Anatomical Kidney Model Fabrication For Ultrasound Simulation Using Direct 3D Printing

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Abstract. With the advance of 3D printing technology showing improvements in increasing number of medical applications, there are more and more 3D kidney model printings emerging in the field. Material selection is an important aspect in 3D printing technology. Having compared many materials, Agilus30 was chosen as our final option due to its high printing accuracy, feasibility to be printed directly and desired ultrasound compatibility. ITK-SNAP 3.6.0, Seg3D and Netfabb2019 were used to segment structures in 3D medical images which were downloaded from embodi website, to smooth the model and to export the model to STL format file respectively. Eventually we printed a whole kidney in Agilus30 using Object500 Connex3 3D printer and two halves kidney in rigid resin using Anycubic 3D printer. Then we used X3-1 3Mhz probe image to get ultrasound result from the Agilus30 model in water to get outer structure and the rigid resin model in paraffin to get inner structure. After validating the result with that of a real kidney ultrasound image, we found the results are in good agreement.

1. Introduction
Traditional ultrasound compatible materials like paraffin[1], PVA-C[2], silicone[2], cannot be directly 3D printed, if they are chosen to make phantoms, a negative mold needs to be manufactured first, and then the liquid materials are poured inside. For kidney models with complicated inner structures, the mold making technique is too difficult to be implemented and the potential results will not be accurate enough. For other promising 3D printable biomaterials like hydrogel[3], Gel-wax[4], their applications are limited in small model fabrication, besides, their low printing accuracy cannot satisfy our needs. All the current 3D printable materials with high accuracy and fast printing speed, are mainly rigid materials, like PLA[5], thus, high attenuation inside these materials of the ultrasound wave and strong reflection on the material surface will result in inside structure disappearance and a lot of artefacts during imaging respectively. To have a more realistic kidney model, Agilus30 was chosen as our final option due to its high printing accuracy, feasibility to be printed directly and desired ultrasound compatibility[6]. In our paper, 6 anatomical kidney models with different pathologies were segmented and then smoothed using medical segmentation software, after model mesh generation, they are printed directly using Agilus30, and validated with ultrasound imaging about both its inner and outer structure.

2. Literature review
Rapid prototyping (RP) is a group of technologies that use computer aided design (CAD) data to produce physical size models in as short a time as possible. The construction process is carried out by "three-dimensional (3D) printing” or "additive manufacturing". The main idea supporting this
technology is building a 3D model by creating a layer over layer. This technology began at 1980s and now have developed into a different set of technologies, which may eventually change the production process awareness of different industries [7]. 3D technology has showed its prevalence in the manufacturing industry for its utility in lowering the cost of the process to levels that make it more feasible for general manufacturing use [8]. Meanwhile, this technology is becoming increasingly important in the medical field. In the last decades, rapid prototyping has been used in a variety of medical applications including individual patient care (surgical planning, implant and tissue designing), research and as an educational and training tool. There have been many studies demonstrating the significant improvements in diagnosis and treatment due to more detailed appearance of pathological structure, increased accuracy and possibility of pre-planning [9]. For patients themselves, 3D models can help them gain a basic understanding of kidney physiology and anatomy, tumor location and characteristics and the proposed surgical procedure with its related risks, which is important to obtain patients’ permission to do the renal surgery before it’s arranged [10].

To plan a renal surgery, abdominal CT scans are acquired preoperatively to localize the tumor on kidney[11]. There are kidney and other surrounding organs in the image, thus accurate segmentation of the tumor and kidney is often a first step to extract features useful for the identification of disease-specific morphological differences[12]. Time-consuming as it is, manual segmentation by expert with deep knowledge of underlying anatomy and pathology is much more accurate than automatic segmentation. Even in problems where fully automatic segmentation works well, manual segmentation is still often needed to train the automatic algorithms. Thus here comes semi-automatic segmentation which combines the advantages of the two above methods to allow the human expert to make big-size objects as accurate as possible while relying on the computer to perform time-consuming repetitive tasks [13].

With the advance of 3D printing technology showing improvements in increasing number of medical applications, there are more and more 3D kidney model printings emerging in the field. At the present stage, we have with different colors and different materials [10] to show different parts and also have kidney printings with different levels of transparency and hardness in different structures to distinguish whether the area is soft or hard, normal or calcified [14]. However, the high financial cost of the models has always been the limitation to prevent the researches from producing a large amount of samples. In addition, sometimes those researches are inclined to pick those typical kidneys with seriously-deteriorated or obvious tumours to be printed in order to show the significant effect of their achievements, which makes the result not that objective.

After the kidney is printed, it will be tested to see if it is clearly visible to recognize the structure inside using ultrasound. Ultrasound imaging is designed to help surgeons see how the catheter shuttles inside the body, which is widely used in the diagnosis and image guidance of human diseases[15]. This technology is used more and more extensively because of its simple principles, relatively cheap equipment compared with tomography (CT) or magnetic resonance imaging (MRI) and the most important, non-toxic to human health (without radiation) [16].

3. Methodology

3.1 Segmentation

An original DICOM (Digital Imaging and Communications in Medicine) CT dataset with a voxel spacing of 0.6 * 0.6 * 0.6 was chosen for this project from the website Embodi3D. This dataset contains patients with a certain degree of diseases, for example, patient 1 & 2 have slightly enlarged kidney cavities while patient 3 has a huge tumor on top of the left kidney. The contrast of the images were enhanced by adjusting the software Image-J, then snake semi-automatic segmentation tool in ITK-SNAP 3.6.0 (PICSL, USA), a software in which you can set the step size for it to grow and control the evolution to see the updated 3D model in the 3D window beside (see Figure 1), was used to segment the rough kidney and the segmented model was smoothed in Seg3D using the level 2 median filter in the data filter tool column to get the uneven surface flat and give a better appearance. Then get back to the ITK-snap and export the processed model to STL format file (Stereolithography File), which is the 3D printable format file, to be ready for printing.
3.2 Agilus30 printing and clear rigid resin printing
Six models were segmented eventually. After comparing the 6 kidney models, the one can best represent was decided to print due to the high cost of printing and limitation of the budget. We chose the flexible Agilus30 because of its flexibility performance based on the reference tables. A printing order for the kidney with an enlarged renal capsule was made to the company ‘STRATASYS’ due to the lack of the equipment for material Agilus30. It is printed using commercial Object500 printer (Stratasys, USA) using Agilus30 with 0.027mm layer thickness in high mix mode. Meanwhile, another half kidney was also printed for later inner structure ultrasound process using Anycubic photon printer in our lab in clear rigid resin with 0.020mm layer thickness. Both of the two printers are UV-light cured resin printers and the resin used here is cured sensitive to 405nm UV-light.

3.3 Ultrasound experiments
For the inner structure, the clear resin half kidney model was processed in ultrasound in both water and paraffin. When first using water, we were not satisfied with the result due to its dark background which made the outline of structures unclear and we thought using paraffin (see Figure 2) mimicking the tissue environment could be a better idea. Then the paraffin gel was first heated up on the magnetic stirrer and then poured around the half kidney model inside a water tank. The Philips IE33(Philips, Netherland) ultrasound machine and X3-1 3MHz probe with transmission gel were used to do the ultrasound imaging. During the imaging, the image depth was adjusted for a proper view and then the loops were acquired.

Figure 2. Ultrasound experiment for kidney model with paraffin.

The whole process which consists of segmentation, printing and ultrasound experiments is shown in the flow chart below in Figure 3.
4. Results

4.1. Segmentation result
Figure 4 shows the 6 segmented kidney models from 3 different patients. Red label, blue label and green label were used to represent kidney, vessel and tumor respectively.

The first two models are from patient1 whose right kidney is in normal condition while left kidney has been invaded by a big chunk of tumour. The second two models are from patient2 whose right kidney is in normal condition while left kidney has a tumour in initial stage due to its slight deformation on the top but no visible tumour generated yet. The last two models are from patient3 whose right kidney is in normal condition while left kidney has enlarged inner chambers. This left one was also the one we thought can best present due to its clearly visible inner structures and chambers and eventually we sent this model to the company STRATASYS to be printed in Agilus30.

4.2. Printing Result
Figure 5 shows the printed real Agilus30 whole kidney model and the rigid resin separated kidney halves.
4.3. Ultrasound Result
The first graph of Figure 6 is the result when imaging the model with water while the latter one is with paraffin. In the one with water, the background is almost too dark to see any structure because water is lack of scattering while paraffin can be used to create an environment mimicking real tissues to give a clearer view of the inner structure.

Comparing to the real kidney ultrasound image (see the last graph of Figure 6), there is a great deal of similarity between our results of the printed kidney models and the real one and we can see there has clear outline of the inner structure.

5. Discussion and Analysis
This paper demonstrates the material Agilus30 has both high printing accuracy and desired ultrasound compatibility by printing a deformed kidney in real size in Agilus30 and did ultrasound image test on it both for outer and inner structure. The results validated that the models in our paper are in great agreement with the real human kidney. However there still exists defect between the printed model and the real one due to the software default conditions thus deep learning based segmentation is considered to be used to get a more accurate 3D model.

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