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Clinical experience of using virtual 3D modelling for pre and intraoperative guidance during robotic-assisted partial nephrectomy

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Abstract

Objective: Surgical planning for robotic-assisted partial nephrectomy is widely performed using two-dimensional computed tomography images. It is unclear to what extent two-dimensional images fully simulate surgical anatomy and case complexity. To overcome these limitations, software has been developed to reconstruct three-dimensional models from computed tomography data. We present the results of a feasibility study, to explore the role and practicality of virtual three-dimensional modelling (by Innersight Labs) in the context of surgical utility for preoperative and intraoperative use, as well as improving patient involvement.
Methods: A prospective study was conducted on patients undergoing robotic-assisted partial nephrectomy at our high volume kidney cancer centre. Approval from a research ethics committee was obtained. Patient demographics and tumour characteristics were collected. Surgical outcome measures were recorded. The value of the three-dimensional model to the surgeon and patient was assessed using a survey. The prospective cohort was compared against a retrospective cohort and cases were individually matched using RENAL (radius, exophytic/endophytic, nearness to collecting system or sinus, anterior/posterior, location relative to polar lines) scores.
Results: This study included 22 patients. Three-dimensional modelling was found to be safe for this prospective cohort and resulted in good surgical outcome measures. The mean (standard deviation) console time was 158.6 (35) min and warm ischaemia time was 17.3 (6.3) min. The median (interquartile range) estimated blood loss was 125 (50–237.5) ml. Two procedures were converted to radical nephrectomy due to the risk of positive margins during resection. The median (interquartile range) length of stay was 2 (2–3) days. No postoperative complications were noted and all patients had negative surgical margins. Patients reported improved understanding of their procedure using the three-dimensional model.
Conclusion: This study shows the potential benefit of three-dimensional modelling technology with positive uptake from surgeons and patients. Benefits are improved perception of vascular anatomy and resection approach, and procedure understanding by patients. A randomised controlled trial is needed to evaluate the technology further.
Level of evidence: 2b

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Introduction

Partial nephrectomy (PN) is the standard of care for clinically organ-confined renal tumours.[1–4]

This is a complex and demanding procedure that aims at complete tumour resection and accurate repair of injured renal structures, to achieve cancer control and functional preservation within an acceptable burden of complications. Surgical planning for PN is complex, with numerous patient and tumour characteristics having to be accounted for, especially the relationship between the tumour and renal hilar anatomy.

Historically, the appreciation of these anatomical factors has been through the examination of two-dimensional (2D) coronal, sagittal and axial images of computed tomography (CT) datasets. By performing this function, surgeons cognitively construct a three-dimensional (3D) model that is their singular guide to simulate the patient's anatomy. Although repetition over the course of the surgeon's career lends a certain comfort and familiarity with this technique, it is unclear if this cognitive representation accurately depicts the real anatomy with all its complexities.

To overcome the limitations of 2D viewing of images, dedicated computer software has been developed to classify medical scan voxels into their anatomical components in a process known as image segmentation.[5] Once segmented, stereolithography files are generated which can be used to visualise the anatomy, interactively as a 3D model.[5]

Pioneering work showed that surgeons can benefit from virtual 3D models in the theatre, particularly with regard to improved appreciation of hilar vascular anatomy and enhanced preoperative planning and simulation.[6]

In recent years, several studies have shown the benefits of 3D modelling for preoperative planning in robotic-assisted partial nephrectomy (RAPN). A recent prospective study showed that 3D models increased the ability for selective clamping from 13% to 57%, thus limiting the chance of long-term ischaemic damage to the kidney.[7] A retrospective study showed 20% of surgical decision changes with 3D models,[8] and another retrospective survey-based study showed a 27% increase in possible organ-sparing operations for complex cases.[9]

For intraoperative use, a prospective randomised clinical trial (n=92) demonstrated that patients whose surgical planning involved 3D models had reduced operative time, blood loss, clamp time and length of hospital stay.[10]

This feasibility study aims at exploring the potential role, practicality and safety of 3D modelling for preoperative planning and intraoperative use during RAPN at our institution. To the best of our knowledge this is the first prospective UK-based study of this kind and was approved by the local ethics committee.

The main novel contributions of this work, in addition to providing a highly detailed and interactive 3D model of the kidney tumour, are as follows:

1. A novel way of coloring vessels to highlight uncertainty within the 3D model and improve safety.
2. A surgeon survey assessing the utility of the 3D models during the different phases of the operation.
3. A patient survey evaluating whether it is feasible to carry out a future randomised controlled trial of this technology.
4. A detailed discussion on the practicality and safety considerations when using 3D modelling as part of routine practice.

Materials and methods

Twenty-four patients with a renal mass scheduled for RAPN at the Specialist Centre for Kidney Cancer at the Royal Free London NHS Foundation Trust were prospectively enrolled in the study. The study was approved by the South West Frenchay Research Ethics Committee (ethics number 18/SW/0238).

Imaging and 3D model generation

CT scans were performed by standard protocol for the staging of a solid renal mass, which is a contrast-enhanced CT with 1–3 mm sections of the renal region with an arterial phase.

CT scans for patients in the intervention cohort were converted to de-identified 3D models prior to the patient's operation by the surgical planning company Innersight Labs.[11] Three-dimensional models were made available to surgeons preoperatively using a web-based application, allowing for interactive rendering using a mobile phone or tablet. Buttons enabled the surgeon to render structures solid or transparent. The 3D model was also shown to the patients to explain the procedure better and highlight potential risks of the operation. Intraoperatively, a tablet was mounted on a stand next to the robotic-console to allow the surgeon to refer to the 3D model throughout the operation at any point.

Data collection

Clinical data collected included mass size, RENAL (radius, exophytic/endophytic, nearness to collecting system or sinus, anterior/posterior, location relative to polar lines)

Table 1. Clinical characteristics, patient demographics and surgical outcomes.

Variable	RAPN with 3D (*n*=22, prospective)	RAPN without 3D (*n*=22, retrospective)	*P* value
Age, years, mean (SD)	56.6 (11.1)	56 (11.7)	0.875
Sex, *n* (%)			
Male	15 (68.2)	16 (72.7)	1
Female	7 (31.8)	6 (27.3)	
BMI, kg/m^2 median, mean (SD)	28, 29 (4)	28.5, 36.1 (20.4)	0.105
RENAL score, median (IQR)	8 (6-9)	8 (6-9)	1
Clinical tumour size, mm, median (IQR)	35.5 (28.5-45)	37.5 (24.3-45)	0.704
Operative time, min, mean (SD)	158.6 (35)	153.4 (38.8)	0.677
Console time, min, mean (SD)	126.8 (36.7)	120.5 (46.4)	0.673
WIT, min, mean (SD)	17.3 (6.3)	17.8 (7.2)	0.724
EBL, mL, median (IQR)	125 (50-237.5)	100 (100-200)	0.993
Hospital LOS, days, median (IQR)	2 (2-3)	2 (2-2)	0.362
Conversion to radical, *n* (%)	2 (9.1)	4 (18.2)	0.664

BMI: body mass index; EBL: estimated blood loss; IQR: interquartile range; LOS: length of stay; RAPN: robotic-assisted partial nephrectomy; RENAL: radius, exophytic/endophytic, nearness to collecting system or sinus, anterior/posterior, location relative to polar lines; SD: standard deviation; 3D: three-dimensional; WIT: warm ischaemia time.

nephrometry score, laterality, T stage and patient demographics age and sex. The primary outcome measure, operative time, and secondary outcome measures, clamp time (warm ischaemia time; WIT), estimated blood loss (EBL), and hospital length of stay, were collected from the operation notes.

Patients were asked to complete a short survey before the operation, after having seen the 3D model. At the end of the operation, surgeons also completed a survey. For some questions, a Likert scale in the range 1–5 (strongly disagree, disagree, neutral, agree, strongly agree) was used.

All operations were led by three consultant surgeons who were beyond their learning curve, having completed 100+ of RAPN operations, and were assisted by three trainee surgeons. Cases were equally distributed according to the RENAL score between the three consultants. Surgeons were not blinded to the source CT as part of the preoperative and intraoperative planning.

Statistical analysis

The prospective surgical outcomes were compared to a retrospective control group which did not receive 3D modelling. Individual case matching was performed using the RENAL score. This single matching variable was selected with the intention to balance the variable most likely influencing operative bias. Statistical analyses were carried out utilising the *t*-test and Fisher's exact test for continuous or categorical variables, respectively.

Results

Two of the 24 patients were excluded from the study because their operations had to be postponed due to other medical complications. The retrospective cohort was selected from patients having undergone RAPN at our centre within the past 12 months. Overall, 12 (55%) were cT1a and 10 (45%) cT1b tumours. No postoperative complications were noted and all patients had negative surgical margins. Two patients (RENAL score 11A and 10P) underwent conversion to radical nephrectomy due to the risk of positive margins during resection. Clinical characteristics, patient demographics and surgical outcomes are shown in Table 1. Results from the surgeon survey and patient survey are shown in Table 2 and Table 3, respectively.

Three-dimensional model use cases for surgical planning

Three-dimensional models were found to be most useful for cases with multiple feeding arteries and/or complex hilar tumours. Two such examples are shown in Figure 1. In other cases the 3D model helped in deciding whether a partial nephrectomy was feasible or whether instead a radical

Table 2. Surgeon survey results (n=22).

Surgeon survey question	Likert score (1–5), median (IQR)
Did you find the 3D model useful for preoperative planning?	5 (5–5)
Do you believe that the 3D model helped to reduce clamp time?	4 (3.75–4)
Did the 3D model improve the patient's understanding of the procedure?	5 (4–5)
For preop planning, which of the following did you use the 3D model for?	**Number of answers yes (max *n*=22)**
Assisting with surgical approach, i.e. transperitoneal vs. retroperitoneal	7 (31%)
Clarification of vascular anatomy	22 (100%)
Assessing feasibility of selective clamping	13 (59%)
Not needed	0 (0%)
Any other item?	'Planning shape of dissection plane', 'Extent of hilar involvement'
During the operation, which of the following did you use the 3D model for?	**Number of answers yes (max *n*=22)**
Renal hilum dissection	21 (95%)
Identifying feeding arteries for clamping	20 (91%)
Assessing feasibility of tumour enucleation vs. partial nephrectomy	14 (64%)
Clarification of the tumour margins	12 (55%)
Assisting with excision and suture planning	9 (41%)
Not needed	0 (0%)
Any other item?	None

IQR: interquartile range; 3D: three-dimensional.

Table 3. Patient survey results (n=22).

Patient survey question	Likert score (1–5), median (IQR)
Do you think that the use of the 3D model led to you having a better understanding of your procedure ?	5 (4–5)
	Number of answers yes (max *n*=22)
Would you agree to take part in a future randomised controlled trial?	22 (100%)

IQR: interquartile range.

nephrectomy should be pursued to avoid otherwise likely complications, see Figure 2. The 3D model was also useful for planning and performing selective clamping, see Figure 3. For intermediate complexity tumours, further from the hilum, the 3D models were useful for managing vascular control and excision/suture planning, see Figure 4. For lower complexity tumours with standard vasculature of one main feeding artery and vein, the 3D model added little additional information to the surgeon. However, reconfirmation of the anatomy and tumour position found intraoperatively against the 3D model, and tumour depth findings from ultrasound against the 3D model, was still reassuring to the surgeon and of benefit, see Figure 5.

Discussion

The present feasibility study showed that 3D models of the renal anatomy can have a wide range of use cases in aiding with pre and intraoperative planning for RAPN. We also found that patients responded positively to their 3D models as it allowed them to understand the operation and possible difficulties better.

From the surgeon survey carried out (Table 2), surgeons agreed (Likert score 4) in 14/22 and strongly agreed (Likert score 5) in 1/22 cases that the 3D model helped to reduce

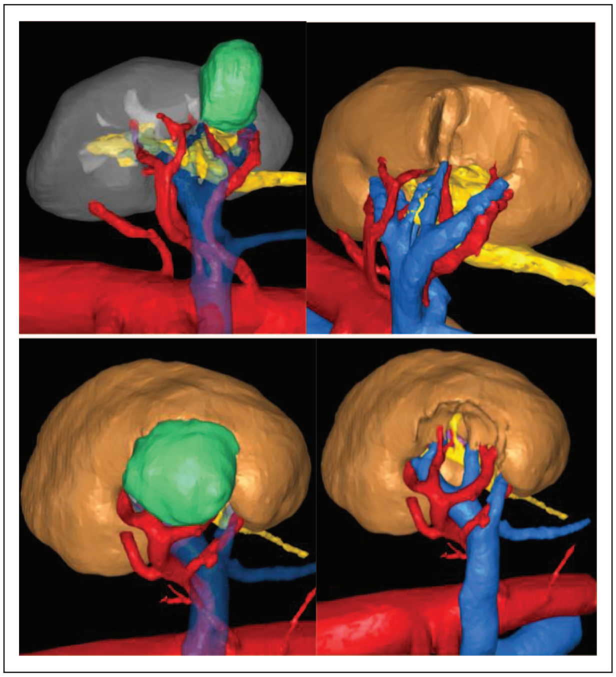

Figure 1. (Top) Hilar tumour with four feeding arteries. (Top left) The vein is turned transparent so the four arteries can be seen clearly with respect to the main vein and clamped to control bleeding. (Right) The tumour is removed from the three-dimensional model to show the tumour bed and the 'V' shaped vessels beneath, which could then be identified intraoperatively to aid with the enucleation of the tumour. (Bottom) Hilar tumour with two feeding arteries. (Bottom left) View to aid in hilum dissection and vascular control (clamping) of both arteries. (Bottom right) The tumour is removed to show the tumour bed and tertiary arteries feeding the tumour that can be clipped and secondary arteries that are to be preserved.

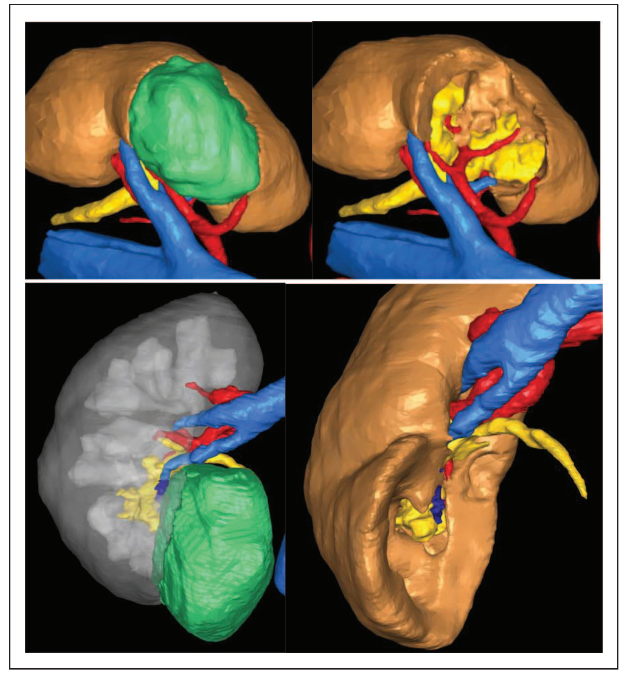

Figure 2. (Top) Large hilar tumour with involvement of the main arteries and large sections of the collecting system. Due to the high complexity, possibility of tumour invasion into the sinus fat, high chance of postoperative complication and a healthy second kidney a radical nephrectomy was carried out instead. (Bottom) Large lower mass. From inspecting the three-dimensional model one can see how the tumour is pushing into the collecting system. Because of the high risk of damaging the collecting system beyond repair during tumour excision, a radical nephrectomy was carried out instead.

clamp time. We acknowledge that this was not formally shown in the results section due to the small sample size of this feasibility study; however, we feel that it was strongly suggested that the 3D model helped with the understanding prior to clamping of the exact depth of the tumour and the shape of the defect. This allowed the surgeon to plan precisely the excision of the tumour and renorrhaphy, which in turn would reduce the time planning this part of the procedure while on clamp. This is very well illustrated in Figure 1 which shows the nature of the defect and how one should plan the closure of the defect pre clamp.

Several studies have already investigated the use of 3D models for pre and intraoperative planning of RAPN. Porpiglia et al. focused on the current use of 3D models in urology highlighting how this technology is perceived as a useful tool for surgical planning, training, education and patient counseling.[12] Studies were conducted to compare preoperative planning using 3D and CT only, and both showed an improved understanding of the anatomy when using 3D models.[8,13] Furthermore, 3D models have been used for nephrectomy scoring, with preliminary results indicating that these could improve the prediction of complications compared to nephrometry scoring using CT.[14]

Multiple research groups have previously used 3D models intraoperatively via the da Vinci console using the TilePro function (Intuitive Surgical, Sunnyvale, USA), or using the Google cardboard virtual reality headset.[6,15,16] We found that displaying the 3D model on a tablet assembled on a stand next to the robotic console allowed the surgeon to refer to the 3D model when needed without restricting the intraoperative view.

It is also important to consider the practicality of using 3D models routinely in clinical practice. We only used arterial enhanced CT scans to generate the 3D models, so applicability to other scanning modalities, such as magnetic resonance imaging (MRI) or CTs without arterial phase, remains to be tested.

Giving surgeons access to the 3D model through a secure website meant the 3D model was readily accessible by surgeons on a portable platform, such as their mobile phone, irrespective of the operating system (iOS/Android), at any time and could be viewed whenever convenient, without having to install any specialised software. One

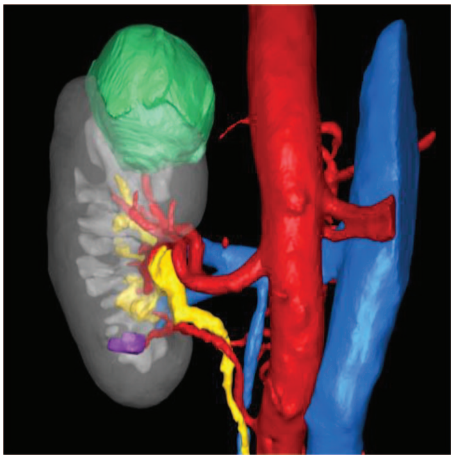

Figure 3. Posterior view of left kidney, with two feeding arteries. Selective clamping was performed, leaving the lower artery unclamped to limit ischaemia.

Figure 4. Intermediate complexity tumour with some limited amount of collecting system involvement. The three-dimensional model aided with assessing the depth and amount of collecting system involvement (left), as well as suture planning (right).

practical limitation was that during the study a 3D model could only be requested from a dedicated computer with a full PACS installation. This meant that clinicians often had to go to a different floor to find such a dedicated computer to carry out the 3D model request which caused some inconvenience. Further integration with the PACS system is required to allow for seamless 3D model requests from any computer within the hospital.

Safety considerations when using 3D models

Using the 3D models for surgical planning was found to be safe, primarily because the surgeon is always in full control and can choose how and when to use the additional information of the 3D model within the complex surgical planning decision-making process. Preoperatively, the 3D model is only used alongside the CT scan, intraoperatively the 3D model is used alongside the intraoperative findings

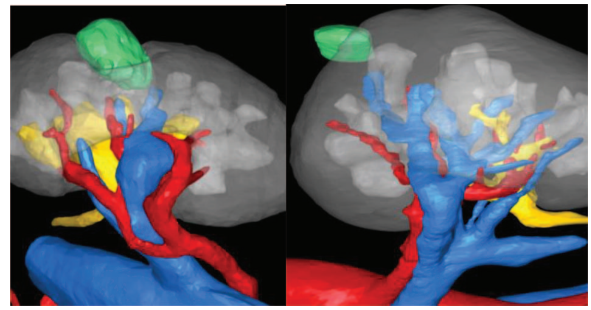

Figure 5. Smaller and lower complexity tumours. (Left) The three-dimensional (3D) model was still useful for reconfirming intraoperative ultrasound findings that showed a dip in the tumour, towards the right in the image, which helped to plan the excision. (Right) Small proximal and exophytic tumour and with single feeding artery. For this simpler case the 3D model was not needed but it did reconfirm the intraoperative findings.

from the endoscopic camera feed and ultrasound probe. Therefore even if the 3D model were to be inaccurate, then these inaccuracies would be found using other available information, and thus the potential for patient harm is reduced by this inherent redundancy in visual systems. This is somewhat supported by our surgical outcomes data that showed no significant difference between the 3D and non-3D group, which is not surprising for such a small cohort. The accuracy of the 3D model depends on the quality and resolution of the input CT scan and the experience of the engineer and clinician reviewing the 3D model during the validation step. Three-dimensional model inaccuracies can occur. For example, if it is difficult to see a small vessel in the preoperative CT scan due to relatively low image resolution (partial volume effect), or poor contrast uptake, then this vessel may not feature in the 3D model. We introduced a novel way of adding uncertainty information to the 3D model by coloring vessels that have a higher chance of being labelled incorrectly with a darker colour, as shown in Figure 6. In all of the 22 cases carried out during this study we found that the 3D model matched the anatomy found intraoperatively.

Limitations

Two limitations of the study need to be disclosed: being a feasibility study, a major limitation is the small size of the cohort and consecutive and non-randomised nature, which exposes it to risks of cohort and selection bias.

Future directions

Three-dimensional modelling seems to be most effective for highly complex tumours such as tumours with a RENAL score of 9 or greater or T2a tumours which are starting to be attempted robotically. Furthermore, a recent analysis of the

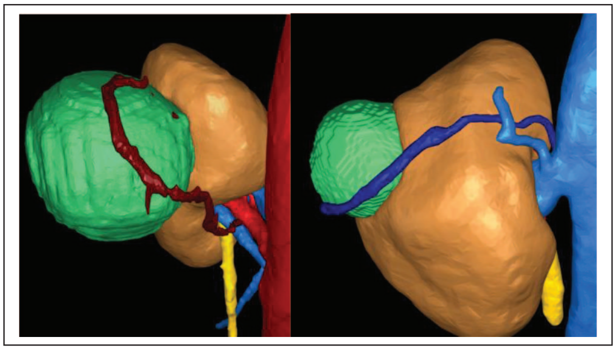

Figure 6. Thin vessels that start off near complex artery/vein crossing points are difficult to identify as being arteries, veins or other structures/vessels present in the perirenal fat, and therefore have a higher uncertainty associated with their labelling. To communicate this information to the surgeon in the three-dimensional model a dark red and dark blue colour were used for uncertain arteries (right) or veins (left), respectively.

RObotic SUrgery for Large (ROSULA) renal mass consortium dataset showed that RAPN over radical nephrectomy for T2a renal masses can be safe while retaining the functional benefits associated with partial nephrectomy. We hypothesise that for these challenging cases there is a strong potential for 3D modelling to improve surgical outcomes such as operative time, WIT, blood loss, and to reduce the number of complications and conversions to radical nephrectomy. A large multicentre randomised controlled trial investigating the use of 3D modelling for partial nephrectomy is required to confirm this hypothesis.

Conclusions

Three-dimensional modelling for surgical planning of RAPN was found to be safe. The main uses of 3D model technology for RAPN include assisting with the identification and control of vasculature, approach to the renal masses and excision planning. To assess properly whether this technology improves surgical outcomes a larger randomised clinical study is needed.

Conflicting interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Lorenz Berger is a shareholder and director of Innersight Labs Ltd. Eoin Hyde is a shareholder and director of Innersight Labs Ltd. Matt Gibb is a shareholder of Innersight Labs Ltd. Faiz Mumatz is a shareholder of Innersight Labs Ltd. Sebastien Ourselin is a shareholder of Innersight Labs Ltd. All other authors have no conflict of interest to declare.

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Ethical approval

This research was approved by the South West Frenchay Research Ethics Committee (ethics number 18/SW/0238).

Informed consent

Signed informed consent was obtained from the patients enrolled in this study and for their anonymised information to be published.

Guarantor

FM.

Contributorship

FM, AB, LB, EH, SO and PG researched the literature and conceived the study.
EH and FM were involved in the protocol development and gaining ethical approval.
LB, AB, EH, TK, JN, PS, MM, RB, MT, PP and FM were involved in patient recruitment, patient consenting, surveying patients and surveying surgeons.
LB, AB, EH, MM and FM were involved in data collection and analysis.
MG, EH and LB were involved in software development.
LB wrote the first draft of the manuscript.
All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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