Case Report
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Easy and Low-cost Three-dimensional renal immersive visualization from contrast-enhanced CT

Abstract

Background: The widespread use of CT imaging has increased the detection of incidental renal masses. Partial nephrectomy is technically demanding, particularly in anatomically complex tumors, where spatial understanding is essential. Three-dimensional (3D) reconstruction and immersive visualization may support anatomical interpretation, but commercial platforms can be expensive.

Objective: To describe a low-cost workflow for renal 3D reconstruction from contrast-enhanced CT scans and immersive visualization using an affordable virtual reality (VR) headset, and to report its preliminary clinical application.

Methods: This initial technical report describes a preliminary experience in three consecutive patients undergoing partial nephrectomy for localized renal cancer, without a comparator group. Contrast-enhanced CT scans were segmented using 3D Slicer®, and the models were viewed with an Oculus Quest 2® headset. Three urologists reviewed the models preoperatively and, after surgery, assessed subjective perceived spatial understanding, intraoperative orientation and usefulness for surgical planning through an ad hoc questionnaire.

Results: Models depicting renal anatomy and tumor location were generated for all three cases; objective geometric accuracy was not assessed. Median operative time was 100 minutes, median estimated blood loss was 90 mL, and hospital stay ranged from 1 to 2 days. Two of the three urologists (2/3) reported improved depth perception and spatial understanding compared with conventional CT, and perceived that the model allowed personal better orientation during surgery and considered it helpful for surgical planning; the third surgeon preferred conventional CT. No specific changes to the operative strategy attributable to the models were documented.

Conclusions: Open-source segmentation software and a consumer VR headset permitted immersive visualization of renal 3D models in this initial technical report, and two of three urologists perceived better intraoperative orientation. Larger comparative studies with objective anatomical validation are needed to evaluate effects on surgical planning and outcomes.

Keywords: three-dimensional imaging virtual reality, renal tumors, partial nephrectomy, computed tomography, surgical planning

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Introduction

Renal cancer is the fourteenth most common malignancy worldwide and the sixteenth leading cause of cancer-related mortality, which makes it the most lethal of the common urological cancers.[1] Most cases are sporadic, with only 4–6% linked to hereditary syndromes.

The clear cell subtype is the most common histological variant of renal cell carcinoma. The widespread use of cross-sectional imaging has led to a high frequency of incidental renal findings. In large cohorts of patients undergoing abdominal CT scans, renal incidentalomas have been detected in up to 37% of cases, a proportion of which are clinically relevant masses needing follow-up evaluation.[2] Additionally, studies using CT colonography have reported incidental renal lesions in approximately 14% of asymptomatic individuals, and a significant proportion of small renal masses are identified incidentally in routine imaging.[3]

The gold standard treatment for localized small renal masses, as well as for patients with a solitary kidney or an elevated risk of recurrence, is nephron-sparing surgery, typically performed as a laparoscopic partial nephrectomy when anatomically feasible.[1] Although partial laparoscopic nephrectomy provides optimal functional preservation, the procedure is technically more demanding than radical nephrectomy and has been associated with a higher rate of perioperative complications such as bleeding, urine leak, and conversion to open or radical nephrectomy.[4]

Three-dimensional (3D) medical visualization has become increasingly relevant in surgical specialties, particularly for procedures with complex anatomical regions such as the kidney.[5] In this context, medical image segmentation plays a critical role in accurate diagnosis and treatment planning, enabling precise analysis for a wide range of clinical tasks. Traditional cross-sectional CT interpretation can hinder the spatial understanding of a tumor location and its relationship to surrounding blood vessels. However, advances in open-source imaging software now enable clinicians to reconstruct patient-specific 3D models from standard DICOM data sets at no additional cost.

Virtual reality (VR) devices, such as the Oculus Quest 2®, although originally designed for gaming, offer an inexpensive and widely available platform for creating an immersive environment to interact with anatomical reconstructions. This technology may support surgical planning and communication with patients or trainees,[6] which

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is why VR is extensively used in undergraduate medical education, especially in anatomy.

Despite their potential, commercial platforms for three-dimensional reconstruction and immersive visualization are expensive, which may limit their routine use in many centers. This initial technical report describes a preliminary, low-cost experience with a workflow for generating and viewing three-dimensional renal models derived from contrast-enhanced CT data. In particular, we describe its feasibility and surgeons perceptions, including orientation during the surgical procedure; objective model accuracy and changes in clinical decision-making were not measured.

Study design and ethical considerations

This is an initial technical report describing a preliminary experience in three consecutive patients scheduled for partial nephrectomy for stage I renal cell carcinoma. There was no comparator group, baseline assessment of spatial perception, or formal accuracy validation. The study was conducted in accordance with the Declaration of Helsinki. The protocol was reviewed and approved by the Ethics Committee of Universidad Anáhuac Puebla, with special emphasis on the blinding and anonymization of all patient information to prevent any possible identification. Written informed consent was obtained from all patients for the anonymized 3D rendering of their anatomy and its hosting on a third-party platform for surgical planning.

Workflow description: Contrast-enhanced CT datasets included arterial, venous, and excretory phases. The arterial phase was selected to facilitate identification of renal parenchyma, vascular anatomy and tumor margins. Image processing was performed using 3D Slicer® (version 5.6.2; The Slicer Community, USA), an open-source medical imaging platform built on VTK and ITK libraries.[7] The four steps of the workflow were as follows:

Volume rendering: the selected phase was imported into 3d slicer®, and the volume rendering module was used to visualize the dataset and confirm correct orientation and contrast quality.

Segmentation: The Segment Editor module was employed to isolate the renal structures. A new segment ("Kidneys") was created, and a threshold between +20 HU and +300 HU was applied to include the renal parenchyma and tumor, while excluding fat and air. Manual refinement using Scissors and Paint tools was used to remove the surrounding abdominal tissues and background noise. A separate segment ("Tumor") was manually delineated to highlight it. Using the "Grow from Seeds" tool, two separate layers were created. The first layer was named tumor, and several "seeds" were painted in the 2D CT Scan panel to teach the algorithm the desired area of interest. Finally, another layer named "Background" was created to teach the algorithm the surrounding area. Segmenting was then refined using the "Smoothing" tool (Figure 1).

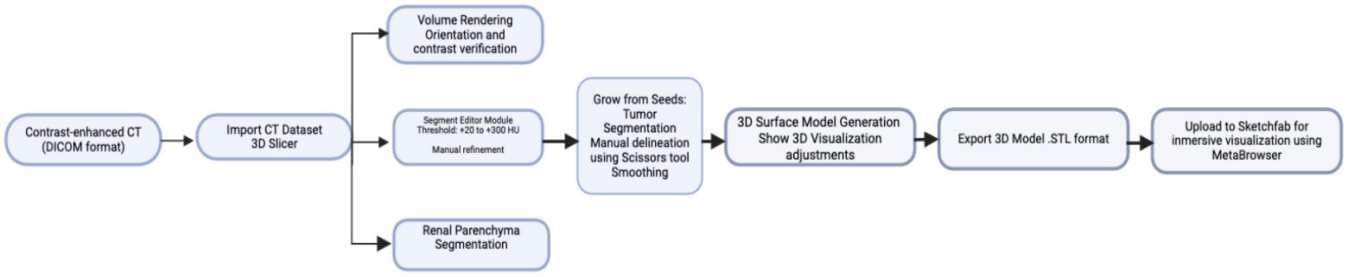


Figure 1 Workflow for three-dimensional renal tumor reconstruction and immersive visualization. Contrast-enhanced CT images were imported into 3D Slicer for volume rendering and segmentation of renal parenchyma and tumor. Segmented structures were converted into 3D surface models and exported in STL format for immersive visualization using an Oculus Quest 2 headset via Sketchfab.

3D Model Generation: The processed segments were rendered into a 3D surface model using the Show 3D function. Additional visualization parameters (smoothing, opacity, and lighting) were adjusted to enhance anatomical detail.

Export and visualization in virtual reality: The final model was exported in .STL format and uploaded to Sketchfab® (Sketchfab Inc., New York, USA), a third-party platform for displaying interactive 3D models. Visualization was achieved using the Oculus Quest 2® headset through the Sketchfab webpage in the Meta Browser, enabling immersive exploration of renal anatomy and tumor relationships (Figure 2).

Patient data protection and model access: The models originated from clinical CT data. In accordance with the protocol approved by the Ethics Committee, all patient information was blinded and anonymized before processing to prevent any possible identification. Only de-identified surface models in .STL format, which contain geometric data only and no DICOM headers or patient metadata, were exported and uploaded to Sketchfab® under non-identifying file names. The models were set to private visibility on Sketchfab® and were accessible only to the authors (Figure 3).

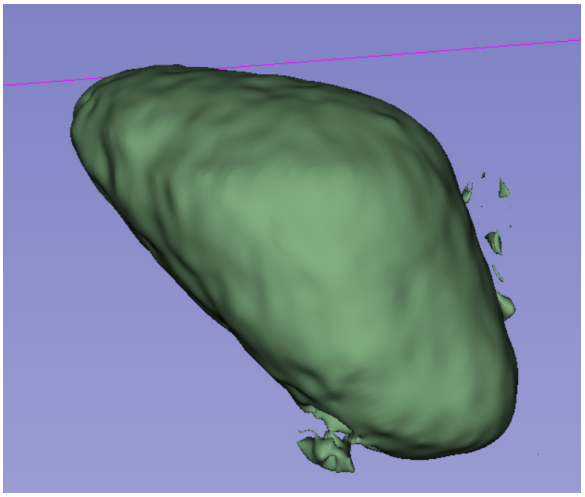


Figure 2 Contrast enhanced CT-Scan from a patient presenting with a solid mass on lower pole of the right Kidney.

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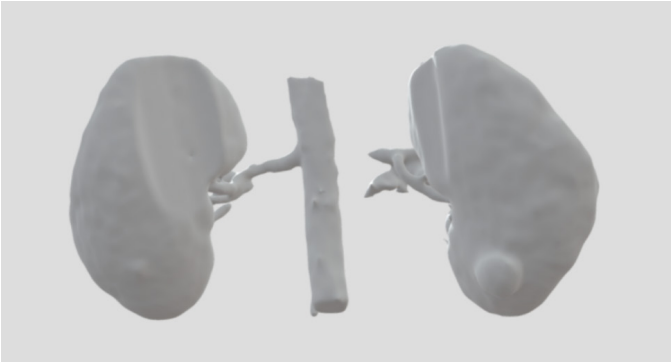


Figure 3 Finished segmentation of CT-Scan. An exophytic mass can be seen on the lower pole of the right kidney.

Prior to surgery, three urologists experienced in laparoscopy reviewed the 3D models. After the procedures, they completed an ad hoc questionnaire addressing overall satisfaction, perceived depth perception and spatial understanding, orientation during the surgical procedure, and perceived usefulness for surgical planning. The questionnaire was not validated. No paired baseline questionnaire, objective geometric concordance assessment, or standardized documentation of operative-plan changes was available for analysis; therefore, the responses were summarized descriptively (Figure 4).

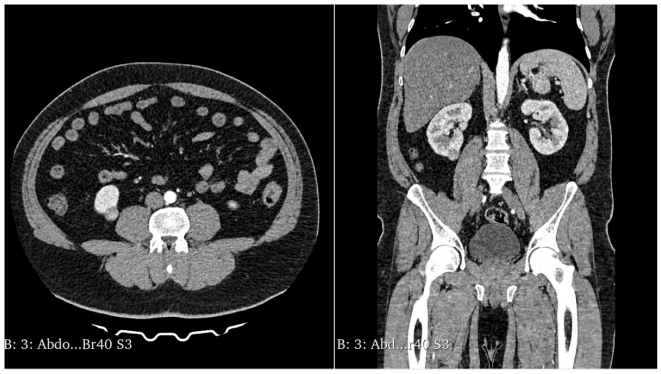


Figure 4 .STL file visualization using Sketchfab, the file can be easily accessed on MetaQuest headset for a 3D immersive visualization.

Clinical results

Three patients underwent partial nephrectomy. Median operative time was 100 minutes (range 75–140), and median estimated blood loss was 90 mL (range 70–250). No vascular clamping was performed in any case. Hospital stay was 1 day in two patients and 2 days in one patient because of postoperative pain management. Pathology reported clear cell renal cell carcinoma in all cases, with Fuhrman grade I in one patient and grade II in two, according to Table 1. Negative surgical margins were achieved in two patients, and one case showed focal margin contact; all three were staged pT1a (Table 1).

Table 1 Summary of patient characteristics.

Characteristic	Case 1	Case 2	Case 3
Sex	Male	Female	Male
Age (years)	40	57	51
Tumor location	Lower pole	Lower pole	Posterior lateral
Operative time (min)	100	75	140
Estimated blood loss (mL)	90	70	250
Vascular control	None	None	None
Hospital stay (days)	1	1	2
Pathology	Clear cell RCC, Grade I	Clear cell RCC, Grade II	Clear cell RCC, Grade II
Tumor size (mm)	21 × 16	20 × 15	25 × 12
Margin status	Negative	Negative	Focal contact
Stage	pT1a	pT1a	pT1a

Technical and visualization outcomes: The workflow generated a blinded patient-specific three-dimensional rendering of renal structures and the associated tumor from the arterial phase of CT imaging. Threshold-based segmentation and manual refinement provided a visually interpretable representation of parenchyma, lesion location and surrounding anatomy. Model appearance depended on the resolution and contrast of the original CT scan. Differentiation among cortex, medulla and tumor was variable. No quantitative validation against source images or intraoperative anatomical measurements was performed. Resection depth was not measured intraoperatively; measurements were obtained only from the surgical specimen after its extraction at the end of the procedure.

The 3D Slicer rendering appeared smooth on visual inspection, and the exported. STL model could be viewed interactively on Sketchfab®; geometric fidelity after export was not assessed objectively. Through the Oculus Quest 2® headset, users could rotate, scale and inspect the models and the tumor–vessel relationships. Two of the three participating urologists (2/3) reported improved depth perception and understanding of spatial relationships compared with conventional CT images, and perceived that the model could allow a better orientation during the surgical procedure to identify the solid mass to be resected, which they considered helpful for surgical planning; the third expressed a preference for traditional two-dimensional CT images, that could be because he is not used to 3-D glasses. These are subjective assessments; no case-specific modification of the operative strategy was documented, and an improved clinical outcome cannot be confirmed.

Discussion

Several commercial platforms for three-dimensional reconstruction are available; however, their cost may limit implementation. In this context, segmentation using open-source software and consumer VR hardware may offer a technically accessible option for preoperative anatomical review. Whether this workflow improves patient understanding, surgical decisions or outcomes was not assessed in this series.

Previous studies have reported an influence of 3D reconstructions on preoperative decision-making in partial nephrectomy, particularly for more complex tumors. Reported applications include better appreciation of tumor–vascular and tumor–collecting system relationships and potential support for selecting surgical strategies.[8] A randomized clinical trial also evaluated patient-specific VR models as an adjunct to conventional preoperative imaging in robotic partial nephrectomy.[9] Those results provide external context but cannot be confirmed from our uncontrolled three-case experience.

In our limited experience, two of three urologists reported improved perception of tumor location and surrounding anatomy after viewing the immersive models and perceived better orientation during the surgical procedure to identify the solid mass to be removed, which they considered helpful for surgical planning. However, no case-specific change in resection strategy, vascular clamping, or intraoperative

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imaging attributable to the models was documented, and resection depth was not objectively measured intraoperatively; therefore, these perceptions should not be interpreted as a demonstrated change in the surgical plan or as improved operative outcomes. Given the small sample size and the initial nature of this technical report, we consider that this model might help in certain procedures and for certain surgeons to improve surgical planning and, eventually, the surgical procedure itself. A future study is planned to evaluate measurable intraoperative landmarks and compare them with the 3D model, in order to obtain an objective measure of its anatomical concordance, as well as artificial intelligence could be used to help the process be easier and more accurate.

Study limitations

An important limitation of this initial technical report is the small sample size (three patients and three surgeon assessments), the absence of a comparator group without 3D images or planning, and the lack of objective validation and measurements. Surgeon feedback was subjective and obtained with a nonvalidated instrument, and no baseline questionnaire, independent comparison with operative anatomy, formal recording of changed surgical plans, or assessment of reproducibility across operators was performed. These limitations are emphasized by the unfavorable perception of one participant, who preferred conventional 2D CT; we consider that this might be because this participant was not accustomed to the use of 3D headsets and this technology. The limited sample size precludes claims of efficacy or safety.

Conclusion

This initial technical report suggests that open-source segmentation software combined with a consumer VR headset can produce useful renal 3D visualizations suitable for preoperative review. Two of three urologists perceived better spatial understanding and better orientation during the surgical procedure, while one preferred standard CT images. The study does not establish anatomical accuracy, changes in surgical decision-making or improvements in surgical outcomes. Further studies with standardized geometric validation, comparative assessments and larger samples are warranted, as well as artificial intelligence in order to optimize the image obtained.

Acknowledgements

None.

Ethics approval and consent

The protocol was reviewed and approved by the Ethics Committee of Universidad Anáhuac Puebla, with special emphasis on the blinding and anonymization of all patient information. A written informed consent was obtained from all patients. Data privacy: all patient information was anonymized before processing, and only de-identified. STL models without patient metadata were uploaded to Sketchfab®.

Conflicts of interest

The authors declare no conflicts of interest; they did not receive any grants or support from the medical industry.

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