A complex dual-modality kidney phantom for renal biopsy studies

Vargas, Jose, Le, Phuc, Shahedi, Maysam, Gahan, Jeffrey, Johnson, Brett, et al.

Jose Vargas, Phuc Le, Maysam Shahedi, Jeffrey Gahan, Brett Johnson, James D. Dormer, Sarah Shahub, Matthew Pfefferle, Blake O. Judson, Yasmeen Alshara, Qinmei Li, Baowei Fei, "A complex dual-modality kidney phantom for renal biopsy studies," Proc. SPIE 11319, Medical Imaging 2020: Ultrasonic Imaging and Tomography, 113190J (16 March 2020); doi: 10.1117/12.2549892

SPIE.

Event: SPIE Medical Imaging, 2020, Houston, Texas, United States

A complex dual-modality kidney phantom for renal biopsy studies

Jose Vargas [a], Phuc Le [a], Maysam Shahedi [a], Jeffrey Gahan,[b] Brett Johnson,[b] James D. Dormer [a], Sarah Shahub [a], Matthew Pfefferle [a], Blake O. Judson [a], Yasmeen Alshara [a], Qinmei Li [a], Baowei Fei [a,c,d*]

[a] Department of Bioengineering, The Univ. of Texas at Dallas, TX
[b] Department of Urology, University of Texas Southwestern Medical Center, Dallas, TX
[c] Advanced Imaging Research Center, University of Texas Southwestern Medical Center, Dallas, TX
[d] Dept. of Radiology, University of Texas Southwestern Medical Center, Dallas, TX
* Email: bfei@utdallas.edu, Website: https://fei-lab.org

ABSTRACT

We developed a reliable and repeatable process to create hyper-realistic, kidney phantoms with tunable image visibility under ultrasound (US) and CT imaging modalities. A methodology was defined to create phantoms that could be produced for renal biopsy evaluation. The final complex kidney phantom was devised containing critical structures of a kidney: kidney cortex, medulla, and ureter. Simultaneously, some lesions were integrated into the phantom to mimic the presence of tumors during biopsy. The phantoms were created and scanned by ultrasound and CT scanners to verify the visibility of the complex internal structures and to observe the interactions between material properties. The result was a successful advancement in knowledge of materials with ideal acoustic and impedance properties to replicate human organs for the field of image-guided interventions.

Keywords: kidney phantom, renal biopsy, mold casting, three-dimensional, additive manufacturing, image segmentation, ultrtasound imaging (US), computed tomography (CT)

1. INTRODUCTION

A renal biopsy is an interventional procedure whereby kidney tissue is extracted from a patient and examined for pathological abnormalities, which can reveal the existence of malignant lesions or conditions associated with renal diseases. Proper pathological diagnosis of abnormal renal tissue is critical, and early identification of a disease can guide surgical or medical intervention[1]. However, there is risk associated with renal biopsy. Bleeding complications, with or without gross hematuria, occur in approximately 3.5% of cases[2]. Rates become more variable when considering differing biopsy techniques. Real-time ultrasound (US) image-guided biopsies lead to lower rates of hematuria but are more challenging to clinicians as they require increased cognitive fusion of images to locate the lesion in three-dimensional (3D) space[2]. Therefore, there exists a compelling argument to increase biopsy accuracy through improved surgical simulation.

Phantoms are anatomical replicas of bodily structures used in the testing of imaging systems and medical procedures. Biopsy phantoms viewable in ultrasound are usually single-use, limiting the number of trial insertions a surgeon can perform before terminating the usability. Commercial phantoms are available that emulate organ material and image properties but are often expensive. Further, many of these do not have characteristics that allow for realistic characterization with both ultrasound and CT modalities. Here, we present methods to create realistic kidney phantom models which, due to the reduction in expense, allow for repetitive training.

2. MATERIALS AND METHODS

2.1 Materials

A list of phantom materials with weight and volume (w/v) concentrations was proposed prior to the fabrication of the phantom. These materials had to meet specific criteria that would best mimic the image contrast observed during *in vivo*

Medical Imaging 2020: Ultrasonic Imaging and Tomography, edited by Brett C. Byram, Nicole V. Ruiter,
Proc. of SPIE Vol. 11319, 113190J · © 2020 SPIE · CCC code: 1605-7422/20/$21 · doi: 10.1117/12.2549892

scans of the renal system. Ultrasound images of the phantom model needed to show the boundary transition between the kidney cortex and body cavity while simultaneously exhibiting a higher intensity signal for the interior medulla/ureter complex. For CT imaging, the phantom model needed to show significant signal intensity for the cortex component while providing an observable boundary transition between the medulla/ureter and body cavity. Previous experiments with varying concentrations of readily available materials led us to create a table of concentrations and mixtures that would provide us with our desired characteristics. Concentrations for specific materials were deliberately increased to guarantee that signal intensity would be achieved, facilitating future image segmentations. Below is the list of material concentrations used for each component in solution with distilled water.

Table 1. Complex Kidney Phantom Recipe.

Tissue	Ingredients	% (w/v)
Ureter	Agar	2
	Cellulose (type 20)	0.2
Cortex	Bovine gelatin (225 bloom)	10
	Povidone-iodine* (10%)	50
Body	Agar	2
Lesion	Agar	2

2.2 Data

We used an anonymized contrast CT image from a patient to segment the desired internal kidney structures using 3D Slicer[3]. The segmentation was done by an expert clician. 3D visualizations were generated from the masks and saved as stereolithography (STL) files. To create the desired high fidelity kidney phantom, the extent of the anatomical complexity from the images was limited to the kidney cortex, medulla, and collecting system. The masks were segmented manually and simplified to ease fabrication later in the process.

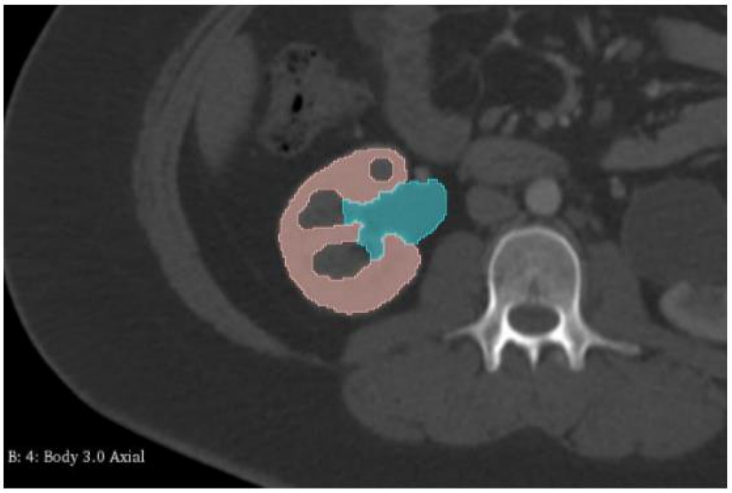

Figure 1. Contrast CT image. The segmentation masks of the kidney cortex and ureter showed in pink and blue, respectively.

In Figure 1, the pink segmentation mask represents the cortex of the kidney while the blue mask represents the segmentation of the renal pelvis. 3D models were generated from the manual segmentations and exported as STL files[4]. A similar process developed by Adams achieved proper mesh integration by applying corrections to the generated STL file. Instead, we obtained a similar level of integration by editing the masks directly. The three-dimensional visualization was

generated from mask segmentations and saved as stereolithography (STL) files. The STL files were all converted to volume models to create molds in SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France).

2.3 Molds

Using the largest transverse plane of the reconstructed kidney models, two halves of a mold were created using the molding tools found in SolidWorks. Holes for nylon screws were created along the edges of the molds to ensure a tight fit of the molds. Additional holes were made for the injection point and air hole. Finally, the mold models were saved as STL files to be 3D printed using VeroClear (Stratasys, Rehovot, Israel). Figure 2 shows the created molds for the renal cortex, renal pelvic, and medulla.

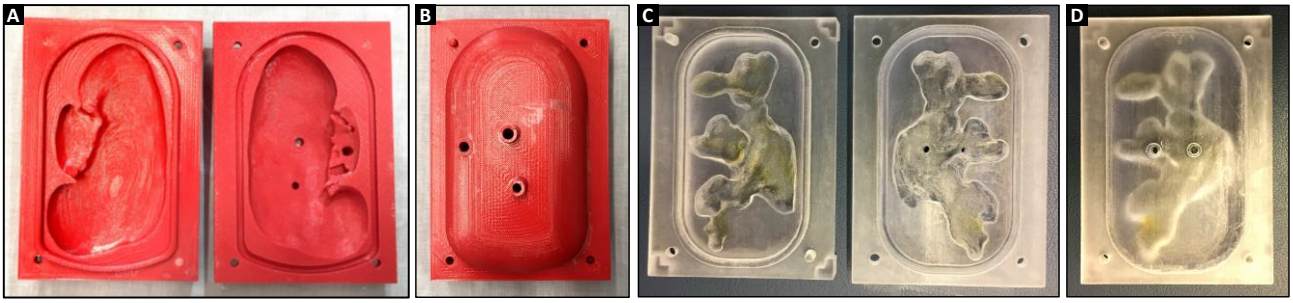

Figure 2. 3D printed molds for kidney phantoms: Renal cortex and pelvis mold (A and B) and medulla mold (C and D).

Prior studies have described the fabrication process of a soft, 3D printed kidney including the collecting system. These studies determined the material best suited to mimic kidney tissue is agarose gel (4%)[4,5]. Thus, the initial fabrication of our kidney phantoms builds on the information from the past work. 3D models were generated from the manual segmentations and exported as STL files. Unlike Adams *et al.*[4], all modifications including proper meshing and stitching were performed directly on the masks to avoid intermediate steps. Once STL files of the medulla and ureter were created, a mold was designed in SolidWorks. Similarly, after exporting an STL file of the complete kidney segmentation, the former was used to create a mold. The molds were created along the largest transverse plane. Finally, the SolidWorks models were exported as STL files to be 3D printed.

2.4 Workflow

After receiving the 3D printed molds, an internal "complex" structure composed of the medulla and renal pelvis segmentations was created using the 3D printer. Then the newly created piece was placed inside of the larger mold for rapid casting. Additionally, the separate piece allowed more modularity throughout phantom production. Each structure iteration could be fabricated using a different combination of materials which would yield any desired appearance under a desired imaging modality. Figure 3 shows the workflow of the complex kidney fabrication process.

Fabrication began by weighing out all the ingredients in Table 1. Agar (1.5 g) and cellulose (0.15 g) were added to a beaker with 75 mL of water. The solution was properly mixed and allowed to set inside the phantom cortex mold. The mold was allowed to set for at least 1 hr before removal. A simulated lesion was created by adding agar (1 g) to a beaker with 50 mL of water and properly mixed. After allowing the material to set, it was shaped into an approximately 6 mm lesion. After creating the lesion, bovine gelatin (30 g) was poured into a beaker containing a 300 mL mixture of water (200 mL) and iodine (100 mL). The beaker was thoroughly stirred and allowed to set after reaching a temperature nearing 37ºC. Before pouring the beaker into the kidney cortex mold, the medulla/ureter component and lesion were placed inside the mold. Then the iodine solution beaker was poured into the phantom cortex mold with internal pieces inside. The mold was sealed and allowed to set for several hours in a 1.6 ºC environment. After the complex kidney phantom has set, agar (20 g) was prepared in a beaker with 1 L of water. The solution was thoroughly stirred and allowed to cool for approximately 1.5 hrs before removing the complex kidney and placing it inside of the body mold. After introducing the kidney phantom, the complete body-kidney phantom was allowed to set in a 1.6 ºC environment for several hours. As can be shown, initial visual inspection of the complex kidneys resulted in successful integration of each separately fabricated component. The final step was incorporating the complex kidney in a body phantom for testing. This body phantom was meant to simulate real tissue a surgeon will need to penetrate before reaching the target lesion.

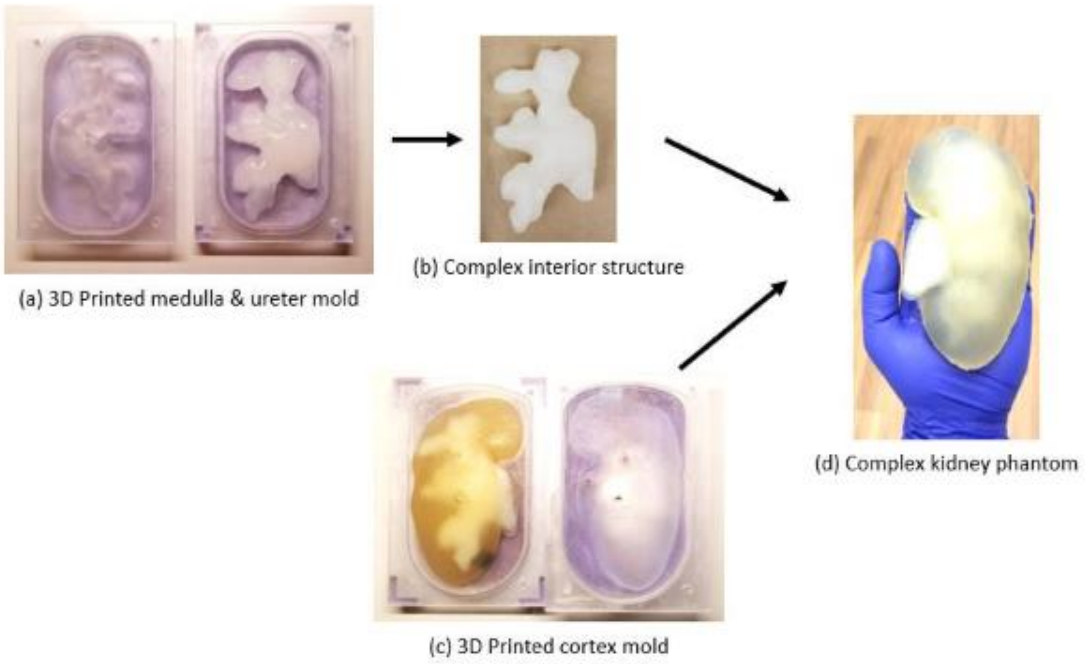

Figure 3. Workflow of building the complex kidney phantom.

3. RESULTS

3.1 CT & Ultrasound imaging

A triplane ultrasound probe (Prostate Triplane 8818, BK Medical) in the end-fire configuration was mounted to a 150 mm linear translation stage with stepper motor (Thorlabs LTS150/M 2009). Ultrasound images of the complex kidney phantom were taken at incremental steps of 0.125 mm for the entire length of the phantom and combined to obtain a 3D ultrasound scan (Figure 4).

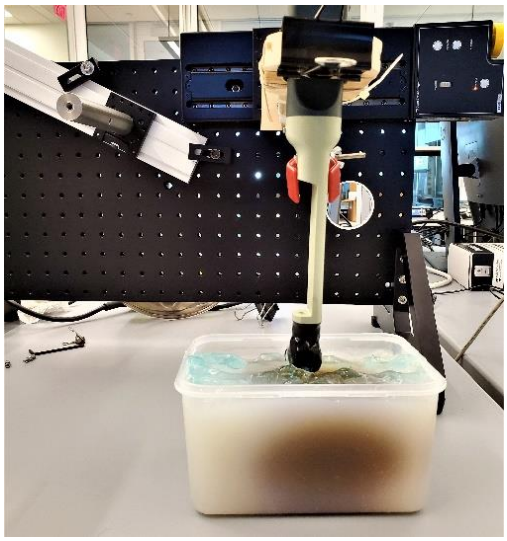

Figure 4. Three-dimensional ultrasound setup using linear actuator and ultrasound probe.

When analyzing the ultrasound images of the kidney phantom, the lesions made from agar and cellulose exhibited echogenicity (Figure 5). The medulla/ureter component also displayed high echogenicity under ultrasound imaging and the boundary between the cortex and body was easily detectable. Under CT, the lesions displayed little to no radiopacity mimicking an *in vivo* fluid-filled growth (Figure 6). Meanwhile, the cortex displayed the desired image contrast and the boundary between the medulla/ureter component was readily detected. Desired material interactions led to a kidney phantom capable of mimicking the image contrast properties of a human kidney. This was achieved by successful dual-imaging segmentations, supporting the hypothesis that the proposed method of fabricating a complex kidney phantom can serve as training standard for innovative surgical-intervention technologies.

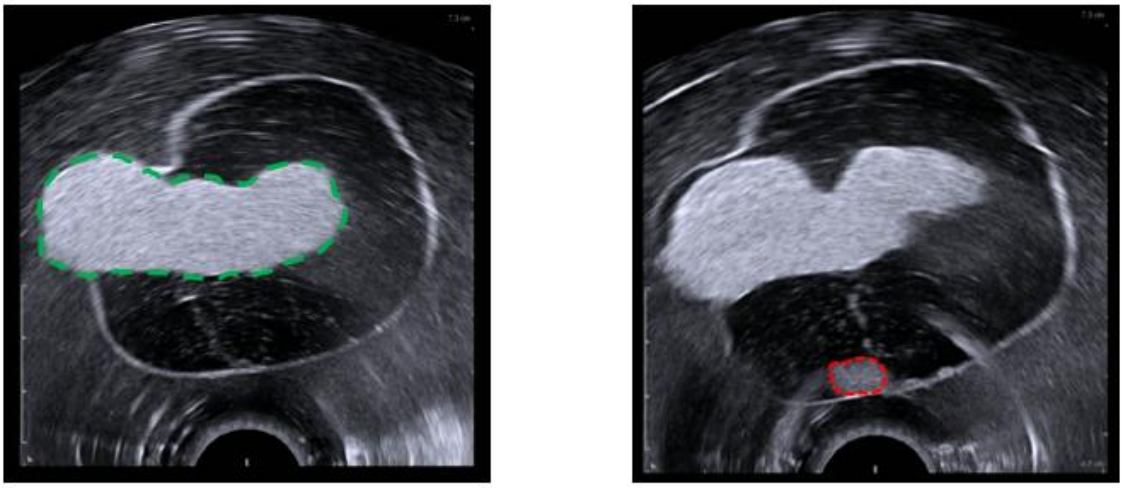

Figure 5. Ultrasound image of body kidney phantom with segmented medulla (left). Ultrasound image of body kidney phantom with segmented surface lesion (right).

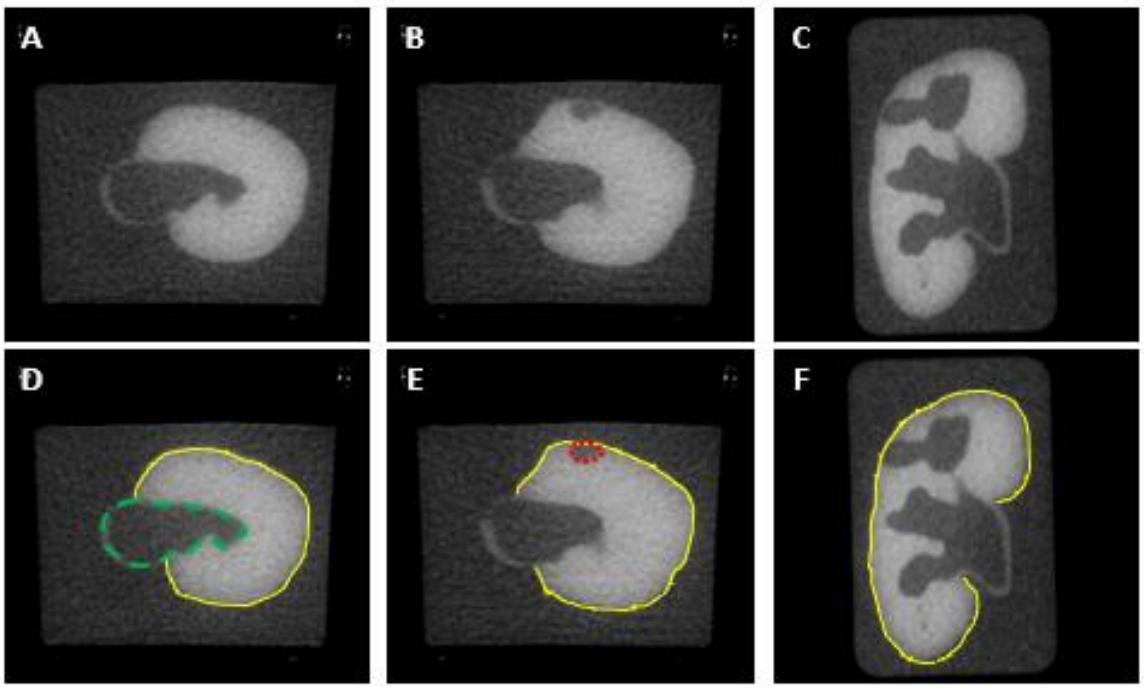

Figure 6. CT image slices of the complex kidney phantom. A-C: three sample slices showing kidney cortex, ureter, and lesions. D-F: segmented structures on the same slices. The kidney cortex contour is shown in solid yellow, lesions in dotted red, and ureter in green dashed line.

4. DISCUSSION

This is the first work to present an affordable and customizable kidney phantom for biopsy which contains the cortex, ureter, lesions, and medulla while retaining realistic imaging characteristics on both US and CT. Once the molds are created, each phantom costs less than $10 in material and takes about two hours to be created. In comparison, commercially available phantoms could cost between $430 - $1400 per phantom, while having limited or no customizability. Implementing an in-house method of reliably creating realistic, complex kidney phantoms can prove to be more effective for testing novel technologies in the field of image-guided interventions. A model with known dimensions and tunable properties can test the accuracy and precision limitations of a system. Furthermore, by modifying the material properties to replicate the variability of tissue composition typically seen in patients, the complex kidney models can test a system's sensitivity to such changes. Another important contribution to the development of this approach is that it can serve as a standard for recreating complex models of other human organs.

5. CONCLUSIONS

In this work, we demonstrated how a complex kidney phatntom which contains the cortex, collecting system, lesions, and medulla could be created economically compared to expensive professional ones. This approach can be easily adapted to match patient-specific cases and requirements, allowing practice procedures to be performed in difficult cases. Future work will explore additional organs and materials to further improve the phantom.

ACKNOWLEDGEMENTS

This research was supported in part by the U.S. National Institutes of Health (NIH) grants (R01CA156775, R01CA204254, R01HL140325, and R21CA231911) and by the Cancer Prevention and Research Institute of Texas (CPRIT) grant RP190588.

REFERENCES

[1] Locatelli, F., Vecchio, L.D., and Pozzoni, P., "The important of eary detection of chronic kidney disease," Nephrology Dialysis Transplantation, 17(11), 2-7 (2002).

[2] Corapi, K. M., Chen, J. L., Balk, E. M., and Gordon, C. E., "Bleeding complications of native kidney biopsy: a systematic review and meta-analysis," American Journal of Kidney Diseases, 60(1), 62-73 (2012).

[3] Pieper, S., Halle, M., and Kikinis, R., "3D Slicer." 632-635.

[4] Adams, F., Qiu, T., Mark, A., Fritz, B., Kramer, L., Schlager, D., Wetterauer, U., Miernik, A., and Fischer, P., "Soft 3D-printed phantom of the human kidney with collecting system," Annals of biomedical engineering, 45(4), 963-972 (2017).

[5] Shikhaliev, P. M., "Dedicated phantom materials for spectral radiography and CT," Physics in Medicine & Biology, 57(6), 1575 (2012).