Augmented Reality During Robot-assisted Laparoscopic Partial Nephrectomy: Toward Real-Time 3D-CT to Stereoscopic Video Registration

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OBJECTIVES To investigate a markerless tracking system for real-time stereo-endoscopic visualization of preoperative computed tomographic imaging as an augmented display during robot-assisted laparoscopic partial nephrectomy.

METHODS Stereoscopic video segments of a patient undergoing robot-assisted laparoscopic partial nephrectomy for tumor and another for a partial staghorn renal calculus were processed to evaluate the performance of a three-dimensional (3D)-to-3D registration algorithm. After both cases, we registered a segment of the video recording to the corresponding preoperative 3D-computed tomography image. After calibrating the camera and overlay, 3D-to-3D registration was created between the model and the surgical recording using a modified iterative closest point technique. Image-based tracking technology tracked selected fixed points on the kidney surface to augment the image-to-model registration.

RESULTS Our investigation has demonstrated that we can identify and track the kidney surface in real time when applied to intraoperative video recordings and overlay the 3D models of the kidney, tumor (or stone), and collecting system semitransparently. Using a basic computer research platform, we achieved an update rate of 10 Hz and an overlay latency of 4 frames. The accuracy of the 3D registration was 1 mm.

CONCLUSIONS Augmented reality overlay of reconstructed 3D-computed tomography images onto real-time stereo video footage is possible using iterative closest point and image-based surface tracking technology that does not use external navigation tracking systems or preplaced surface markers. Additional studies are needed to assess the precision and to achieve fully automated registration and display for intraoperative use. UROLOGY 73: 896–900, 2009.

Partial nephrectomy for renal cell carcinoma remains the standard of care for most small, localized renal tumors <4 cm, with 5-year cancer-specific survival rates comparable to those for radical nephrectomy, with the added benefit of preserving renal function.[1-4]

Recently, laparoscopic partial nephrectomy (LPN) has emerged as an alternative to open partial nephrectomy (OPN), with a reduced hospital stay, intraoperative blood loss, and operative time.[5] Without the tactile feedback available during OPN to aid in assessing the tumor location and depth within the kidney, the precise localization of the tumor during LPN relies on both preoperative cross-sectional imaging studies using computed tomography (CT) or magnetic resonance imaging and routine intraoperative evaluation using real-time laparoscopic ultrasonography.

Discerning the precise border between the tumor and normal kidney can, at times, be challenging despite the use of intraoperative ultrasonography, especially in cases of completely intraparenchymal tumors or those in which the tumor appears relatively isoechoic to the normal surrounding renal parenchyma and therefore difficult to discern by ultrasound evaluation. In addition, experience is required to accurately interpret the ultrasound images and determine the precise line of parenchymal incision along the renal cortex that will ensure complete tumor excision, as well as maximal preservation of nephrons. Inaccurate tumor localization can lead a surgeon to excise

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an inordinate amount of normal parenchyma in an effort to obtain a complete excision or, worse yet, can result in an iatrogenic positive margin.

The largest published comparative study between LPN and OPN noted a slightly greater overall positive margin rate with LPN compared with OPN (2.85% vs 1.26%); however, the cancer-positive margin rates were similar (1.6% vs 1.0%).[5] Another study considering data from LPN of tumors <4 cm found a positive surgical margin rate of 2.1%.[6] Despite the relatively low positive margin rates seen with LPN, additional efforts to improve and simplify intraoperative tumor localization during LPN are warranted to optimize the competing goals of oncologic cure and renal preservation, especially for more challenging tumors (eg, completely intraparenchymal or hilar tumors). Furthermore, these efforts might increase the adoption of minimally invasive surgical techniques for partial nephrectomy, which, until now, have largely remained at centers of excellence with experienced laparoscopic surgeons.

Intraoperative surgical navigation systems have long been used during brain and liver surgery. Human stereotactic brain surgery guides an instrument probe through a small hole drilled in the skull while visualizing the target point using x-ray images, CT, or magnetic resonance imaging.[7-10] In the past decade, technological advancements have led to the development of frameless and armless neuronavigation systems that have improved accuracy and reduced interference by using a combination of stereotaxy, intraoperative magnetic resonance imaging/CT, and ultrasonic, magnetic, or optical tracking sensors.[11]

For liver cancer surgery, intraoperatively acquired three-dimensional (3D) ultrasound data and optical tracking systems have been used for multiplanar visualization of liver tumors.[12,13] Greater detail of the tumor has led to a significant increase in the accuracy of the navigated resections compared with conventional resections. In a study comparing 6 navigated and 6 conventional resections in a tissue model made from a 1.3-cm^3 silicon cylinder embedded in a muscle specimen, the median deviation from the ideal resection margin was 1.6 vs 4.2 mm, respectively ($P < .05$).[13] In clinical application, the positive margin rate was 6% (3 of 54 patients) compared with ≤30% for the conventional hepatic resections. A drawback to that study was that this navigation technology did not involve a transposed image and, therefore, required the surgeon to alternate viewing of the surgical specimen and the navigational system.

Recent adoption of the da Vinci Robotic Surgical System (Intuitive Surgical, Sunnyvale, CA) in many surgical disciplines has provided a distinct advantage over conventional laparoscopic surgery, including improved instrument dexterity, precision, superior visualization, and a 3D operative view. Stereoscopic surgery using the da Vinci Robotic Surgical System offers a platform for 3D-to-3D registration of preoperative cross-sectional imaging with a live intraoperative view. We present a system for accurate real-time stereo-endoscopic visualization of preoperative imaging data during surgery. This system does not require preplacement of markers or fiducial markers on the surface of the target organ or external tracking devices and provides transposed image overlays that account for organ movement, both translational and rotational. This feasibility study reports on the initial results of this system for visualization of a renal tumor and stone in a 3D augmented reality display during robot-assisted LPN.

MATERIAL AND METHODS

Stereoscopic video segments of 2 patients undergoing robot-assisted LPN, one for a predominately intraparenchymal tumor and the other for a partial staghorn calculus subtending a nonfunctioning portion of the lower pole of the kidney, were obtained. After surgery (ie, postprocessing analysis), these video segments were used to evaluate the performance of a novel 3D-to-3D image registration algorithm on a desktop computer workstation. For both cases, the following general steps were taken (Fig. 1).

3D-Registration Algorithm

First, the preoperative CT image was segmented manually to generate a 3D surface model of the kidney, tumor (or stone), and collecting system (Fig. 1, step 1). Second, a segment of the recorded stereoscopic video demonstrating the exposed kidney and tumor (or stone) was calibrated to ensure accurate transfer of the segmented 3D-CT kidney image on top of the endoscopic video. The 3D segmented kidney model was then imported onto the endoscopic video segment as an overlay, and the computer programmer manually calibrated the imported image to obtain the best visual fit between the 3D model and the stereoscopic view (ie, manual registration; Fig. 1, step 2; Video clip 1). Third, surface-based tracking techniques were used to further refine and stabilize the video-to-model image registration after manual registration (Fig. 1, step 3; Video clip 2). The tracking system used an automatic registration algorithm, for which several points on the kidney surface surrounding the renal mass were selected as fixed reference points. Triangulation methods were used to calculate the 3D positions of the points on the surface of the kidney and compute the corresponding orientation and position changes of the 3D model overlay. In our experiment, an operator (a computer programmer in the present study) selected the surface points to be traced; however, this selection can be performed automatically or selected by the operating surgeon in the future. Finally, when necessary, the system refined the registration using a modified 3D-to-3D iterative closest point (ICP) registration (Fig. 1, step 4).

The traditional ICP technique first attempts to find the corresponding 3D features between the preoperative 3D model and the stereoscopic view of the organ and then computes the transformation between the 2 3D feature sets. Because the point correspondence that the technique first finds might not provide accurate registration, the algorithm iterates recursively until the registration error is less than a fixed threshold value. In our experiments, the registration error was set at <1 mm. Although this traditional approach works well for registering 2 full 3D objects, in our application scenario, the 3D surface recon-

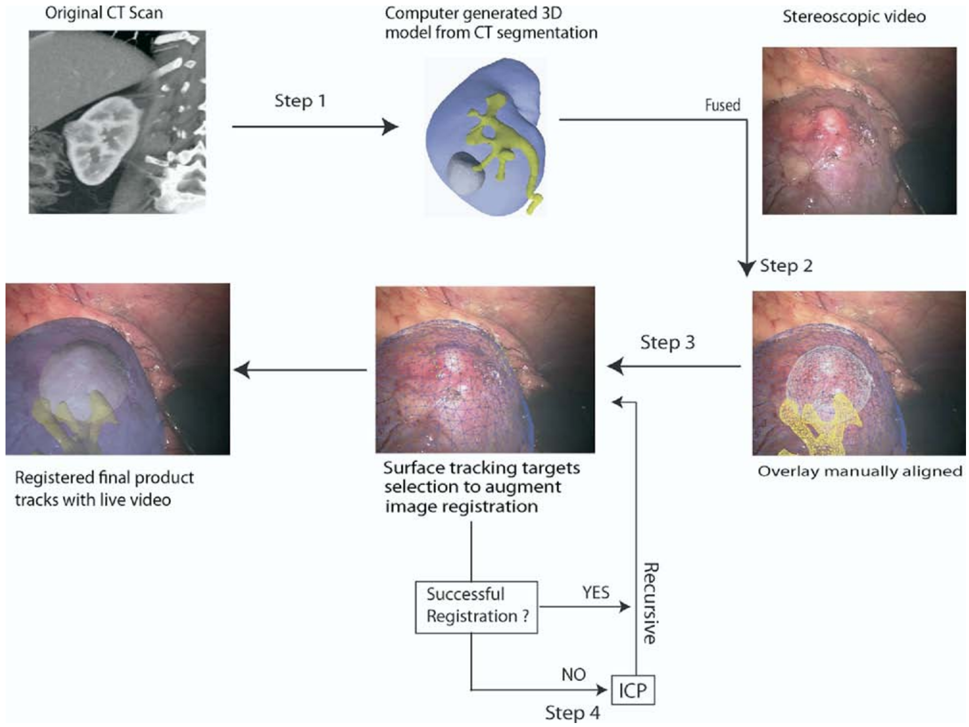

Figure 1. Flowchart displaying intermediary steps needed to achieve successful three-dimensional registration of preoperative computed tomography image to live stereoscopic video.

structed from the stereo video represented only a partial view of the kidney; thus, ICP using the whole 3D kidney model was not able to converge. Therefore, in our system, the ICP technique was modified to first estimate the visibility of the preoperative 3D model in the current view for each iteration and then to restrict the point correspondence search only to this visible part.

Computer Platform

The computer platform used in the present study was a 2.8-GHz Dual Pentium 4 Processor, with 512-MB RAM, 2 Hauppauge WinTV 878/9WDM frame grabbers, and a Gainward NVIDIA GeForce FX55700 LE video card.

RESULTS

The final result of our 3D-to-3D image registration algorithm from our first case of robot-assisted LPN for tumors was a 3D reconstruction of the anatomic surface of the kidney that showed the dimensions and depth of the tumor. The segmented kidney and tumor models were semitransparently superimposed on top of the stereoscopic video images that tracked the anatomic features. Additional overlays, including the collecting system and a ring around the tumor at the surface of the kidney outlining the boundary of the planned incision and allowing for a 3-mm safety margin, were overlaid to further augment surgical navigation (Video clip 3).

For the second case, we processed a segment of video recorded from a robot-assisted LPN performed for a lower pole staghorn calculus. Using the same image registration algorithm, we were able to display the segmented 3D kidney model, stone, and collecting system onto the segment of stereoscopic video, allowing for 3D registration and tracking of the kidney and stone, similar to our first case (Video clip 4).

Our investigations have demonstrated that we can identify and track the kidney surface in real time when applied to intraoperative video recordings and overlay the 3D models of the kidney, the tumor or stone, and the collecting system semitransparently. Using a basic computer research platform, we achieved an update rate of 10 Hz and an overlay latency of 4 frames. This update rate and latency can be easily improved by using a higher-end computer workstation and associated algorithmic improvements, which we plan to incorporate during future studies.

COMMENT

Partial nephrectomy has emerged as an effective surgical treatment for small tumors, with the added benefit of preserving nephrons in an effort to avoid renal failure.[1-4] LPN has curative and functional outcomes comparable to those of OPN while reducing patient morbidity and convalescence.[5]

A recent publication by Ukimura and Gill[14] demonstrated the use of a transposed image overlay during conventional LPN. Their study suggested that the use of augmented reality might improve surgical precision and increase surgeon confidence in operative excision.[14] This system required the use of an external optical tracking system to register the preoperative cross-sectional image to the live surgical view.

Technological advancements, such as teleoperated robotic surgical systems (eg, the da Vinci Surgical System), have the potential to further enhance the minimally invasive surgical technique by providing high-quality 3D magnification of the tumor site. Moreover, the pre-existence of a stereovision system offers the opportunity to develop a 3D-to-3D registration system with the patient's preoperative CT scan without modifying the surgical procedure and without the need for external tracking devices. In our feasibility study, for both cases, we successfully linked and registered the segmented 3D-CT scan of the kidney and tumor (or stone) to a segment of the 3D video footage. With our computer workstation system, we created a detailed 3D mesh overlay that accurately displayed the kidney with the accompanying tumor (or stone) and collecting system and followed these structures as they moved during the video footage. The semitransparent mesh design allowed the surgeon to see the underlying kidney, thus avoiding visual impedance of the surgical site by the overlay image.

However, our study had certain shortcomings. First, the foundation for accurate tumor excision using this technology relies on precise segmentation of the preoperative CT image of the kidney. The manual segmentation of the 3D-CT image used in the present study is subject to human error in tracing the precise contours of the kidney, tumor, and other structures, such as the collecting system and renal vasculature. The use of automated segmentation software to obtain more precise segmentation images of the kidney, tumor, collecting system, and, even, the renal vasculature will allow for more accurate registration between the 3D model and live image. As such, we plan to incorporate automated segmentation in our future studies.

Second, the final accuracy of our image registration algorithm still warrants testing and validation. The accuracy of the registration technique depends on 2 factors: the stereo triangulation and the 3D ICP registration. The true accuracy of the stereo triangulation is difficult to determine because without having an actual measurement of the anatomic shape we cannot compare the results of the stereo reconstruction with reality. However according to our phantom experiments, we were able to achieve submillimeter accuracy with the stereoscopic da Vinci endoscope in the typical working distance of <12 cm from the target organ, within the approximate range used during both of our cases. In contrast, the accuracy of the modified ICP algorithm can be predetermined. In our experiments, this was set at <1 mm by the computer programmer.

Finally, deformation of the kidney when the renal artery is clamped, such as is routinely performed during partial nephrectomy, might affect the accuracy of the 3D registration to the preoperative 3D segmentation map, because our system accounts for gross movement but not anatomic deformations. Although future developments of our technique will need to account for the change in the size of the kidney during ischemia, the current technology might still allow for more accurate determination of the most appropriate line of parenchymal incision before clamping of the renal artery. A similar concern has been found in stereotactic neuronavigation systems in which changes in the shape of the intracranial structure owing to cerebrospinal fluid leakage, gravity, or tissue removal renders the correlation between the preoperative image and the live surgical ultrasound image inaccurate.[11] In addition, during liver cancer surgery, organ shifting has been known to decrease the precision of the navigation system.[13]

Additional studies are underway to assess the precision of the image overlap in phantom models, followed by a formal system validation in an animal model. In addition, we are working to parallelize the algorithm to improve the speed of both stereo processing and registration. Our future efforts are to accomplish these accuracy studies and to develop a fully automated augmented reality image registration and display.

CONCLUSIONS

We have presented a system for performing registration to track gross movement and display on solid organ surfaces observed with a stereovideo endoscope operating at near real-time rates. Augmented reality overlay of a reconstructed 3D-CT image onto real-time stereo video footage is possible using ICP and image-based surface tracking technology that does not use external navigation tracking systems or preplaced surface markers. Additional studies are needed to assess the precision and achieve fully automated registration and display. We have targeted an intraoperative application to bring the advantages of this system to the surgeon.

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Video

Video Clips cited in this article can be found on the internet at:10.1016/j.urology.2008.11.040.