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The 3D printing of patient-specific kidney models to facilitate pre-surgical planning of renal cell carcinoma using CT datasets

Catalina Lupulescu, Zhonghua Sun
Discipline of Medical Radiation Science, Curtin Medical School, Curtin University, Perth, Australia

RESEARCH

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Corresponding Author:
Zhonghua Sun
Discipline of Medical Radiation Science,
Curtin University, GPO Box U1987, Perth,
Western Australia 6845, Australia
Email: Z.Sun@curtin.edu.au

ABSTRACT

Background
Three-dimensional (3D) printing in medicine is a rapidly growing field of research. This study endeavoured to investigate the feasibility of using 3D-printed kidney models for pre-surgical planning of renal cell carcinoma (RCC) resection and provide insight into medical 3D printing technologies and materials.

Aims
To enrich current research on applications of 3D printing for renal disease including training, education and pre-operative planning.

Methods
Three kidney models were 3D-printed from computed tomography (CT) datasets: two of which were from the same clinical case. The models were CT scanned on a 192-slice scanner using exposure factors for an abdominal CT. Quantitative analysis was performed by measuring and comparing four critical anatomical structures on the model CT, original CT dataset and Standard Tessellation Language (STL) file. Qualitative assessment of the models was achieved through an interactive survey-questionnaire presented to 5 urologists. The models were also ultrasound scanned to generate insight into their uses in radiographic imaging.

Results
The 3D-printed models displayed no significant differences between the original CT and model CT (p>0.05). The STL file measurements were significantly larger than the original and model CT measurements for models 2 and 3 (p=0.000-0.005). All 5 urologists agreed that the 3D-printed models could facilitate pre-surgical planning and serve educational purposes to clinicians and patients with RCC. The ultrasound scans of the models demonstrate potential for radiographic imaging using realistic 3D-printed models, showing the importance of material considerations.

Conclusion
3D-printed kidney models can facilitate pre-operative planning for renal surgery and education. Further studies utilising diverse clinical cases and a cost-benefit analysis of material feasibility are required to better assess the applications envisioned.

Key Words
3D printing, computed tomography, education, model, renal cell carcinoma, surgery

What this study adds:

The study provides insight into the feasibility of using 3D printed renal models for pre-surgical planning and education of surgeons and patients on RCC. It also assesses the ability to apply radiographic imaging to 3D printed models and supplements existing research on 3D printing for ameliorating surgical outcomes.

1. What is known about this subject?
Multiple studies have investigated the ability of 3D-printing to assist with the creation of medical implants and devices and improve the outcomes of patients with various diseases.

2. What new information is offered in this study?
3D-printed renal models have potential to be used in pre-surgical rehearsal for urologists and enable patient

education through physical visualisation and interaction with the model. There is also opportunity for radiographic imaging of 3D printed models thus serving as a training purpose.

3. What are the implications for research, policy, or practice?

The current study invites further research into improving surgical outcomes in the context of full or partial organ resection and creates possibilities of material considerations and cost-benefit analysis for the creation of patient-specific organ models.

Background

Three-dimensional (3D) printing in medicine is an advancing area of research, with current literature investigating applications regarding the 3D printing of surgical and dental equipment, medical devices, and prosthetics[1-4]. In the last 10 years, numerous studies have emerged exploring the feasibility of 3D printing for education and treatment of various diseases including hepatic, cardiovascular, and recently, renal disease[1-28].

Renal cell carcinoma (RCC) is an aggressive cancer typically presenting as a unilateral lesion[13,14]. Surgical treatment for RCC has deviated from a radical technique in recent times, whereby minimally invasive partial nephrectomy surgery is performed to salvage the maximum amount of healthy tissue[5,8,12,16-20]. Partial nephrectomy surgery is typically employed when the lesion is 4cm or smaller in diameter, and the carcinoma is still confined to the renal fascia in the T1 (localised) stage, as per the globally recognised TNM Staging System[13-15]. The volume of resected tissue depends on the lesion(s) proximity to vital structures[13,14]. Accuracy and familiarisation with the planned surgical path and patient's complex anatomy are imperative to avoid injuring proximal anatomical networks and preserve healthy renal parenchyma.

Pre-operative planning is based on computed tomography (CT) scans whereby two-dimensional (2D) multi-planar and 3D volume reconstructions are performed to enable urologists to visualise the kidney from different orientations, and render accurate measurements[2,5,8,15]. Whilst volumetric imaging has guided the pre-operative planning process since its infancy, it is limited by viewing on a 2D, flat-screen monitor, and thus lacks a true demonstration of 3D spatial relationships and depth[15].

The construction of patient-specific, 3D-printed kidney models may overcome these limitations, by encapsulating topological relationships and structural depth, which may assist the pre-operative planning process and thus improve intra-operative accuracy[2,5,8-12,15-25]. 3D-printed kidney models can be constructed from CT datasets, which are segmented to form Standard Tessellation Language (STL) files compatible with 3D printing technology[2,5,8-12,15-25]. Many different software and computer aided design (CAD) tools exist to facilitate the segmentation and post-processing stage of the 3D-printing process[8,23,26,28].

Upon an analysis of relevant literature, 27 studies have evaluated the applications of 3D-printed kidney models for renal disease[5,8,11,12,20,21,23,26-28]. A small number of these studies evaluated the characteristics and costs of different 3D printing technologies and materials, with most studies qualitatively evaluating 3D-printed kidney models for the education of inexperienced surgeons[1-3,5-12]. It is evident that a limited number of studies have investigated the use of 3D-printed kidney models for operative planning of RCC, and a lack of studies have performed a comprehensive analysis of the dimensional accuracy of the models. Further to this, only one study has evaluated radiographic imaging features of 3D-printed models[24]. A recent systematic review endorses the need for a comprehensive evaluation of the holistic clinical value of 3D-printed kidney models, in combination with an in-depth assessment of dimensional accuracy and potential for imaging, to address gaps in the literature[29].

This purpose of this study was to investigate the feasibility of personalised, 3D-printed kidney models for pre-surgical planning of RCC resection. Further to this, the study comprehensively examined the 3D-printed kidney models both quantitatively and qualitatively, through the expert opinion of relevant clinicians practicing in the Perth Metropolitan area. It is expected that this study will supplement current research on applications of 3D printing for renal disease and provide an additional insight into 3D printing technologies and materials.

Methods

Imaging dataset collection

The study was approved by the Curtin Human Research Ethics Committee (ethics approval number *HRE2018-0796)*. Informed consent was waived from participants due to the retrospective nature of the study.

The 15 de-identified Digital Imaging and Communications in Medicine (DICOM) CT datasets were retrospectively collected from the Picture Archiving and Communication

System (PACS) database of a metropolitan radiology branch in December 2018. The datasets were retrieved utilising key search terms such as 'abdomen', 'KUB (kidney ureter bladder) and 'renal cell carcinoma' to generate appropriate searches, and no search filter was applied to the number of years since the imaging was performed.

Datasets with contrast and non-contrast studies were essential for comparison of lesion enhancement characteristics, and triphasic studies were encouraged. Datasets of kidneys with lesion(s) which exceeded the renal fascia and resembled the late (T3-T4) stages of the disease were excluded, due to having a low probability of being suitable candidates for partial nephrectomy surgery[13-15].

Data segmentation and reconstruction

Out of the 15 datasets, 2 cases were selected for reconstruction with the selection process outlined in Figure 1. Case 1 was a patient with a small, low-grade RCC in the inferior pole of the right kidney, and case 2 was diagnosed with congenital renal agenesis and a low-grade lesion in the middle pole of the patient's solitary right kidney. The two datasets were post-processed using the commercially available biomedical software Analyze 12.0 (AnalyzeDirect, Inc., Lexana, KS, USA) following a series of steps to segment the volume data for extraction of the regions of interest. Firstly, each CT dataset was 3D volume-rendered, and a range of 10-100 Hounsfield Units (HU) was applied to include soft tissue and blood vessels and exclude bones[29]. Secondly, an automatic object separator tool was utilised to colour-code objects based on differences in density. This enabled the separation of objects with similar densities located near each other, such as the kidneys and liver. Data was edited until only the kidney(s), lesion, renal vessels, and distal third of the aorta remained.

3D printing technology and materials

After the successful segmentation of the two datasets, they were converted into a STL file format which is compatible with 3D printing technology[2,30]. The STL files were then refined through the meshing software *MeshLab* (ISTI-CNR, JavaScript, Italy) to optimise the data for 3D printing. The edited STL files were sent to the Ultimaker 2 Extended 3D printer (Ultimaker BV, Geldermalsen, Netherlands) for 3D printing. The STL file of case 2 was then edited to be sliced along the coronal plane to create two separate, 3D-printable sections that could demonstrate internal kidney anatomy. It was then 3D printed using the ProJet 6000 printer (3D Systems Corporation, Rock Hill, SC, USA), with a 250mm^3 print volume bath.

Fused filament fabrication (FFF) technology was used for the two models constructed with the Ultimaker 2 Extended 3D printer (Models 1 and 2). The models were 3D printed with thermoplastic polyurethane (TPU) 95A material, which is a semi-flexible polymer. A material called VisiJet SL Flex was used for the third model (model 3), which is considerably more rigid and smooth than the TPU material.

CT scan of the 3D printed models

After successful 3D printing of the models, they were scanned on a dual-source, Siemens Force 192-slice CT scanner (Siemens Force, Siemens Healthcare, Forchheim, Germany). Exposure factors of 100kVp ~~of~~ and 20mAs were used with a slice thickness of 1.25mm to achieve a high spatial resolution. 3D volume rending was rendered using the open-source DICOM viewing software ~~*RadiAnt DICOM Viewer 2.0*~~ (https://www.radiantviewer.com) to generate 2D and 3D reconstruction images.

Ultrasound scan of the3D printed models

The 3D-printed models were ultrasound scanned using the Canon Aplio 500 version 6 ultrasound scanner. Both curvilinear and linear array transducers were used, and the models were placed in a water bath to mimic sound wave propagation throughout the abdomen and improve conduction. This was achieved using a large, rectangular plastic container, with water filled to 3cm above the model surface.

Study participants for qualitative assessment of clinical value

Six urologists (consultant or registrar) with clinical expertise performing surgery for RCC were invited to partake in a qualitative survey-questionnaire evaluating the 3D-printed kidney models. The questionnaire was composed of 16 questions, of which 6 were open-ended questions, and 10 were multiple-choice questions. The questionnaire was designed for participants to visually critique the clinical value and potential applications of the models. The 3D-printed kidney models were presented to participants so they could touch and compare the models to assist them with the questionnaire.

'Yes' or 'no' questions and questions formulated on a scale of 'slightly' to 'significantly' enabled participants to categorically rate their perceived accuracy and clinical value of the models. Open-ended questions enabled participants to describe their perception of the models and offer feedback. Several questions were included to address the gaps in the literature and supplement the study aim and objectives. For example, "Would the 3D-printed model facilitate you in the pre-surgical planning stage for a kidney eligible for surgical resection?" and "Does the 3D-printed model provide you with an improved visualisation of the extent of the lesion in relation to the healthy renal tissue?"

Quantitative analysis of dimensional accuracy

The dimensional accuracy of the 3D-printed kidney models was evaluated by measuring and comparing the dimensions of 4 critical anatomical structures on the CT scan of the models, original CT, and STL files. Measurements on the original CT and STL files were conducted by the open-source software 3D Slicer 4.10.2 (https://www.slicer.org), while measurements on the CT images of the models were performed using RadiAnt DICOM Viewer 2.0. Measurements were performed 5 times by two independent observers separately, to reduce measurement bias and strengthen measurement credibility[31]. As case 2 was 3D-printed twice using two different materials, CT dataset measurements and STL file measurements were the same for models 2 and 3. All measurements were performed from left to right in the antero-posterior (AP) direction, and in the coronal plane, to achieve consistency amongst observers.

The measured critical anatomical structures are as follows:

- The width of the RCC lesion at its widest point
- The diameter of the renal artery just prior to its bifurcation at the renal hilum
- The diameter of the abdominal aorta located just superiorly of the renal arteries
- The width of the kidney from the central hilum to the edge of the cortex

Statistical analysis

SPSS 25.0 (SPSS, Chicago, ILL) was used for statistical analysis of continuous and quantitative data which were presented as mean ± standard deviation. The mean of results between the two observers was taken as the final. Three-way Analysis of Variance (ANOVA) tests were performed (one per model) to assess for any significant differences between mean measurements on the model CT, STL file, and original CT dataset. Pairwise Comparisons Post-Hoc tests were conducted to assess for where the differences between measurements occurred, as well as the degree and direction of differences[31,32]. A p-value of less than 0.05 indicated statistical significance. Qualitative data including participant answers to multiple-choice questions were treated as nominal and ordinal categorical variables and assessed as percentages and frequencies to determine how the models were rated amongst participants in different areas[31]. Answers to open-ended written questions were qualitatively interpreted and compared.

Results

The segmentation and conversion process took approximately 1.5-2 hours per model. This included reconstruction, segmentation and refining of the data in preparation for printing. The 3D printing duration was approximately 10-12 hours per model. The two models made from TPU each cost AUD$50 to manufacture, while the single model made of VisiJet SL Flex material cost AUD$70. The 3 models are depicted in Figure 2, and 2D coronal and 3D volume rendered reconstructions of the model CT scans are demonstrated in Figure 3. A comparison of the original CT dataset, STL file, and model CT for model 1 is included in Figure 4 to demonstrate the effects of the segmentation and conversion processes.

Quantitative analysis of dimensional accuracy

Table 1 shows measurements of dimensional accuracy in different locations amongst post-processing methods and 3D-printed models. Results were not statistically significant for model 1 ($p>0.05$). Results were statistically significant for models 2 and 3 ($p=0.019$ and 0.001). This suggests that a significant degree of variance exists between measurements of critical anatomical structures on the original CT, STL file and model CT for models 2 and 3.

Pairwise Comparisons Post Hoc test results for model 1 show no statistically significant differences across all measurements ($p>0.05$). For Model 2, the measurements between the model CT and STL file, and model CT and original CT were not significantly different, however the measurements between the STL file and original CT were statistically significant ($p=0.005$). For model 3, measurements between the model CT and STL file, and STL file and original CT were both statistically significant ($p=0.002$ and 0.000) respectively, with no statistically significant differences between the model CT and original CT. All measurements between the original and model CT were not statistically significant ($p>0.05$).

Profile plots were constructed for each model, to visualise mean differences between each critical anatomical structure measured on the original CT, model CT and STL file, and evaluate which anatomical structures differed the most (Figure 5). For all models, the kidney width presented a greater degree of variation than the other 3 critical anatomical structures. In contrast, the means of the renal artery were the most consistent, and the abdominal aorta and lesion were also consistent for models 2 and 3. The profile plots show the STL file means being, on average, slightly larger than those of the original and model CT amongst all anatomical structures measured on models 2 and 3.

Qualitative analysis of clinical value

Five out of the 6 urologists participated completed the survey-questionnaire. Four were consultant urologists exhibiting 6-20 years of experience performing surgical procedures for RCC, and one participant was a registrar urologist with just under 5 years of clinical experience. Two participants had also encountered 3D-printed models previously in their practice. Three multiple-choice questions depicted in Figures 6-8 enabled participants to rate the models on various clinical aspects on a scale of 'not at all, slightly, moderately, and significantly'. Forty percent of participants rated the models as being able to demonstrate anatomical spatial relationships between tissue, vasculature, and lesion(s) significantly or moderately better than 2D imaging (Figure 6). Forty percent of participants also rated the models as being able to significantly improve the visualisation of tumour infiltration into healthy parenchyma compared to 2D imaging (Figure 7). Further to this, 40% of participants rated the models as being able to moderately improve perception of the depth of inter- and intra-renal relationships, whilst 20% of participants rated them as either slightly or significantly compared to 2D imaging (Figure 8).

Pre-surgical planning for RCC resection

Table 2 elucidates that all participants were satisfied that the 3D-printed models could facilitate pre-surgical planning, however 4 out of 5 participants were unsure whether the 3D-printed models could reduce the need for intra-operative imaging. One participant was unsure if prognostic benefits could be attained by models, as multiple factors influence post-surgical outcomes. Participants were also asked if they believe the 3D-printed models could reduce the probability of intra-operative complications occurring. Two participants responded 'yes, in all cases', one responded 'yes, in simple/straightforward cases only' and 2 responded 'unsure' and that it is case-dependent.

Education applications of 3D-printed models

All 5 urologists agreed that the 3D-printed models could be implemented for the training of inexperienced surgeons, and for patient education on their condition. One participant additionally indicated that implementing patient-specific models could promote patient-practitioner communication and decision making regarding the treatment approach.

3D printing technology and materials

Table 3 demonstrates participant material preferences. Sixty percent of participants preferred the VisiJet SL Flex model due to the material's more detailed and realistic representation, with separation along the coronal plane enabling superior visualisation of internal details. Participants preferred the TPU material for reasons of more flexible and thus user-friendly for pre-surgical rehearsal.

Ultrasounds scan of the 3D-printed models

Only the models made from TPU enabled sufficient propagation to generate an outline of the kidney surface and exophytic renal lesion, however, internal structures such as the calyces were difficult to identify.

Figure 9 demonstrates the dimensions of the kidney lesion which were vaguely measured longitudinally and transversely on the case 2 TPU model. The lesion measured 16.5mm transversely, which is 1.6mm different to the average measurement of 18.1mm reported amongst the original CT, model CT and STL file. This suggests that either the lesion was not measured at its widest point in the ultrasound scan, or that the true size of the lesion was not successfully represented on the ultrasound scan.

Discussion

The results of this study highlight multiple advantages and applications of 3D-printed kidney models that transcend beyond pre-surgical planning. These include the education of inexperienced surgeons in their operative technique and using different imaging modalities such as ultrasound on patient-specific phantoms.

The study findings also demonstrate that 3D-printed models can be created with a sound degree of dimensional accuracy, as no statistically significant differences between measurements on the original and model CT were identified amongst all 3 models ($p>0.05$)[32]. Measurements of critical anatomical structures on the STL file were statistically larger than those on the original and model CT for models 2 and 3 ($p=0.000$-0.005). This is likely a limitation of the image processing or measurement process, which required selecting a point on a critical anatomical structure on a 2D CT dataset and translating it to the exact location on a 3D STL file. The measurement is also affected by inter-observer variability, considering that two independent observers collected measurements independently[31].

Two previous studies measured the width of anatomical structures on the 3D-printed models and compared these to measurements of the original CT datasets from which the models were retrieved[22,24] One study utilised digital callipers, and the other used a meshing programme to perform measurements, with discrepancies ranged from 0.3 to 4mm. The study by Liu et al[22] was the only study to perform statistical testing on the measurement values; using a t-test to identify statistically significant differences between the width of the tumour measured on the model and the original CT dataset. Authors reported no statistically significant differences between structures on the model and dataset ($p>0.05$).

It is difficult to determine what constitutes a dimensionally accurate model, as very few studies have performed a quantitative analysis of 3D-printed kidney models. Furthermore, the measurement approaches used in the two previous studies differ to the current study, making it difficult to compare and standardise model accuracy amongst the studies. Future research should identify a universal standard to define 3D-printed models as 'dimensionally accurate', to enable consistency in quantitative assessments and a comparison of results between studies.

Clinical applications in pre-surgical planning

All participants deemed the models suitable to facilitate the pre-surgical planning process in some way. One participant identified the models as being specifically valuable for pre-surgical planning for patients with recurring renal cell tumours or polycystic kidney disease, whereby salvaging the maximum possible healthy kidney parenchyma is paramount for preserving renal function. The participant suggested that physical assessment of topological relationships would better enable the surgeon to demarcate the location and volume of tissue to be respected and increase the chances of resecting the minimum possible healthy tissue. Despite a high level of satisfaction reported with the models' ability to facilitate pre-surgical planning, participants suggested feedback regarding how the models could be improved for this clinical application. For example, manufacturing the models using a more user-friendly material closely resembling renal tissue, as this would enable clinicians to physically cut into the model and perform a surgical rehearsal prior to the patient's actual surgery. Furthermore, participants suggested that adding colour and vessel detail would further assist surgeons in separating the tumour from important vasculature.

Previous studies have evaluated the clinical value of 3D-printed kidney models for pre-operative planning, with most results being similar, in that the models were able to assist in identifying the most appropriate surgical path prior to the patient's surgery[9-12,16,21,24,26]. Two studies evaluated the application by inviting urologists to complete a survey-questionnaire related to pre-surgical planning of different clinical cases of RCC using 2D and 3D CT volume-rendered datasets[5,16]. Afterwards, the surgeons were re-invited to analyse the same cases using the volumetric imaging, and the addition of a corresponding 3D-printed kidney model, and results were compared. Questions regarding how they would operate on the cases, such as what direction they would enter were included, to assist in the pre-operative analysis. It was found that most participants altered their decision to perform open or laparoscopic surgery and enter the kidney trans-peritoneally or retroperitoneally following introduction of the 3D-printed models[5,16]. Whilst data collection methods were different to the current study, participants similarly suggested that being able to manually position and visualise the patient's complex renal anatomy using the model prior to the surgery provided an additional perspective to volumetric imaging alone, hence the alteration in decision-making[5,16]. The 3D-printed models analysed in the current and previous studies provide a starting point for further research into the potential for user-friendly 3D-printed kidney models to be implemented into clinical practice for pre-operative applications.

Clinical applications in education

All the participant urologists involved in the study reported positive findings in the light of the models facilitating the education of junior surgeons. Areas of potential addressed by participants include improving the cutting accuracy of junior registrars, given the material utilised for manufacturing the models is highly malleable, and improving the recognition of anatomical networks in the kidney if the models are sufficiently detailed. One study performed by Monda et al[12] conducted similar research to evaluate the value of models to facilitate the education of inexperienced laparoscopic surgeons, however invited participants to perform simulation surgeries on the models, rather than just a visual assessment. Models were fabricated from a silicone-based material. In the study, each participant performed two simulation surgeries on two different days, a week apart: one using only volumetric imaging, and one with the addition of the models. Aspects of their surgery were 'marked' by two fellowship-trained and experimentally blinded surgeons. The study found that using the models showed improvement in new and existing cutting skills and technique accuracy of participants, which suggests that utilising models as training mediums may evoke long-term benefits for inexperienced clinicians, whilst reducing the need for cadaver cases to be used for training[12].

All 5 participants involved in the current study agreed that patient-specific 3D-prined kidney models could provide educational benefits to patients undergoing surgery for renal cell carcinoma, in terms of being able to better comprehend basic renal anatomy and tumour location. Other benefits assist urologists to discuss the prescribed surgical approach with them in a way that is easier to understand and encourages patient decision-making regarding their operation. Furthermore, participants suggested that the models used for patient education could be simplistic and therefore inexpensive to manufacture. This, along with the cost of the models manufactured in the study ranging from AUD$50-70 suggests that there is feasibility in fabricating patient specific 3D-printed models targeted at patients.

Clinical applications in multi-modality training

The CT and ultrasound imaging of the models indicate potential for the training of practitioners to visualise renal anatomy on different imaging modalities. For example, for the inexperienced surgeons to perform ultrasound-guided mock surgeries on 3D-printed kidney models. Another more-expensive 3D-printed kidney model manufactured in a previous study by Liu et al[22] (Figure 10) was ultrasound-scanned in comparison with the current models. The model was fabricated using a silicone-based material TangoPlus, which better resembled soft-tissue texture. The outline of the exophytic lesion was demonstrated superiorly on ultrasound compared to the models created in the current study, showing the importance of material considerations for this application.

Only one other study by Adams et al[24] performed ultrasound imaging of the models manufactured in the study, using kidney models made of either silicone or a material called agarose gel. Like this study, only the outer surface of the model was visualised, with internal dimensions lacking detail. However, it was found that the more flexible agarose gel models rendered superior imaging compared to the silicone models[24].

While there are promising applications of using radiographic imaging such as ultrasound on 3D-printed models, the rigidity of the models and thus poor sound wave propagation reinforces the importance of considering and comparing different material properties for optimising this application.

Study limitations

The current study encompasses several limitations. The first limitation lies in measuring the dimensional accuracy of the 3D-printed models. While the 4 critical anatomical structures were measured and compared to define dimensional accuracy, it is worth noting that this may not be a true reflection of the entire accuracy of the model. This is because only 4 anatomical structures were measured, and measurements were collected solely in the coronal plane, meaning discrepancies in the other planes may exist. Therefore, an assessment of more anatomical structures in all planes is encouraged. Secondly, only 3 models were 3D printed, with two being from the same clinical case, and both cases were low-grade, exophytic lesions. Therefore, the results may not be explorative of a range of cases, especially cases where the lesion is endophytic, interpolar, or embedded in dense adipose tissue and vasculature. Hence, manufacturing more models with a range of tumour presentations would further assess model usefulness for pre-operative planning. Another limitation lies in material feasibility. Most participants suggested that whilst simple, inexpensive materials could be employed for patient education, for the models to facilitate pre-operative planning more effectively, a coloured material textured like soft tissue would be more user-friendly. It is likely a coloured material of that level of anatomical detail would be expensive to manufacture, and therefore make it unfeasible to construct a patient-specific 3D-printed model for every patient undergoing partial nephrectomy surgery. Hence, further research is needed to identify ways to create models which are cost effective. The final limitation lies in participant diversity. Although the participant size of 5 was deemed suitable in assessing a range of perspectives on the clinical value of 3D-printed models, 4 of the participants were consultant urologists with 6-20 years of experience, and one was a registrar urologist with under 5 years of experience. Thus, it is possible that responses may be influenced by most clinicians being highly experienced. To receive more credible results about education of junior urologists, a larger participant pool with more registrar urologists is encouraged.

Conclusion

This study has examined the feasibility of fabricating dimensionally accurate, 3D-printed kidney models for pre-operative planning, patient and clinician education, and radiographic imaging. Results show that models may be useful resources for the education of patients with renal cell carcinoma, in addition to the pre-operative planning process. The current study presents opportunity for future studies to create improved 3D-printed models and further assess their value and potential applications in the medical field. It also warrants the investigation of 3D-printed models for pre-surgical planning and education of diseases in other organs. As the factor of cost presents a significant impediment to this technology, an in-depth cost-benefit analysis of implementing 3D-printed kidney models into clinical practice is required.

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PEER REVIEW

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CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

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ETHICS COMMITTEE APPROVAL

Curtin Human Research Ethics Committee (ethics approval number *HRE2018-0796)*.

Figures

Figure 1: Flow chart showing the steps to acquire the 2 datasets for creation of 3D-printed kidney models.

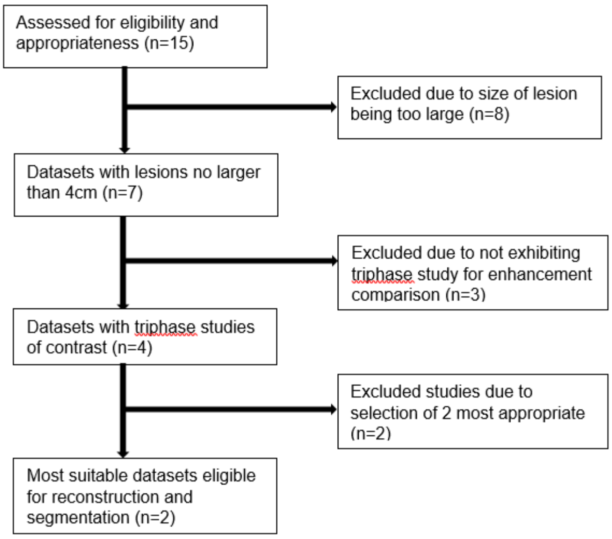
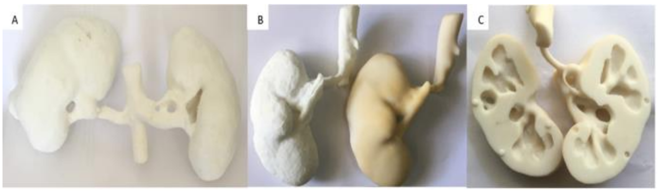
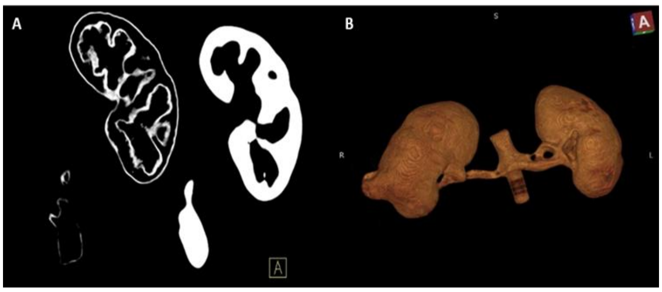


Figure 2: 3D printed models.



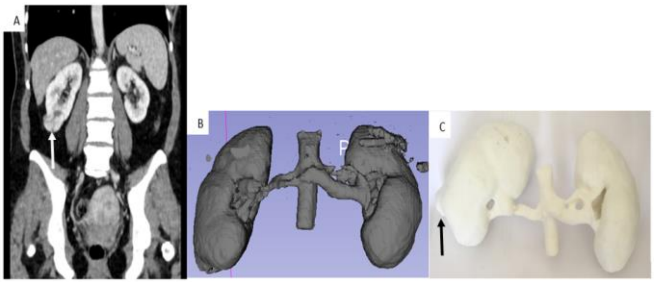
A: anterior view of Model 1. B: Posterior view of models 2 and 3 sitting adjacently. C: Model 3 sliced coronally to demonstrate internal renal anatomy.

Figure 3: CT scan of 3D printed kidney models.



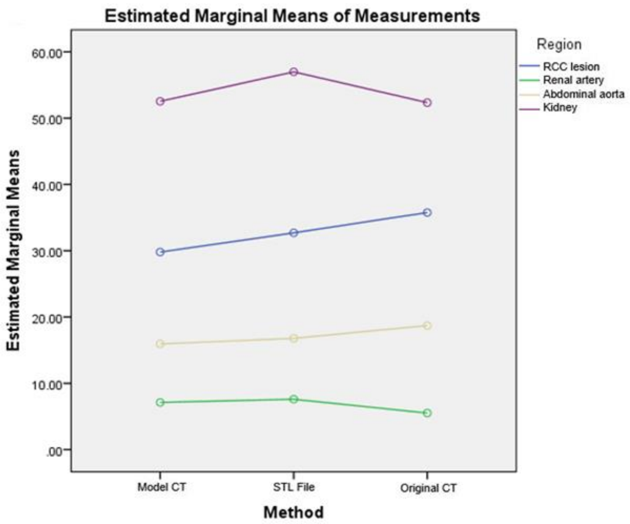
A: Coronal CT reformatted views of the models 2 and3 printed with different materials. B: 3D CT volume rendering of model 1.

Figure 4: Creation of 3D printed model from original CT images to STL and physical model.

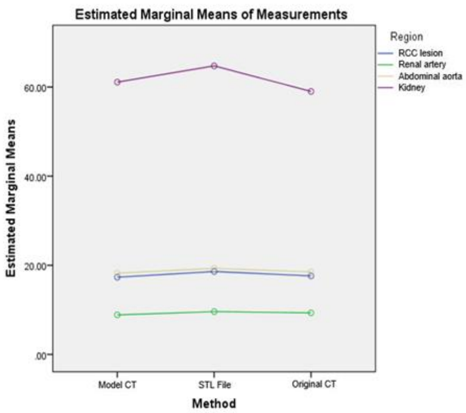


A: Coronal reformatted image showing a tumour at the lower pole of right kidney (arrow). B: STL file of 3D segmented volume data. C: 3D printed model with TPU material with tumour located on the posterior aspect of right kidney (arrow).

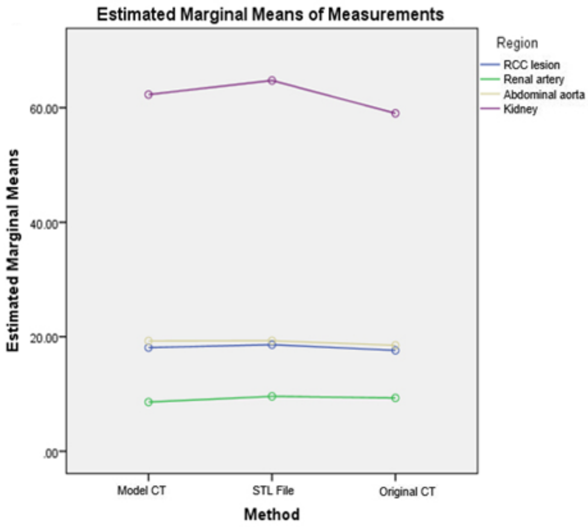
Figure 5: Plots showing measurement differences in these 4 anatomical locations between original CT, STL and 3D printed models.



A



B



C

A-C: Measurement differences in Models 1 to 3.

Figure 6: Participants rating of 3D printed kidney models in demonstrating spatial relationship in comparison with 2D images.

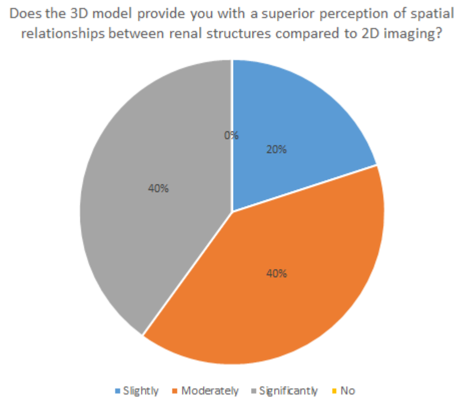


Figure 7: Participants rating of value of 3D printed kidney models in revealing renal lesion.

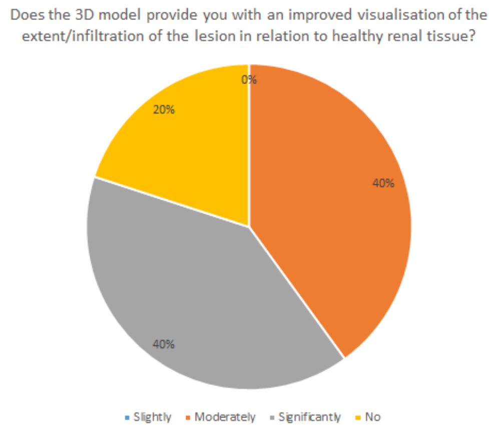


Figure 8: Participants rating of value of 3D printed kidney models in revealing depth details of inter- and intra-renal relationships.

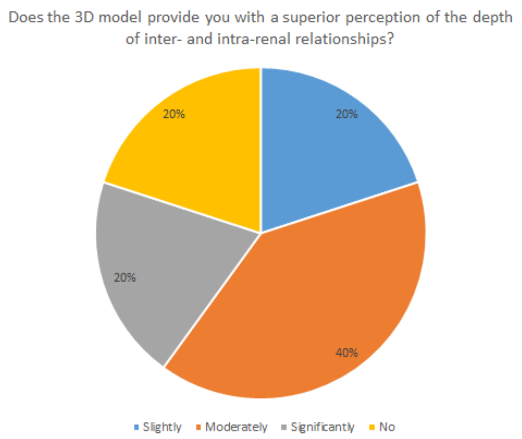
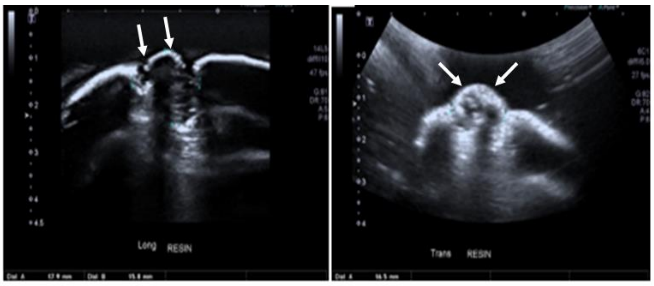
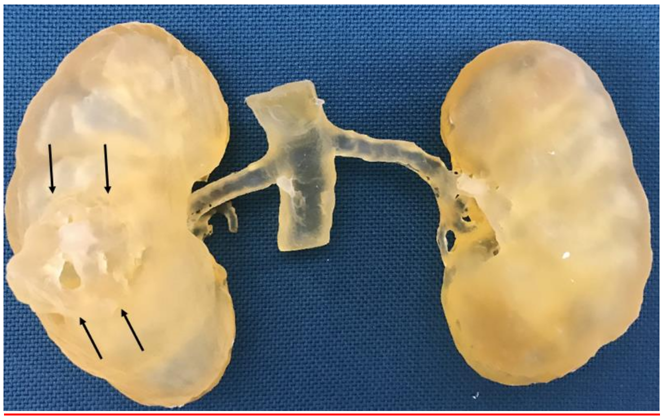


Figure 9: Ultrasound images of 3D printed model with TPU material.

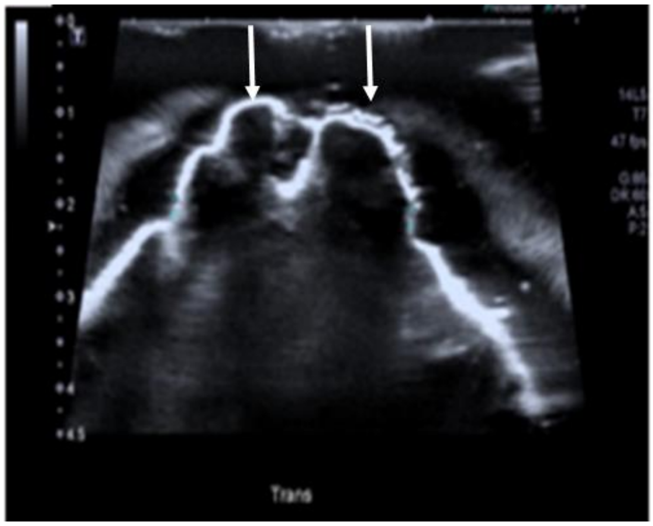


Longitudinal and transverse views (left and right images), respectively showing the renal tumour (arrows).

Figure 10: Ultrasound images of 3D printed model with TangoPlus material.



A



B

A: 3D printed model showing renal cell carcinoma at the posterior aspect of left kidney (arrows). B: Ultrasound scan of the model showing renal tumour with protrusion outward (arrows).

Tables

Table 1: Measurements performed on all CT scans of 3D-printed models, corresponding STL files and original CT datasets (mean ± standard deviation)

Structures to be measured	Dimensional differences in anatomical structures (mm)		
	Model CT Models 1/2/3	STL file Models 1/2/3	Original CT Models 1/2/3
Renal lesion (RCC)	29.80±0.85 18.10±1.21 17.32±0.36	32.70±0.43 18.60±0.91 18.60±0.91	35.76±0.55 17.62±0.64 17.62±0.64
Renal artery	7.12±0.63	7.60±0.59	5.52±0.20

	8.60±0.67 8.86±0.44	9.60±0.26 9.60±0.26	9.31±0.21 9.31±0.21
Abdominal aorta	15.94±0.42 19.26±0.41 18.22±0.22	16.78±0.60 19.30±0.58 19.30±0.58	18.72±0.39 18.50±0.24 18.50±0.24
Kidney	52.54±0.42 62.30±4.96 61.10±2.34	56.98±11.36 64.76±4.93 64.76±4.93	52.34±0.47 59.02±0.22 59.02±0.22

Table 2: Usefulness of 3D-printed models for pre-surgical planning as rated by participants

	Survey-Questionnaire Questions		
Frequency (%)	Would the model facilitate you in pre-surgical planning for a kidney eligible for surgical resection?	Could 3D printed models assist in reducing operative times by replacing and/or reducing the use of intraoperative imaging required? i.e. Doppler US	Do you believe 3D printed kidney models could provide prognostic benefits to patients undergoing surgery for RCC?
Yes	100%	0%	80%
No	0%	20%	0%
Unsure	0%	80%	20%
Total	100%	100%	100%

Table 3: 3D printing material preference as rated by participants

Frequency (%)	**Survey-Questionnaire Questions** Out of the two different materials, which did you find the most suitable?
Thermoplastic Polyurethane (TPU)	40%
VisiJet SL Flex	60%
Unsure	0%
Total	100%