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Use of Personalized Printed 3-Dimensional Kidney Models for Simulation before Nephron Sparing Surgery: Methodology and Examples from a Case Series

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Abstract

Introduction: Nephron sparing surgery may be challenging in cases of complex or aberrant renal anatomy. 3-Dimensional printing technology has allowed the creation of 3-dimensional models that can aid in preoperative surgical planning and simulation. We describe the construction of personalized 3-dimensional kidney models, and present a series of patients with complex surgical anatomy to illustrate their use in surgical planning and performance of complex nephron sparing surgery.

Methods: Three patients with complex renal masses were identified. Contrast enhanced computerized tomography studies were used to create segmentation images based on separate scan phases, which were overlaid to create virtual 3-dimensional models. High-fidelity 3-dimensional physical models were then created using 3-dimensional printing technology. The 3-dimensional models were used as an aid in the surgical planning and performance of nephron sparing surgery.

Results: Three patients with complex renal anatomy presented with T1b or T2 renal masses. Two patients had absolute or relative indications for nephron sparing surgery and in 1 patient a benign mass was suspected on imaging. The 3-dimensional kidney models were constructed based on preoperative cross-sectional imaging to evaluate the feasibility of nephron sparing surgery and to simulate the surgical approach. All patients underwent successful nephron sparing surgery with negative surgical margins and preservation of renal function at followup.

Conclusions: We describe the creation of personalized 3-dimensional kidney models to facilitate the visualization of the renal mass and its relationship with surrounding structures, the identification of renal and tumor vasculature, and the evaluation of aberrant anatomy. These 3-dimensional models represent a valuable tool for preoperative planning and simulation in cases with complex anatomical considerations.

Key Words: printing, three-dimensional; kidney; models, anatomic; organ sparing treatments; simulation training

Abbreviations and Acronyms

3D = 3-dimensional

CT = computerized tomography

EBL = estimated blood loss

IVC = inferior vena cava

MRI = magnetic resonance imaging

NSS = nephron sparing surgery

STL = stereolithography

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Nephron sparing surgery is recommended as the standard management for T1a renal masses and as an alternative standard for T1b renal masses.[1,2] NSS may be considered for even larger lesions in cases with absolute or relative indications for renal preservation and it may be highly preferable when lesions are suspected to be benign based on imaging. NSS has been associated with improved renal function preservation and an overall survival advantage compared with radical nephrectomy.[3–5] However, NSS may be technically difficult in some cases due to complex or aberrant renal or tumor anatomy, and new techniques are needed to aid in planning the surgical approach for such cases.

Cross-sectional imaging based 3D reconstruction and simulation have been described as an aid to surgical planning.[6–9] More recently with the introduction of 3D stereolithographic printing technology,[10] 3D models have been used to facilitate surgical planning in several settings, including oral and maxillofacial surgery,[11] open and percutaneous cardiac surgery,[12–14] endovascular aortic aneurysm repair,[15] podiatric surgery,[16] orthopedic surgery[17] and pediatric pyeloplasty.[18] A 3D model is created from preoperative cross-sectional imaging and used to evaluate the feasibility of a particular surgical approach, to simulate surgery and to counsel the patient.

Recently we began using 3D kidney models in select cases for planning complex NSS. The models facilitate visualization of the precise location of the renal mass, the renal and tumor vasculature, and anomalous anatomy to allow simulation of NSS. In this study we describe the methodology used to construct personalized 3D kidney models from preoperative cross-sectional imaging, and present our early experience in 3 patients with complex surgical anatomy to illustrate their use in the surgical planning and performance of complex NSS.

Materials and Methods

This retrospective review of our experience with 3D kidney models was approved by the Mayo Clinic institutional review board. Three patients with complex renal masses who were candidates for NSS were identified by a urologic oncologist (BCL) for the creation of preoperative 3D physical models. The models were used as an aid in surgical planning and performance of NSS. Preoperative clinicopathological features and followup data were abstracted from the medical record.

Image Acquisition and Segmentation

High resolution, contrast enhanced CT studies using 3 or 5 mm slice image thickness were obtained for each patient. CT scans were reviewed in collaboration by the surgeon, radiologist and biomedical engineer to ensure adequacy for construction of a physical 3D model. Slice image thickness is an important factor for reconstructive quality, with thinner sections (eg 1.5 to 3.0 mm) offering higher detail. Three-phase CT was available for 2 patients and 2-phase CT was available for 1 patient.

Imaging data were imported into Mimics® software (fig. 1, *A*). The software was used to perform segmentation (identification of target structures) using separate scan phases, which were then overlaid (fig. 1, *B*). The arterial phase was used to segment the aorta, renal arteries and renal cortex. The venous (or nephrographic) phase was used to segment the IVC, renal veins, renal parenchyma and renal mass. The excretory phase was used to segment the collecting system. Each phase of enhancement provides useful information. Different series can be overlaid as long as there are accurate, discrete and reliable reference points (eg aortic bifurcation, vessel origin, vertebral body endplates).

Multiple tools available in the Mimics software were used to facilitate segmentation. Thresholding was used to separate structures that are higher in density than the surrounding tissue. Automatic thresholds can be used but they can also be manually set to optimize the variable enhancement in each individual CT. The automatic thresholds commonly used were soft tissue and bone, which correlate with Hounsfield units of −700 to 224 and 226 to approximately 3,000, respectively (supplementary fig. 1, http://urologypracticejournal.com/). Thresholding was used in the bolus contrast phase to capture enhancing vessels, in the venous phase to outline the renal parenchyma and distinguish the margins of the renal tumor, and in the delayed phase to segment the dense contrast in the ureters and bladder.

With the bolus contrast phase the vessels can be further delineated using the region growing and dynamic region growing tools. These tools connect structures of similar density that are continuous. After discrete segmentation of the renal arterial system, the Boolean operation tool can be used to subtract these from the total renal vessels to obtain the renal veins (supplementary fig. 2, http://urologypracticejournal.com/). Thresholding tools were used to generate a general outline for the renal tumor but final margins were hand drawn slice by slice using reconstructed images in all 3 planes. This portion of segmentation takes the longest amount of time, and requires anatomical and clinical expertise.

The segmented images were further processed using 3-maticSTL software (Materialise, Leuven, Belgium) to prepare them for conversion into STL files, the standard software for 3D printing. Various techniques can be used to smooth the contour of segmented structures, which can be

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