Virtual Surgical Planning: A Novel Aid to Robot-Assisted Laparoscopic Partial Nephrectomy

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Abstract

Background and Purpose: Incidental detection of small renal masses has significantly increased over the last two decades with the advent of cross-sectional imaging. The shift in stage has been met with a shift in treatment modality because the preservation of renal parenchyma can prevent adverse outcomes. Robot-assisted laparoscopic partial nephrectomy (RALPN) needs significant surgeon expertise, and preoperative planning is imperative.

Patients and Methods: Between December 2010 and September 2011, virtual surgical planning (VSP) was used in consecutive patients with renal tumors that were suspicious for renal-cell carcinoma who were undergoing RALPN by a single surgeon. Three-dimensional (3D) reconstructions were examined and manipulated preoperatively, and an operative plan formulated. Intraoperative anatomy and preoperative 3D reconstructions were compared in real time.

Results: A total of 10 patients underwent RALPN with preoperative VSP. Average patient age at intervention was 54.6 years and average tumor size was 4.3 cm (range 1.7–7.5 cm). Tumor laterality was evenly distributed. Nephrometry score ranged from 5A to 10P, and final tumor pathology results revealed malignancy in 80%. No complications occurred intraoperatively, and an excellent correlation was noted between preoperative 3D reconstruction and intraoperative anatomy. All patients underwent a successful partial nephrectomy with no positive margins on final pathology results. Mean length of surgery was 232.9 minutes (range 156–435 min), and mean estimated blood loss was 370 mL (range 75–1800 mL). Warm ischemia time ranged from 20 to 50 minutes (mean 33.9 min). Data regarding postoperative renal function were available for six patients with an average loss of function of 9.5% (range 2%–17%).

Conclusions: The implementation of this novel technology has significantly improved our ability to plan RALPN preoperatively. Tumor depth and complexity of tumor resection are assessed and the appropriate operative intervention and approach planned. Tumor proximity to vascular structures and collecting system were reliably predicted and therefore anticipated. Overall, these advantages created a safer surgical endeavor.

Introduction

The incidental detection of small renal masses has significantly increased over the last two decades with the advent of cross-sectional imaging.1 This shift in stage of detection has been accompanied by a similar shift in surgical treatment modality. The implementation of nephron-sparing surgery (NSS) has proven to significantly reduce the onset of chronic renal failure when compared with radical nephrectomy.2 Preservation of renal parenchyma can also prevent adverse outcomes, including cardiovascular events, hospitalizations, and mortality.3,4

Minimally invasive laparoscopic and robotic approaches to NSS have the potential to further enhance the benefit to patients via diminished convalescence and complications while maintaining oncologic efficacy.5,6 The implementation of robotic technology during robot-assisted laparoscopic partial nephrectomy (RALPN) is safe and may facilitate the learning curve.7,8 Its augmented maneuverability is particularly ideal in partial nephrectomy. This is especially true during the extirpation of complex tumors and the reconstruction of the collecting system during technically challenging cases. Despite the clear advantages of RALPN, significant surgeon expertise is necessary, and preoperative planning is imperative in all cases.

Detailed cross-sectional imaging with MRI or CT and three-dimensional (3D) reconstructions give detailed information about the anatomy of the kidney and the tumor. Despite these
advances and the detailed 3D intraoperative visualization afforded by the robot, surgical approaches to robot-assisted partial nephrectomy are often modified intraoperatively. It would thus be beneficial to gain detailed knowledge of the anatomic relationships and tumor characteristics using detailed 3D reconstructed images. The actual resection of the tumor can be planned and performed preoperatively with these data, and a surgical blueprint can be constructed.

Preoperative virtual surgical planning (VSP) uses adjustable 3D reconstructions of CT images and has the potential to predict surgical difficulty and augment resection and reconstruction. Its utilization can assess complexity of tumor resection and plan the appropriate operative intervention. The advantages of similar technology have been well documented in head and neck surgery as well as hepatobiliary surgery. We describe our experience with 3D preoperative VSP and its utilization during RALPN.

Patients and Methods

Patients

From December 2010 to September 2011, VSP was performed in 10 consecutive patients with renal tumors that were suspicious for renal-cell carcinoma who underwent RALPN by a single surgeon (RG). Preoperatively, 3D images were reconstructed from a detailed CT protocol described below. The 3D reconstructions were examined and manipulated in detail preoperatively. Tumor size, renal vascular pedicle anatomy, depth of tumor penetration and proximity to vessels and collecting system, and resection margins were reviewed and an operative plan formulated. Through the implementation of the robot’s TilePro display, the surgeon was afforded the ability to compare intraoperative anatomy and preoperative 3D reconstructions in real time in the surgical console. Intraoperative and postoperative data were accrued and analyzed using Microsoft Excel 2008 (2007 Microsoft Corporation; Redmond, WA).

CT

All CT imaging was obtained from a 64-slice LightSpeed VCT General Electric scanner (GE Healthcare; Milwaukee, WI). In each case, an arterial, nephrographic, and excretory phase imaging at 0.625 mm slice thickness was obtained after intravenous contrast administration. The arterial phase scan was initiated when the contrast bolus reached the level of the renal arteries, as monitored by SmartPrep (GE Healthcare, Milwaukee, WI). The nephrographic phase was initiated 100 seconds after the contrast injection, the and excretory phase was initiated 5 minutes after contrast administration. All phases were reconstructed to 2.5 mm slice thickness, and both 0.625 mm and 2.5 mm axial slices were made available for review and analysis.

3-D reconstruction

An index case of a 48-year-old man with a central tumor is presented here to describe the VSP technique (Fig. 1). Both the 0.625 mm and 2.5 mm high-resolution CT images were sent to a medical modeling company (Medical Modeling Inc, Golden, CO) for 3D reconstruction and VSP. Using both manual and automatic segmentation techniques, 3D digital models were created from the two-dimensional CT images. The following anatomic structures were digitally created in each case: Skeleton, liver, pancreas, spleen, renal artery, renal vein, ureter, kidney, renal tumor(s), and resection margin(s). A Web-based virtual planning session was held with the surgeon during which the digital tumor anatomy was assessed and tumor resection strategy and margins established. Both kidneys were included in the reconstruction regardless of tumor laterality. A resection plane was generated allowing for adequate parenchymal margins for virtual resection (Fig. 2). Furthermore, the amount of functioning renal parenchymal surface area and volume are automatically calculated. After the resection exercise, the volume of renal tissue resected with the tumor is accurately measured, and the final renal parenchymal volume in the renal remnant is provided for the surgeon.

The anatomic and planned resection and reconstruction 3D images were then electronically transferred to the surgeon in a portable document format (PDF, Adobe Systems Incorporated; San Jose, CA) that allowed for 360-degree manipulation along all axes of all anatomic structures (Fig. 3). The final PDF file afforded the surgeon the luxury of manipulating the kidney and the operative target to assess its proximity to the collecting system and segmental vessels. Detailed anatomic information with relation to the surrounding viscera was available. The organs could be removed from the screen to allow better visualization and focus on the target organ, simulating dissection and retraction away from the surgical field intraoperatively. Viewing windows could be changed from solid phase to transparency to allow excellent visualization of intrarenal anatomy and tumor extension with relation to the overall contour of the kidney (Fig. 3). The relationship of the tumor and resection margin with the collecting system could be superbly predicted, assessed, and augmented through the rotational capability of the reconstruction. The kidney and its relevant anatomic relationships were oriented in a surgical
position and plane to mirror the actual intraoperative views of the surgery (Fig. 4) in the console using the TilePro feature of the robotic surgical system. This effectively created a virtual reality environment for the surgeon. The tumor can be resected from the 3D reconstruction in the exact same position, with exposure of possible collecting system entry, segmental vessel transection, and view of the remnant tumor crater before the actual surgical resection.

Surgical procedure

In all cases, including the index case depicted in the images, a standard four-arm approach to RALPN was used. The kidney was fully mobilized and hilum dissected to expose the vasculature. The kidney surface was exposed and the tumor was visualized, when an extr-parenchymal component was present. Before resection, 12.5 g of mannitol was injected intravenously, and intraoperative ultrasonography (US) was performed. The double TilePro window was used to correlate the US images with the VSP images within the surgeon console (Fig. 4B). This allowed for visualization of the entire intraparenchymal component of the tumor. The parenchyma was then marked for resection.

After 5 to 7 minutes, renal hilar control was obtained with laparoscopic or robotic Scanlon bulldog clamps and the tumor was resected, maintaining a 5-mm rim of normal parenchyma when possible, with cold articulating robotic scissors (Fig. 4C). Entry into the collecting system was repaired with 3-0 polyglactin sutures. Major segmental vessels were ligated with Hem-o-lok clips (Teleflex Medical, Research Triangle Park, NC) or were oversewn robotically. The tumor crater was oversewn with a 3-0 V-lock absorbable polyglyconate suture (Covidien, Norwalk, CT) and anchored to the external parenchyma using a Hem-o-lok and Lapra-Ty (Ethicon, Somerville, NJ) clip. The parenchyma was then closed over a small Surgicel (Ethicon, Somerville, NJ) and absorbable gelatin sponge bolster using 3-0 polyglactin sutures with Lapra-Ty and Hem-o-lok anchors in a sliding-clip renorrhaphy method. Floseal Hemostatic Matrix (Baxter, Hayward, CA) was then applied to the tumor crater before closure.

All patients were entered into our robotic partial nephrectomy clinical care pathway. All patients who undergo partial nephrectomy at our institution undergo a nuclear renal scan at 2 months and 1 year and a repeated CT scan to evaluate the healing of the renal remnant at 4 months.

Results

RALPN

A total of 10 patients underwent RALPN with preoperative VSP from December 2010 to September 2011. The average patient age at intervention was 54.6 years, and average tumor...
size was 4.3 cm (range 1.7–7.5 cm). Tumor laterality was evenly distributed with five right- and five left-sided tumors. Nephrometry score ranged from 5A to 10P, and final tumor pathology results revealed malignancy in 80% with five clear-cell, two papillary, and one chromophobe renal-cell carcinoma. No complications occurred intraoperatively, and all patients underwent a successful partial nephrectomy with no positive margins on final pathology results. Mean length of surgery was 232.9 minutes (range 156–435 min), and mean estimated blood loss was 370 mL (range 75–1800 mL). Warm ischemia time ranged from 20 to 50 minutes (mean 33.9 min), and data regarding postoperative renal function were available for six patients; the remaining four patients had not yet obtained their postoperative nuclear renal scan. The average loss of function as measured by renal scan was 9.5% (range 2–17%).

**3D reconstruction anatomic detail**

Preoperative imaging was obtained, and 3D reconstructions were successfully generated in all patients. Preoperatively, a Web-based conference was held between the surgeon (RG) and the medical modeling company during which a surgical resection margin was measured and generated in all cases.

An excellent correlation was noted between the preoperative 3D reconstruction and the intraoperative anatomy. Both extrarenal visceral anatomy and renal anatomy mirrored the details identified within the 3D reconstructions. In all cases the tumor laterality was correct and intraoperative ultrasonography confirmed depth of penetration identified in the 3D images. Intraoperative tumor resection confirmed the relationship of tumor to vascular structures and collecting system in all cases. In several cases, the tumor abutted segmental vessels and the collecting system. The preoperative knowledge of these relationships allowed the surgeon to anticipate their presence and avoid vascular violation and collecting system entry. Intraoperative use of the TilePro was successful in each case and enhanced the surgeon’s ability to appreciate anatomic relationships intraoperatively and manipulate the images and the tumor in real time, generating a virtual reality experience. The ability to separate renal tumor and planned resection margin provided an ability to accurately and reliably predict tumor blood supply and collecting system proximity, and the surgical plan was adjusted as necessary.

**Discussion**

NSS achieves similar oncologic outcomes when compared with radical nephrectomy for small renal masses. A growing body of evidence demonstrates that the preservation of renal parenchyma can prevent the onset of chronic renal insufficiency as well as adverse outcomes, such as death, cardiovascular events, and hospitalizations. These considerations helped formulate the American Urological Association guidelines for the management of clinical stage 1 renal tumors.
mass. The guidelines advocate for the implementation of partial nephrectomy in healthy patients with clinical stage T1a renal masses as well as in those with larger tumors (T1b) and a need to preserve renal parenchyma.\textsuperscript{12}

Minimally invasive approaches to NSS have further enhanced the benefit to the patient by potentially decreasing morbidity. Laparoscopic partial nephrectomy (LPN) is a technically challenging procedure necessitating significant surgeon expertise with a rate of conversion to laparoscopic radical nephrectomy of 13.6\%.\textsuperscript{13} The implementation of the da Vinci robotic surgical system (Intuitive Surgical, Inc, Sunnyvale, CA) during RALPN allows for excellent 3D visualization and depth perception. In addition, superior dexterity and intracorporeal suturing allows for enhanced renal reconstruction. These advances have extended the benefits of LPN to urologists with less laparoscopic experience through the use of the RALPN.

Despite the plethora of literature documenting the feasibility, safety, and efficacy of the RALPN, some surgeons have avoided its use in complex tumors. Tumor complexity (measured via R.E.N.A.L. [radius; exophytic/endophytic; nearness; anterior/posterior; location] nephrometry score\textsuperscript{14}) has been documented to predict a longer operative time, warm ischemia time, hospital stay, and higher complication rate.\textsuperscript{15} Even in complex tumors, the ultimate goal of the preservation of healthy renal parenchyma remains steadfast, further illustrating the necessity to adequately assess the feasibility of tumor resection as well as a need to formulate a detailed operative plan preoperatively.

Factors that are essential during the preoperative assessment include the surrounding visceral relationships, renal vascular anatomy, tumor complexity and depth of penetration, and tumor proximity to collecting system and vascular structures. 3D CT has been used to assess these factors preoperatively previously.\textsuperscript{16–18} The implementation of 3D CT evaluation preoperatively has been proven to accurately predict the number and location of lesions as well as the intraoperative renal vascular anatomy.\textsuperscript{17,18} Despite this, methods to preoperatively predict the potential anatomic relationships and characteristics that can create intraoperative difficulties remain elusive. Furthermore, a method to construct resection strategies and assess possible remnant viability as well as predict vascular transection and collecting system entry would be immensely advantageous. This would help the surgeon determine if partial nephrectomy is feasible and if so, what maneuvers should be anticipated in both resection and reconstruction of the renal remnant and tumor crater. In addition, the TilePro feature of the robot affords the surgeon the ability to manipulate these preoperatively constructed 3D images and the planned resection side by side with live intraoperative images within the robotic console.

We report on a novel technology that further assists the surgeon’s ability to preoperatively perform VSP. Our ability to manipulate the surgical anatomy preoperatively provided the surgeon with an unparalleled understanding of the surgical anatomy. The capability to individually removes organs, collecting system, arteries, veins, tumor(s), and/or resection margin(s) facilitated surgical planning. We found that the 3D

\begin{figure}[h]
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\caption{The relationship of tumor and collecting system: (A) Incorporation of resection margin in the deep plane, results in exclusion of multiple calices. (B and C) enucleation along the deep margin is possible preserving the collecting system.}
\end{figure}
renderings accurately predicted surgical anatomy in all cases. In this preliminary experience, the utilization of the TilePro feature of the daVinci Si surgical platform (Intuitive Surgical, Inc, Sunnyvale, CA) was instrumental because it provided the surgeon with the ability to accurately compare intraoperative anatomy with that of the 3D imaging in real time. In addition to an accurate depiction of the details of renal anatomy and contour, even mild abnormalities in surrounding viscera and their proximity to the kidney and tumor were accurately reconstructed and anticipated.

The technology used during the planning phase allows for assessment of the normal anatomy and relationship of the tumor to the kidney in general. After this determination, a resection margin is constructed. A specimen (tumor + associated resected normal surrounding parenchymal margin) is then formulated and removed, allowing for visualization of the tumor crater and renal remnant. The 3D reconstructions and VSP allowed for assessment of the feasibility of RALPN. When used in the setting of a centrally located tumor closely abutting the renal collecting system or sinus where a large resection margin can jeopardize renal viability, removal of the tumor with or without the resection margin allows the surgeon to assess crater size and if an enucleation would be a better option (Fig. 5). In cases where tumor extension beyond the renal sinus was noted and resection would have resulted in nonviability, dissociated renal remnants, or potentially jeopardized oncologic efficacy, a laparoscopic radical nephrectomy was performed.

We do not advocate the implementation of this technology for every routine partial nephrectomy. Our experience represents an initial series and as such, some patients with low nephrometry scores were included. Small exophytic renal masses with low nephrometry scores do not necessitate VSP. The true value of this technology lies in patients with tumors of high complexity in which a challenging resection and reconstruction is anticipated. For two tumors that were intraparenchymal and centrally located, the technology allowed us to predict feasibility and success of partial nephrectomy using an enucleation technique rather than one with a resection margin because the latter would have excluded calices and rendered the remnant nonfunctional (index case).

In an additional patient, the 3D imaging was able to predict significant collecting system involvement leading to the decision to proceed with radical nephrectomy (Fig. 6). This patient was a 75 year-old man with a 5.1-cm tumor. Nephrometry score was 11XH preoperatively, and the tumor was infiltrating the renal sinus fat. In this case, our preoperative VSP identified renal sinus involvement as well as significant collecting system involvement. Our VSP demonstrated a need to resect the collecting system with resultant excluded calices and possible poor renal function. Robot-assisted radical nephrectomy was performed without complication. The renal sinus fat was involved as correctly predicted, and final pathology results revealed stage pT3A clear-cell renal-cell carcinoma.

We recognize that this is an initial report of a novel technology and as such has several limitations. It is intended,

FIG. 5. Intraoperative images. (A) Utilization of TilePro feature of the robotic surgical system to create a virtual reality environment for the surgeon. Images aligned to delineate vascular anatomy. (B) Intraoperative ultrasound. Note second Tilepro window with the 3D reconstruction of kidney rotated along the same axis as the surgical image. (C) Tumor resection: the tumor is peeled off the collecting system with cold scissors. (D) Completely resected tumor.
however, to be a descriptive report of technology that has the potential to dramatically improve the understanding of surgical anatomy and, therefore, can facilitate an efficient and successful tumor resection. Our analysis is retrospective and our experience with 10 patients is small. A larger prospective analysis is necessary and is under way at our center to adequately assess the true impact of this technology on surgical outcomes.

It would be interesting to see if this technology can help better predict postoperative renal function after tumor resection because CT imaging alone has previously been correlated to renal function. A valuable aspect of this technology in addition to its anatomic information is the renal functional information that it could potentially provide. Each VSP case provides the surgeon with an estimate of the renal functional surface area preoperatively. It also provides the volume of resected tissue and hence the final functional renal parenchymal surface area. As our experience with this novel technology increases, we plan to correlate the postoperative function with the preoperative imaging. We plan to correlate renal functional parenchymal loss to postoperative renal function measured by nuclear renal imaging and estimate glomerular filtration rates postoperatively. Our goal will be to compare these data with the preoperative renal functional capacity measured in the same fashion. The ability to predict postoperative renal function after partial nephrectomy would further assist surgeons to adequately counsel their patients regarding the utility of NSS.

The use of high-resolution CT to formulate the 3D reconstructions places the patient at potential risk of additional radiation exposure. We think that this is not a significant limitation because the current gold standard for the detection of renal masses is contrast-enhanced helical CT. As technology progresses, it may become possible for MRI to provide reconstructions of comparable quality.

**Conclusions**

We think that the implementation of this novel VSP technology has significantly improved our ability to plan RALPN preoperatively. Through its implementation, the surgeon gained the ability to preoperatively visualize, examine, and manipulate anatomy and anatomic relations. Tumor depth and complexity of tumor resection are assessed and the appropriate operative intervention and approach planned. We have found that tumor proximity to vascular structures and collecting system were reliably predicted and therefore anticipated. This technology is not necessary in routine tumor resections where adequate information can be gained with routine cross-sectional imaging. The technique, however, is invaluable for complex tumor resections and renal reconstructions. In this setting, a virtual preoperative resection assesses both the feasibility of NSS and the viability of the renal remnant. Overall, these advantages create a safer surgical endeavor.

**Disclosure Statement**

Evan Garfein is a consultant for Medical Modeling, Inc. For the remaining authors, no competing financial interests exist.

**References**


**FIG. 6.** Preoperative visual surgical planning (VSP) resulted in a decision to proceed with nephrectomy: (A) Preoperative CT with identification of possible collecting system invasion; (B) VSP demonstrating collecting system involvement; (C) final pathology results with confirmation of collecting system luminal invasion.

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Abbreviations Used
CT = computed tomography
LPN = laparoscopic partial nephrectomy
MRI = magnetic resonance imaging
NSS = nephron-sparing surgery
PDF = portable document format
RALPN = robot-assisted laparoscopic partial nephrectomy
3D = three-dimensional
US = ultrasonography
VSP = virtual surgical planning
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