How I Do It: Cost-effective 3D printed models for renal masses

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3D printing has been growing in many surgical fields including Urology. The primary use has been to print kidneys with tumors to better understand anatomy and to assist with surgical planning and education. Previous studies that utilized 3D printing of kidneys for partial nephrectomies have been limited by the cost and complexity of model creation, rendering them highly impractical to be used on a routine basis. Using a simpler and more cost-effective design and materials allow the 3D kidney models to be used in a wider range and number of patients. We describe our streamlined process to create 3D kidney models costing $30 on average and we believe this process can be repeated by others.

Key Words: 3D printing, kidney models, partial nephrectomies, renal masses

Introduction

The relationship between a renal mass and the structures it abuts or invades is difficult to discern from radiographic images alone, but imaging is often the only visual representation available. Being able to appreciate complex anatomy and pathology in three dimensions allows for enhanced surgical planning, resident education, and patient understanding.[1-3]

With the many three-dimensional (3D) printers, programs, and materials available, 3D printing technology has become less expensive and more readily available.[4] The ability to use a patient's computed tomography (CT) or magnetic resonance imaging (MRI) to create accurate models has also increased the number of cases for which modeling can be applied.[5] Given the number of options available for 3D printing, it is important to narrow down the goal of the model. In partial nephrectomies, being able to fully appreciate the tumor's endophytic component and its relationship to the hilar vasculature and collecting system is essential for surgical planning. However, translucent printing materials are often expensive and highly detailed models typically require intensive human labor to create.[6] Therefore, it is important to weigh the cost and simplicity of the design with the accuracy and use of the model.

In this study, the printer, material, and design of the model were chosen based on cost, simplicity, and effectiveness. The patient-specific models were designed to be used for surgical planning and patient education.

Method and technique

Model segmentation

3D model segmentation defines the boundaries of a region of interest in a stack of 2D images in order to form a 3D object.[7] CT or MRI images previously obtained for the patient's diagnosis were exported as digital imaging and communications in medicine (DICOM) files to be used for the segmentation. The segmentation was performed off of only one imaging series. By using already available imaging, there were no increased costs for obtaining imaging for the study.

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The ability to use either imaging modality increased the number of cases the models could be created for.

For the purpose of this study the imaging series used for segmentation was chosen with the input of and approval of a board-certified radiologist based on the number of slices, resolution of the images, and ability to distinguish the renal vasculature, Figure 1a. A board-certified urologist may also review the images themselves without the aid of a radiologist. The kidney, renal mass, and the renal vasculature to include the renal vessels as well as the aorta and IVC were segmented in the FDA-approved Materialise Mimics (Materialise, Belgium https://www.materialise.com/en) software to create the digital model, Figure 1b. The collecting system was indirectly defined during the segmentation phase as the technician defines the borders of the renal parenchyma. However, the renal pelvis and ureter were not included in segmentation because their borders were difficult to define as most CTs and MRIs did not have a pyelogram phase.

Segmentation was performed by manually denoting the boarders of the desired structures slice by slice through the series, which takes around 2 hours for a technician to perform. Segmentation may also be performed semi-automatically by denoting the threshold range of the structure's intensity on the imaging scan, then "growing" it on the segmentation program. While this method is faster, cutting segmentation time down to as little as an hour, it can be less accurate for soft tissues and non-contrast scans where objects are of similar intensities.

Materialise 3-matic software was used to separate the kidney and tumor in half in order to allow the physicians and patients to see the tumor depth and relation to the vasculature and collecting system. Materialise 3-matic finalized the layout of the model for printing. The models were exported as stereolithography (STL) data files and uploaded to Ultimaker Cura software to be printed.

Model printing and construction

The models were printed on an S5 Ultimaker printer (Dynamism, Chicago https://www.dynamism.com/). This is a fused deposition modeling (FDM) printer that deposits heated filament. Its print volume is 13 x 9.4 x 11.8 inches, or 1442 in^3, allowing a life-sized kidney and vasculature to be printed.[8] Polylactic acid (PLA) was used as filament for the kidneys. The printer allows two separate PLA filaments to be printed at one time, with one of the PLA filaments doubling as part of the support for the structure while being printed. Having

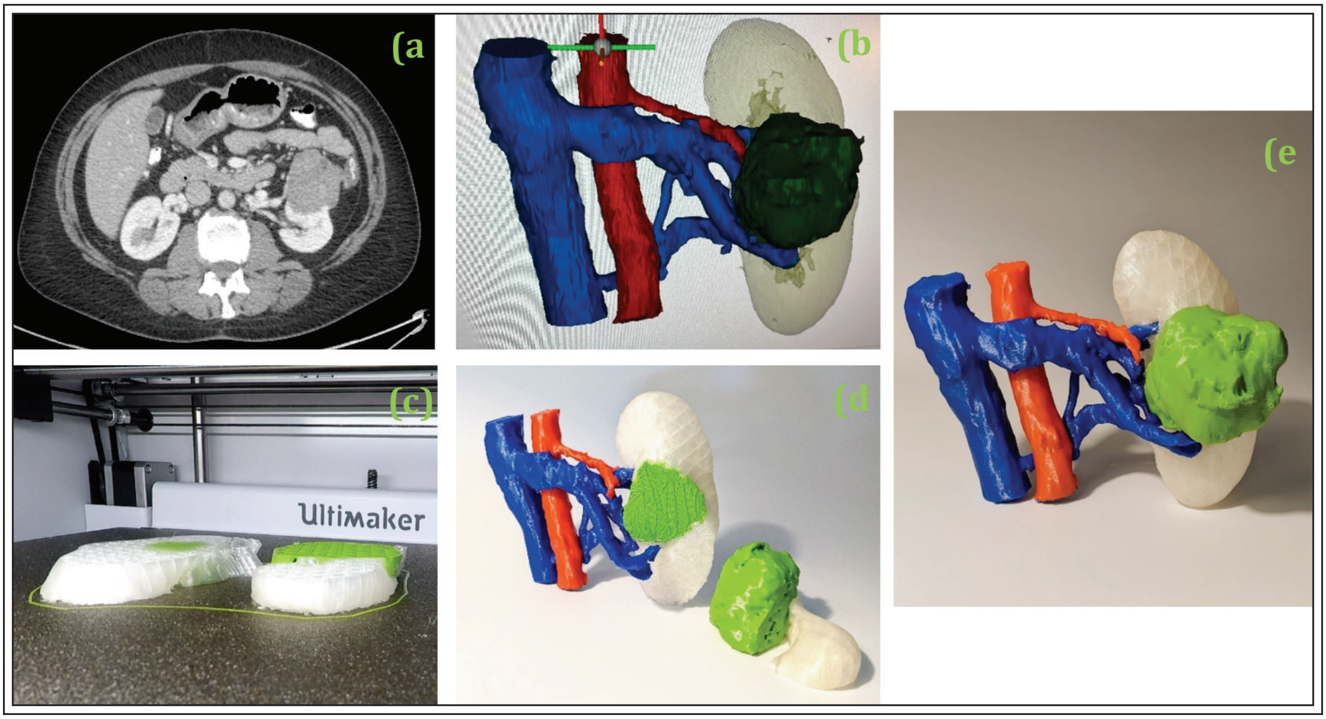

Figure 1. **(a)** Axial CT cut showing left anterior renal mass; **(b)** 3D rendered CT image after segmentation; **(c)** Model being printed; **(d)** The model's two pieces; **(e)** Model with pieces together.

only two filaments at a time prevented the kidney, mass, renal artery, and renal vein, four colors total, to be printed at one time.

PLA is one of the least expensive and most widely used 3D printing materials, costing $0.15 per gram.[9] Its low melting temperature and relatively stiff properties make it one of the easiest materials to 3D print successfully, decreased the amount of time and money spent on reprinting the models. It cannot withstand temperatures above 50 degrees Celsius and has limited impact resistance, which is why other materials acrylonitrile butadiene styrene (ABS) and nylon and are often used when strength and thermal stability are important.[9] The stiff properties also make PLA a poor material to practice surgery on. However, these models were used for education and planning where resilience and flexibility of the models was not paramount.

Three prints were created for each model. Each half of the kidney to include the tumor was printed separately from the vasculature, Figure 1c. The kidney was printed "clear," the tumor green, arteries red, and veins blue. The collecting system of the kidney was segmented and intentionally not printed to facilitate an understanding of its borders and relationship to the tumor. A major limitation of the PLA material is its "clear" color is not translucent, only allowing minimal visualization of the mass within it. By printing the kidney and tumor as two halves, the surgical team and patient were able to clearly define the endophytic component of the tumor, its relationship to the collecting system and vasculature, as well as its location in the parenchyma.

Following printing, the printing supports were removed, and the model vasculature was glued to the parenchyma, Figure 1d. In order to ensure accuracy of the attachment of the vasculature, attachment points were included in the digital model in Materialise 3-matic.

Clinical use of the models

The patients were shown their 3D models on the day of their surgery by the attending or fellow on the case to help explain the kidney, their disease, surgery, and risks involved with surgery again. The patients were able to examine their model and given an opportunity to subsequently ask questions to the surgical team.

The senior or chief resident, fellow, and attending on the case went over the model together on the day of surgery. The model was used to help determine their surgical approach. In the operating room, the model was referenced to identify the relation of the mass with the parenchyma and vasculature in real time.

Discussion

We believed this project to be an excellent adjunct to our multidisciplinary clinic dedicated to the evaluation and management of patients presenting with clinical T1 renal cell carcinoma, the Small Renal Mass Center of the Sidney Kimmel Cancer Center.[10] Forty patient-specific 3D printed kidney models were created at Thomas Jefferson University Health Design Lab for use by the Department of Urology between July 2020 and May 2021. Thirty-seven patients underwent robot-assisted partial nephrectomies, and three patients underwent robot-assisted radical nephrectomies. The models were used by six attending urologists, one urology fellow, and three senior or chief residents. Preliminary results from survey components of this printing effort shows high rates of satisfaction on both the patient and surgical teams with the models.

For the average model, segmentation took 2 hours, designing the print took 15 minutes, printing the model took 8 hours (range 3-10 hours), and post-processing and assembling took 45 minutes. Twelve hours total were spent on each model, with 4 hours being human labor. Because of the reliability of the printer, most models were printed overnight, decreasing the amount of time needed to be spent in the printing lab. Two out of the forty models needed to be reprinted due to a printing error. The first attempt at printing the model was always performed with enough time to reprint the model in case an error did occur. No model suffered breakage or other durability issues.

While multiple CT and MRI imaging modalities were used to create the models, we found it easiest to segment from a CT scan, specifically CT series with contrast in the nephrographic phase. This scan provided the clearest distinction between the kidney parenchyma, vessels, and collecting system on the segmentation software. Imaging series with increased slices resulted in a smoother and more accurate model. We aimed to use series with at least 100 slices, with a minimum of 70 slices in a series used during our study.

The PLA material and printing cost was on average $30 (range $20-50) per model based on the complexity and size of the model. The cost for the Materialise software used in this study varies based on one's contract with the company. However, there are non-FDA-approved programs such as 3D Slicer for segmentation and Meshmixer for design that are available for free online and can be used in place of Materialise based on the goals of one's study. At the time of this study, the S5-Ultimaker printer costs $6,355. The Ultimaker printing software is free to use.

The cost of human labor to segment, validate, and design the print was not captured in this study. It will be important to consider this in the future if the models are to become standard of care in our department. It is important to note that minimal human labor was performed by a physician, instead being undertaken by medical students for segmentation and printing technicians for processing and assembly in this study. These tasks could likely be reliably performed in nonacademic settings by a nurse or physician extender with minimal training.

On the initiation of our project, the review of the literature focusing on 3D kidney models did not capture the time, cost, and effort needed to create medical 3D models. We worked closely with a design team at our institution that specializes in creating models for various medical settings. Through their expert advice, this setup was shown to be the most pragmatic and cost-efficient for our study goals. We hope that by explaining our design, we can facilitate this process for other urology groups to incorporate the models into their own practice.

Conclusions

In this article, we describe our chosen design and materials to create 3D models to facilitate robot-assisted partial nephrectomies. The models were used for patient education and surgical planning with effective results. Given patient and surgeon satisfaction and low price of the model, we suggest that these cost-effective 3D models could become a standard of care for partial nephrectomies. ☐

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