Anatomic Modeling and Visualization of the Kidney and its Associated Major Vessels in Patients with Kidney Cancer

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Kidney cancer patients who have tumors confined to the kidney are typically treated with surgery (about 30% of renal cell carcinoma patients each year), often with the use of Robot-Assisted Laparoscopic Partial Nephrectomy (RALPN). RALPN is challenging because of the complex three-dimensional (3-D) juxtaposition of the critical anatomy within and around the kidney including abundant blood vessels and the urinary collecting system. Inadvertent injury to these structures during surgery can lead to excessive bleeding and transfusion as well as leakage of urine made by the kidney into the abdominal cavity. This research work aims to develop 3-D models of the kidneys, tumors, renal arteries, veins, and surrounding anatomy to assist surgeons in visualization of these critical structures during surgery. Using in-house software, we can examine patient radiography and contour the affected kidney and tumor(s), and extract the vascular structure of the renal arteries and veins from the 2-D patient data sets of MRI and CT scans. We are currently examining CT and MRI scans retrospectively of individuals who underwent Robot-Assisted Laparoscopic Partial Nephrectomy for kidney tumors at UF Health Shands Hospital from 2005-2016. All data collection and handling is conducted under approved protocol IRB-201600940. To date, ten patients have been processed, and high-quality 3D stereolithographic (STL) files have been developed for two of the data sets. While certain limitations exist with regards to limitations of the software code, this research has the potential to increase the quality of care and safety of patients who undergo RALPN procedures.

INTRODUCTION

Cancer is a destructive disease that is caused by the uncontrollable division of cells. Each year, millions of people worldwide are diagnosed with cancer. Kidney cancer, specifically, is the third most commonly occurring genitourinary cancer in adults, with about 273,000 new cases each year worldwide.¹ Of these cases, about 90% are renal cell carcinoma (RCC). Renal cell cancer is a disease in which malignant cancer cells are found in the lining of the tubes in the kidneys.²

Kidney cancer patients who have tumors confined to the kidney are typically treated with surgery (about 30% of RCC patients each year), often with the use of Robot-Assisted Laparoscopic Partial Nephrectomy (RALPN).³ This state-of-the-art surgical technique is a minimally invasive approach which employs the da Vinci surgical system to surgically remove only the tumor and the portions of the kidney in which the tumor is present, while attempting to preserve the remaining healthy portions of the kidney. The da Vinci system used in these procedures is a robotic technology that allows the surgeon’s hand movements to be translated into smaller, precise movements of the robotic arms and instruments within the patient’s body.⁴ Of these instruments, one is a small laparoscope, serving as a camera, to send images to surgeons to guide them during the procedure. With recent advances in robot-assisted surgeries, the RALPN procedure is becoming more popular as the primary method to resect tumors in patients with kidney cancer.⁵ Nonetheless, serious complications may arise during surgery. RALPN is challenging because of the complex three-dimensional (3-D) juxtaposition of the critical anatomy within and around the kidney, including the abundant blood vessels and the urinary collecting system. Inadvertent injury to these structures can lead to excessive bleeding and transfusion as well as leakage of urine made by the kidney into the abdominal cavity. This may occur as the surgeon is unable to anticipate these structures as the tumor is being excised surgically due to the lack of a 3-D road map of the anatomy within and around the kidney, along with relative estimates of the overall boundaries of the tumors. Prior to resecting of the tumor, an ultrasound probe is inserted into the patient to measure the depths and boundaries of the tumor with regards to the kidneys. Also, surgeons often align rulers and other measurement devices along the MRI and CT scans seen on the operating room computer screen to gain estimates of the appropriate size and lengths of the tumor. As such, 8-10% of laparoscopic procedures result in complications,⁶ such as bleeding out, which this research work may help reduce or prevent.

METHODS

3-D modeling of the kidneys, tumors, and renal vasculature has been applied successfully on a case-to-case
basis. Modeling of these critical anatomical structures may allow surgeons to simulate surgery prior to actual operations, and develop methods for efficient resection of tumors. These models can be personalized to each patient for simulation of more accurate surgical procedure methods. Our research lab specifically uses the NIH developed open-source software ImageJ, in which the code has been modified extensively to tailor to desired kidney segmentation processes.

**Image Processing**

In the kidney segmentation process in our lab’s version of ImageJ, CT and MRI patient scans are first imported for analysis. We then manually adjust the pixel intensity threshold so as to maintain the highest contrast of the target organs relative to the bones, bladder, and intestines. For segmentation of the bones, after application of the appropriate high intensity threshold, a seed point is manually selected at any point within the vertebral column and a seeded region-growing algorithm is applied to identify pixels belonging to bone. A mask can be made of the bone-only pixels, saved, and the bone pixels removed from the images. Following this same procedure — adjusting the contrast threshold and selecting a seed in each feature — the ureters, arteries, and veins are segmented.

For each of the ureters, arteries, and veins, the centerline pixels for each branch are determined from application of a 3D thinning operation. From the centerline representation, the vessel tree hierarchy is defined and a mathematical model of each branch centerline is computed using a cubic-Hermite spine formulation. An estimate of each branch radius is obtained from the original seeded region-growing result, and each branch is modeled as a cylindrical tubular structure traversing in 3D space along the modeled centerline. A model is constructed analogously for each bifurcation region to generate a composite mathematical model of the entire vessel tree structure. Finally, from this 3D tree model a stereolithographic (STL) file of each of these individual structures is generated.

After each vessel structure is segmented, the pixels representing that structure are removed from the image so as to not corrupt the segmentation of the remaining structures. The STL files can then be imported into a computer-aided design (CAD) program for visualization and manipulation of all the critical anatomical parts simultaneously, and can be sent to a 3D printer to generate patient specific physical models.

Models of the kidney and tumor were generated using a separate semi-automatic contouring process (“snakes”) that uses active contours. This first involves the importing of patient data sets into the ImageJ software, followed by semi-automated drawing of snakes to the kidney on each CT/MRI slice that contains the kidney. The 3D set of contour points are then used to model the kidney or tumor surface mathematically. From this surface model a 3D surface mesh is generated, which can be saved as an STL file. As with the previously segmented vessels, these STL files of the tumor and kidney can be imported into CAD software, and can be delivered to 3D printers for the completion of the patient specific model.

**RESULTS**

To date, ten total patients have been processed: 6 with CT-only data, 1 with MRI-only data, and 3 with CT and MRI data. Of these 10 patients, high-quality 3D STL files have been developed for two of the data sets. For both of these data sets, STL files have been imported together into CAD software for visualization of the critical anatomical structures, and their relative proximities to one another. These data sets also show the relative size and depth of the tumors present within the kidney, and the associations between the tumors, kidney, and major vessels, allowing for proper visualization of the 3D models.
CONCLUSIONS/DISCUSSION

In-house semi-automated software tools have been developed to generate 3D models of the kidney and surrounding anatomy from serial 2D MRI and CT scans acquired in patients treated with RALPN at UF Health Shands. STL-formatted models for each object have been exported to commercial CAD software for integration of relative proximity of the tumor to vital kidney structures, and to enable the creation of patient-specific physical models via 3D printing.

The ultimate goal is to use these 3D models to aid in planning and performing RALPN with the benefit of reduced procedure time and reduction in complications. The next steps with this project are to streamline the software for routine use, and have the visualization results evaluated by surgeons to identify ways to improve the presentation of this information in the operating room. The hope is that improved three-dimensional visualization of tumor margins and surrounding vital structures adjacent to the tumor within the kidney will allow for safer surgery, less blood loss, and reduced complications during robot-assisted laparoscopic partial nephrectomy (RALPN) for kidney tumors.

It has been noticed that when tissue contrast is adequate, segmenting and modelling of the major anatomic features is significantly more efficient; however, there is often inadequate contrast for all of the anatomic features of interest for a given patient. As such, MRI is seen to be superior to CT for extraction of most anatomic features whereas contrast-enhancement of the ureters and collecting ducts is typically superior with CT. This is likely due to use of a longer post-contrast delay for CT (typically 7 minutes) compared with MRI (typically 3 minutes).

The project has reaffirmed the concepts of anatomic 3D printing to be a feasible method to assist surgeons in pre-surgery planning, and in guiding during surgery. Execution of the idea, however, is very challenging. The creation of 3D models through running radiology scans through the ImageJ software is extremely time-consuming and laborious.15 During this project we have already identified and overcome limitations in the software but additional work needs to be done. With regards to the actual 3D printing process, while the STL files are immediately amenable for printing, in practice when using publically-used printing systems, delays of a day or more may arise before a model is actually at the head of the queue for printing.

Upon completion of the first set of 3D printed models, our next task will be to quantify their perceived utility for clinical use, based on survey results from expert urologists.

REFERENCES

