

Design of Anatomically Accurate, Patient-Specific Renal Tumor Models for Partial Nephrectomy

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Abstract

Soft tissue 3D printing from MR data is feasible, but implementation is challenging and time consuming. The objective of this study was to evaluate the use of patient-specific 3D printed models in the context of renal malignancies. We designed and fabricated anatomically accurate, patient-specific 3D printed renal tumor models, determined the steps required, and the challenges in generating a patient-specific 3D printed renal tumor models from magnetic resonance imaging (MRI) data.

Introduction

Over the last 20 years, there has been an increase in the incidence of renal tumors, with renal cell carcinoma (RCC) accounting for approximately 3.5% of all malignancies.^{i,ii} More complex kidney tumors are associated with longer operative times, warm ischemia times, and greater blood loss.ⁱⁱⁱ High kidney tumor complexity can also be correlated to the risk of major postoperative complications requiring a secondary intervention.^{iv} Patient-specific 3D renal tumor models may help with improved education of the surgeons allowing for better surgical planning thus possibly reducing warm ischemia and intra-operative times. The objective of this study was to design and fabricate anatomically accurate, patient-specific 3D printed renal tumor models, determine the steps required, and challenges in generating a patient-specific 3D printed renal tumor models from magnetic resonance imaging (MRI) data.

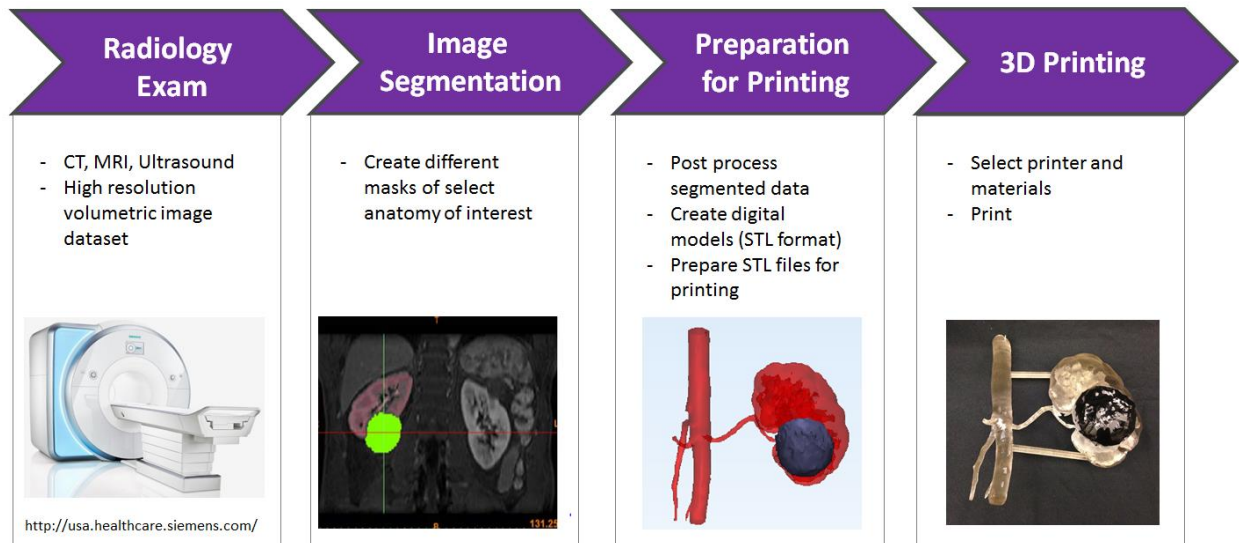


Figure 1: Workflow for creation of anatomically accurate, patient-specific 3D printed renal tumor models

Materials and Methods

The creation of anatomically accurate, patient-specific models requires four main steps which are shown in Figure 1.

Image Acquisition: T1 weighted fat-saturated gradient echo Volume Interpolated Breath-hold Exam (VIBE) after administration of contrast were performed on a 1.5-T system (Avanto, Siemens, Erlangen, Germany). Imaging parameters were as follows:

Case 1: TR=3.58ms, TE=1.3ms, FA=12°, pixel spacing=1.37mm, and slice thickness=2mm.

Case 2: Imaging parameters were as follows: TR=3.27ms, TE=1.2ms, FA=12°, pixel spacing=1.37mm, and slice thickness=2mm.

Image Segmentation: 3D visualization, segmentation, and creation of 3D objects were performed using a 2D workstation (Mimics, Materialise, Leuven, Belgium).

Case 1: The kidney and arteries were segmented as one object and the tumor was segmented as a second object. Two masks were created and were manually edited to ensure that only the regions of interest were selected (Figure 2a).

Case 2: The kidney cortex, kidney medulla, tumor, renal artery, renal vein, and collecting system were segmented as six different objects. Six masks were created using both thresholding and multiple-slice editing and were manually edited to ensure that only the regions of interest were selected (Figure 2b).

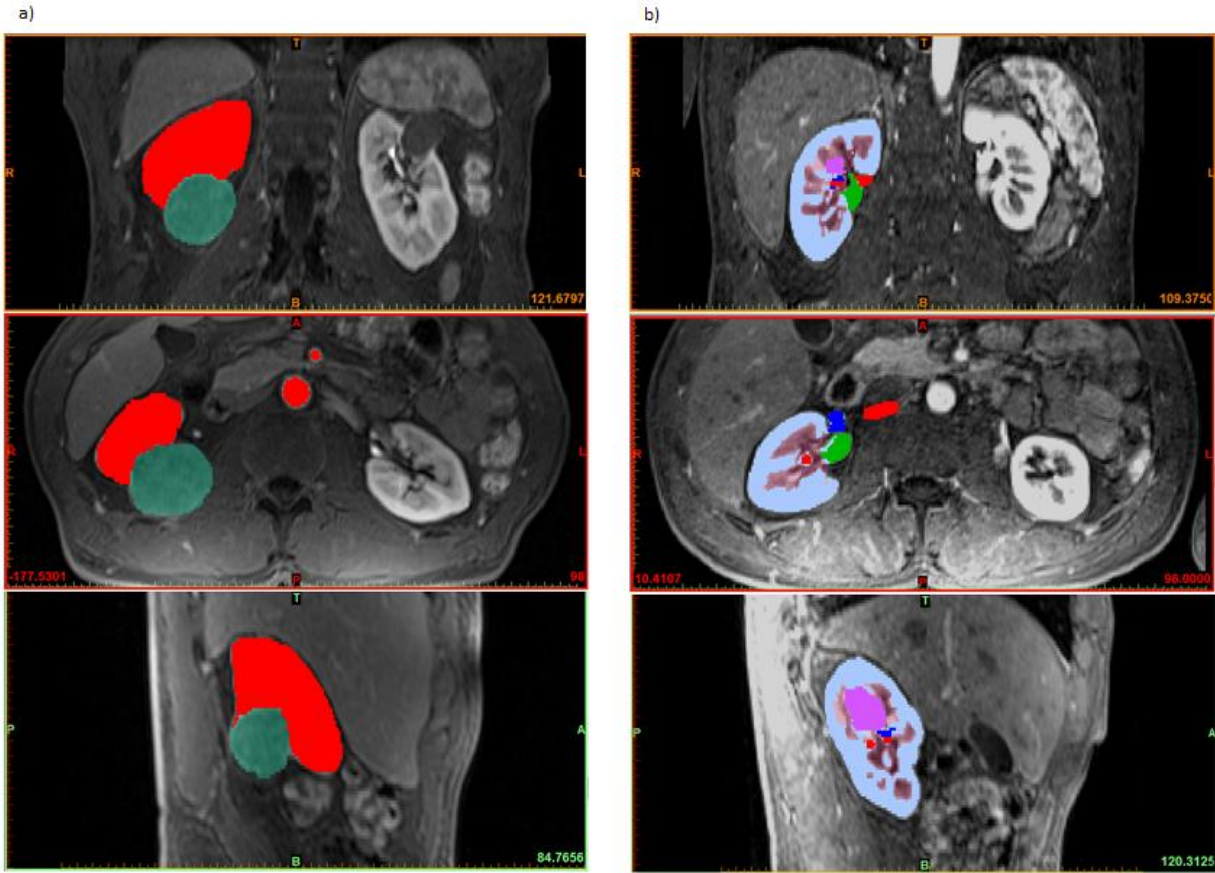


Figure 2a) Coronal, axial, and sagittal views for Case 1. Red = kidney and arteries, green = tumor. 2b) Coronal, axial, and sagittal views for case 2. Kidney cortex = light blue, kidney medulla = pink, tumor = purple, artery = red, vein = dark blue, collecting system = green.

Preparation for Printing: 3D objects were manually edited and converted to (STL) format for printing (3-matic, Materialise, Leuven, Belgium). Local smoothing was performed on each individual object using a paintbrush tool to make each anatomical object appear less pixelated. Contours of 3D rendered model were overlaid to multi-planar reformatted (MPR) images to ensure that the anatomy was correctly represented and that there were no overlaps between objects (Figure 3).

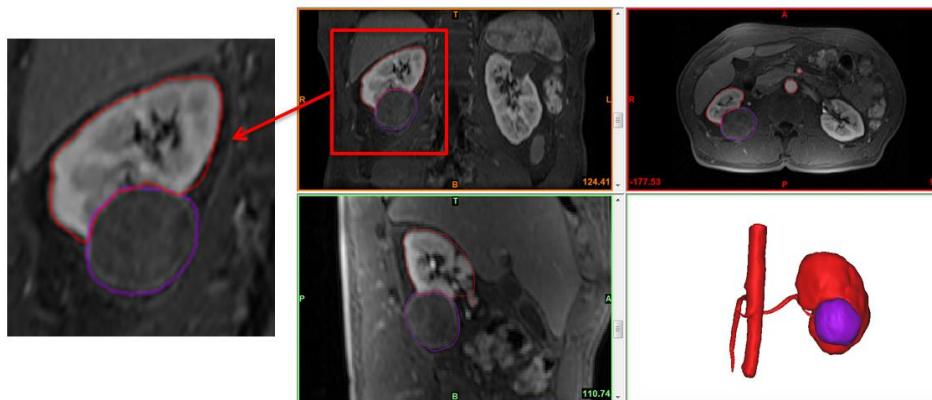


Figure 3: Contours of 3D rendering on MPR Images.

3D Printing: Printing steps are shown in Figure 4 and included the following:

Step 1: Import STL files to 3D printing software

Step 2: Align STL to minimize printing time

Step 3: Select printing materials and colors

Vero Clear, Vero Black, Vero Cyan, and Vero Magenta (Stratasys Ltd, Eden Prairie, MN)

HeartPrint Flex® (Materialise, Leuven, Belgium)

Step 4: Send STL files to the printer (Connex500, Stratasys Ltd, Eden Prairie, MN)

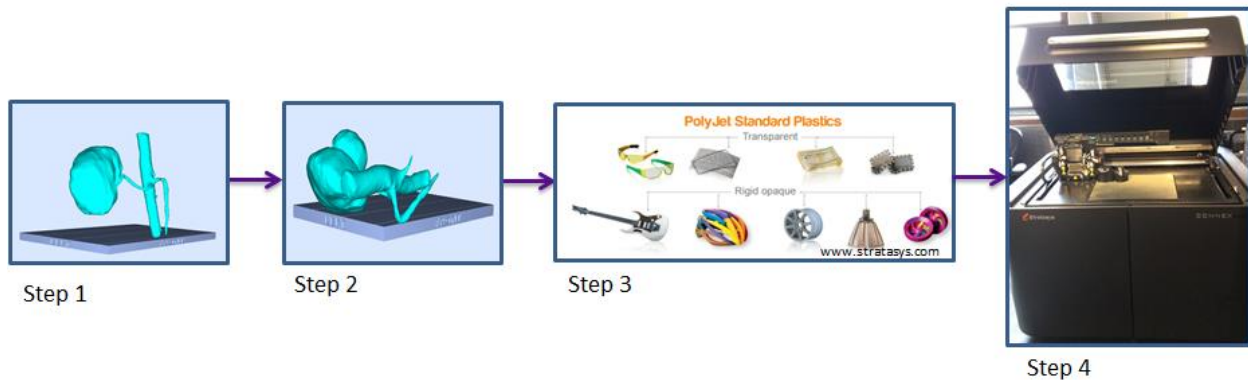


Figure 4: Steps for 3D printing model after the STL file has been created

Case 1: The STL file was used to print a true-sized anatomical model with two different photopolymers: Vero Black for the tumor and Vero Clear for the kidney and vessels. The projected print time and resolution were measured. The model was used to both plan the surgical procedure and assist during the surgery.

Case 2: The STL file was used to print two true-sized anatomical models. A solid model was printed using Vero Cyan, Vero Magenta, and HeartPrint Flex®; and a bi-valved model was printed using Vero Cyan, Vero Magenta, and Vero Clear. For both of these models, the kidney was printed in the clear, transparent material and the cyan and magenta colors were mixed to produce different colors for the remaining structures.

Results

Case 1: Segmentation time, printing time, and resolution were six hours, 14 hours 10 minutes, and 16 microns respectively. The aorta, tumor, renal artery, kidney, and superior mesenteric artery were visualized as 3D objects. Vessel measurements made on the model correlated with those made using orthogonal views and straightened out multi-planar rendering from the 2D data sets. The model helped the surgeon with regards to surgical approach for partial nephrectomy – retroperitoneal versus transperitoneal. During the operative procedure, the model was referred to and was utilized instead of intra-operative ultrasound to guide resection. The patient successfully underwent partial nephrectomy with complete excision of the suspicious renal mass. The resected tumor was compared to the 3D model (Figure 5).

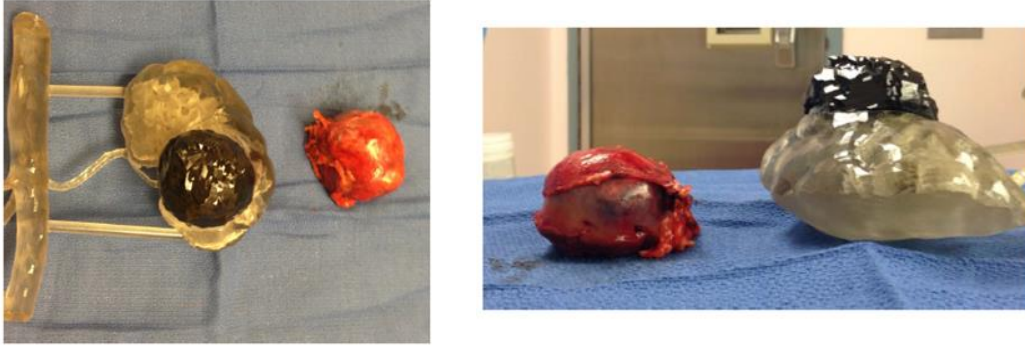


Figure 5: Comparison of 3D printed model to resected tumor.

Case 2: The kidney, tumor, renal artery, renal vein, and collecting system were all well visualized as 3D objects. The solid and bi-valved models both with each demonstrated the relationship of the renal artery, renal vein, and collecting system to the tumor (Figure 6).

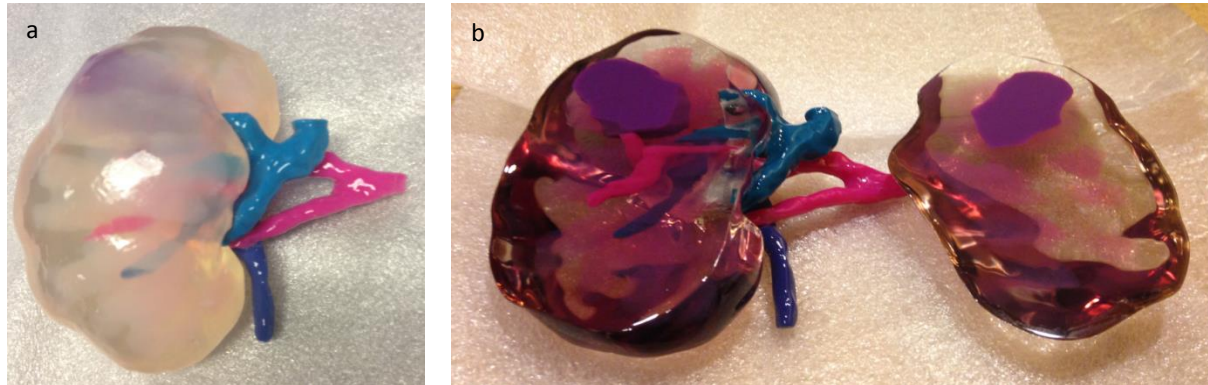


Figure 6: Comparison of solid and bi-valved 3D printed models

Discussion and Conclusions

Soft tissue 3D printing from MR data is feasible, but implementation is challenging and time consuming. Hybrid or semi-automatic segmentation methods specific for MRI data would facilitate rapid prototyping from MRI data in the future. Preoperative physical 3D models created from MRI data may influence surgical planning and provide intraoperative guidance for renal tumors. In addition, 3D printed models may enhance the understanding of patients and their families regarding the goals of their surgery; leading to higher satisfaction by the choice of treatment plan.

Future Work

- 1) A retrospective review will be performed and difficult partial nephrectomy cases will be selected. Mimics and 3-Matic (Materialise, Leuven, Belgium) will be used for image segmentation, 3D object creation, and printing preparation. High-fidelity, patient-specific 3D printed renal tumor models will be created from magnetic resonance (MR) or CT imaging data. Renal tumor cases will be reviewed by the surgical team

(surgeon and surgical trainee separately) with imaging alone or with imaging in addition to the 3D model. A questionnaire will be completed after both scenarios to assess surgical approach and planning with and without the patient-specific 3D model. The presumed pre-operative approach will be compared to the ultimate surgical procedure. Any change between the presumed approach and actual surgical intervention will be recorded.

- 2) A randomized study may be performed to determine the impact of the 3D printed model on clinical outcomes. Patients with complex renal masses on imaging with nephrometry score $\geq 7^{22}$ will be randomized to either to a 3D printing model or conventional imaging without 3D-model group. High-fidelity, patient-specific 3D printed renal tumor models will be created from magnetic resonance (MR) or CT imaging data. As above, renal tumor cases will be reviewed by the surgical team with and without the model. To test the impact of the 3D models, Likert questionnaires will be filled-in by the patients and surgical team. In addition, surgical times and patient outcomes will be recorded and compared to age, gender matched subjects with similar renal tumors in which 3D printed models were not used.

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