the tumor radius. Thus, the tumor radius can be calculated from the segmented volume using the equation,

\[ R = \sqrt[3]{\frac{3}{4\pi}} \text{(tumor volume)} \]

The plug was defined as a cylinder with a height equal to the depth of the initial tumor with extraction of this plug as inevitable in a perfect resection. The volume of the plug was calculated using the equation, plug volume = \( \pi R^2 \) (injection depth). Therefore, the volume of an ideal resection would be calculated as, ideal resection = (tumor volume/2) + plug volume.

A metric of resection was determined to enable the comparison of resection performed under traditional visual guidance and that performed with image guidance. The metric determined to be best was the resection ratio, defined using the equation, resection ratio = resection volume/(ideal resection - tumor remnant). The resection ratio compares the true resection with the ideal resection. The ideal resection volume would be adjusted for the remaining volume in case the tumor is violated. The resection ratio was calculated and plotted in standard visual cases and in visual cases augmented with image guidance.

**RESULTS**

A series of 13 tissue mimicking phantoms were constructed, of which 7 were classified for visual guidance and 6 were classified for image guidance. The phantoms were randomized as to the order of guidance and no guidance. The target zones were injected by hand to provide variations in depth and location within the confines of the phantom body.

Tumor radii were 0.38 to 0.56 cm (mean 0.48). Mean ± SD tumor depth was 2.13 ± 0.43 cm in the visual and image guidance sets. This led to a mean ideal resection volume of 1.75 ± 0.53 cm³.

Calculated resection ratios were plotted against tumor radii (fig. 6). The mean resection ratio for the surgical task without image guidance was 9.01 ± 1.81. The mean resection ratio for the image guided case was 3.26 ± 1.38. These means were signifi-
cantly different (t test $\alpha = 0.05$, rank sum test for small number $\alpha = 0.051$, p <0.01).

The surgeon successfully resected the entire tumor in most cases. However, there were exceptions. In 1 nonimage guided case the tumor was almost completely missed and in 2 of the 7 image guided cases a small volume of the lesion was left in situ (5% to 9%).

Image guided resection required less time to complete than nonimage guided trials. Nonimage guided trials required an average of 13 ± 2.9 minutes, while image guided trials required 8 ± 0.6 minutes.

DISCUSSION

The validation of medical devices requires the examination of their ability to perform not only in the laboratory, but also in real-world applications. Testing and validating a da Vinci S based RIGS system require the performance of a repeatable surgical task in which the quality of resection is measurable. The design of such a task must consider the requirements of the system during a surgical procedure. Using mock surgical scenarios with an inorganic tissue analogue allows repeat system validations.

Evaluating the phantom material and phantom properties validated application of the PVA gel based, tissue mimicking phantom. Measuring tumor volume and location in the phantom showed them to be repeatable. The repeatability of tumor location and size enabled repeat experiments to have the same starting point. Additionally, PVA gel was shown not to tear under the forces applied by retraction and cutting using the da Vinci surgical systems. Finally, the imaging characteristics allowed easy tumor and resection volume segmentation on CT.

Measuring the resection ratio provided a metric of the quality of resection, normalized to the ideal perfect resection. In this series of experiments the surgeons were asked to remove the lesion with the minimal amount of surrounding tissue. As demonstrated, the 2 classes (visual guidance and image guidance) were significantly separable, demonstrating that a benefit was gained from the augmentation of visual navigation with image guidance.

Using the resection ratio method allowed the measurement of resection volume relative to the ideal volume, accounting for partial tumor resection. This method does not penalize resection if the tumor is violated. However, in certain clinical applications violating the tumor clinically is more severe than removing excessive margins. In neither class was a major tumor violation observed, although in 1 control case the tumor was almost completely missed. Given that the visually guided control resections were of a subsurface lesion with no surface identification, this was not unexpected. In visual control cases the surgeons observed that a larger tissue volume incorporating the lesion and the margin needed to be resected to ensure that the lesion was included. In experimental image guided cases in which the tumor was violated this is most likely explained by the surgeon attempting to achieve smaller margins than are practical. Incorporating image guidance allowed rapid identification of the suspected lesion location and the surgeon attempted to reduce the lower limits of the required margin around the lesion. Additionally, incorporating a new technical approach with a learning curve may have had an impact. While improvement was seen in reducing the overall amount of margin tissue resected, further investigation of IGS augmentation should be performed with caution because this potential to reduce the margins could result in inadvertent tumor violation. However, given that this data set is pilot data on this new technology, the positives observed in the decrease in benign tissue resected, decreased resection time, and the surgeon observation of increased comfort with lesion location and identification suggest that the technology may be of benefit and it deserves further development. Interestingly image guidance may potentially allow surgeons to set up a no fly zone around the lesion and an appropriate margin of tissue with preoperative imaging. This would then be set with warnings issued by the system, perhaps even not allowing incision into these areas.

Limitations of the current study are that it was performed using a tissue mimicking material, which allowed us to determine system performance and some user performance but which is not an exact analogue to surgery in humans. Other challenges remain at an engineering level for image guided, abdominal solid organ surgery. A concern is the accurate registration and maintenance of a potentially moving target. However, during standard surgical resection 2 steps are taken that may help minimize target organ motion. 1) The perirenal fat is removed and the kidney is mobilized from surrounding attachments. This decreases the mechanical coupling between the diaphragm and the kidney. 2) When the kidney is clamped at the hilum and placed in a surgical orientation for resection, this decreases the relative motion of the kidney. Currently the types of registration, amount of surface area and surface landmarks needed for accurate registration and organ deformation properties are under study.

The augmentation of current visual navigation with image guidance provides a value added approach to current da Vinci based surgery. Adding image guidance enables the expansion of potential procedures available for robotic assistance since the
visualization of vasculature, structures and tumor margins is made possible.

Using robots in the operating room has been increasing in popularity in recent years. The dexterity and precision of robots make them attractive for delicate procedures. Current guidance techniques available for medical robotics rely on laparoscopic cameras, which provide only surface information. Augmenting this surface information with image guidance allows the visualization of subsurface structures. While some surgeons currently use ultrasound technology combined with open or minimally invasive techniques, this provides limited 3-dimensional information and requires extra personnel and access into the body. Most surgeons favor the 3-dimensional cross-sectional imaging provided by CT or magnetic resonance imaging to estimate the location and determine the approach for preoperative guidance. They would likely favor a similar image for intraoperative guidance. In conclusion, in this study navigational IGS augmentation for the da Vinci robotic system was demonstrated to be feasible for a subsurface tumor resection task and it resulted in an improved resection ratio.

ACKNOWLEDGMENTS
Debbie Deskins, Dahl Irwin, Wayman Bean, Ed Quirante, Kathy Deal, Rowena Ong and Thomas Pheiffer assisted with the study. Dr. Michael Miga provided segmentation support.

REFERENCES


EDITORIAL COMMENT
Few fields have been more impacted by the introduction of robot assisted surgical techniques than what has occurred in urology in the last 5 years. This change has been most notable with the widespread use of robot assisted laparoscopic radical prostatectomy for clinically localized prostate cancer. Robot assisted laparoscopic prostatectomy offers the advantages of decreased blood loss and shorter convalescence compared to the open procedure. Critics of robot assisted techniques often cite the lack of haptic feedback and the inability to palpate tumors as major limitations of this surgical approach.

These authors report their experience using RIGS to remove “tumors” in a phantom model. While this technology may not yet be ready for clinical use, as
evidenced by the fact that tumor was left behind in half of the image guided cases, the theoretical advantages of such an application are exciting. Further advances in image guided technology may allow more precise removal of tissue with an adequate margin while preserving important structures, such as the neurovascular bundle at radical prostatectomy. This technology may also permit surgeons to overcome the absence of haptic feedback associated with current robotic instrumentation. A significant limiting factor when applying this technology to robot assisted laparoscopic radical prostatectomy is the lack of an imaging modality that can precisely characterize the location of a prostate tumor (organ confined vs extraprostatic extension) and its exact relationship to the neurovascular bundle. If these shortcomings in image guided technology and prostate imaging can be overcome, RIGS has the potential to offer improved cancer control while decreasing morbidity in our patients.

REFERENCES
