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3D printed and virtual kidney models as learning tools to improve anatomical and spatial understanding of renal tumors: a pilot educational study (Rein-3D print students – UroCCR 219)

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Abstract

Background Radiological training is often underrepresented in medical education, despite its essential role in clinical practice. Innovations like 3D printing offer detailed anatomical models that enhance understanding. In kidney cancer management, imaging and tumor complexity scores are crucial. This study evaluated whether three-dimensional (3D) kidney models could improve medical students' anatomical and spatial understanding of renal tumors, as assessed through CT-based complexity scoring.

Methods Three kidney tumor cases of varying complexity were selected. CT scans were segmented using Synapse 3D® to create models printed with high-resolution, multi-material technology (Stratasys J750®). Twenty-three fifth-year medical students were randomized into three groups: CT-only, CT + 3D virtual model (3DV), and CT + 3D-printed model (3DP). Each group interpreted the same anonymized CT scans and completed questionnaires assessing complexity scores and anatomical understanding. Accuracy and time efficiency were compared across groups.

Results The 3DV and 3DP groups showed significantly greater accuracy in completing complexity scores (91% [IQR 82–91] and 91% [IQR 73–100]) than the CT-only group (73% [IQR 64–82], $p < 0.05$), reflecting improved spatial understanding of renal anatomy. Total scores and satisfaction were higher in 3D groups, with students endorsing the educational value of both model types. Time to completion was shorter in 3D groups (3DV: 9.4 min ± 4.7; 3DP: 7.1 min ± 3.5) versus CT-only (11 min ± 5.3, $p < 0.05$). Total scores and satisfaction were higher in 3D groups, with students endorsing the educational value of both model types.

Conclusion 3D-printed and virtual kidney models improved students' spatial understanding and task performance in renal tumor complexity assessment, reflecting enhanced anatomical comprehension rather than pure CT

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interpretation skills. Virtual models, offering similar educational benefits at lower cost, may be especially valuable for integration into medical curricula.

Practitioner points

- 3D models significantly improve students' ability to interpret renal CT scans.
- 3D virtual and printed models yield similar educational outcomes.
- These tools can be easily integrated into multidisciplinary medical curricula.

Keywords 3D printing, Medical education, Kidney cancer, CT scan interpretation, Anatomical models, Student proficiency

Introduction

The integration of radiological training within the medical curriculum has traditionally been limited, despite the increasing centrality of imaging in modern clinical practice [1]. As Michalski and Ross illustrate, the advent of 3D printing is poised to significantly impact numerous aspects of medicine, including education, by offering precise and tangible anatomical models [2]. Recent advancements in educational technology have introduced physical 3D-printed models as viable alternatives to cadaveric materials, significantly enhancing anatomical education [3–8]. This evolution is supported by the growing body of literature exploring three-dimensional printing and its applications within medical imaging [9].

In the field of urogenital radiology, precise imaging plays a critical role in the characterization of renal masses and the formulation of treatment strategies for kidney cancer. Tumor complexity scores, such as the R.E.N.A.L. nephrometry score [10] and PADUA classification [11], have become useful indicators in the preoperative planning of nephron-sparing surgeries, enabling clinicians to estimate surgical complexity, predict patient outcomes [12], and tailor treatment plans accordingly.

Three-dimensional (3D) printed kidney models, inclusive of tumors, have demonstrated substantial educational value in enhancing the anatomical understanding of trainees and practicing urologists in previous studies [13–15]. However, most of these works focused on surgical or postgraduate education. The present study specifically targeted medical students, aiming to assess whether such tools could also benefit pre-graduate learners in developing spatial understanding of renal anatomy and tumor complexity. These models provide a tangible, spatially accurate representation of complex renal structures, aiding in the visualization and understanding of anatomical relations and pathological conditions. Furthermore, personalized 3D kidney models have proven beneficial not only for education but also for practical clinical applications, such as preoperative planning and patient counseling [16–18]. The rapid evolution of technologies like 3D printing and augmented reality is further enhancing kidney surgery planning, offering improved visualization and interactivity [19, 20].

Building on these advancements, our study aims to evaluate the educational impact of 3D-printed kidney models on medical students' anatomical and spatial understanding of renal tumors, assessed through their ability to perform CT-based complexity scoring. Through a systematic assessment, we seek to determine whether these models can improve students' diagnostic accuracy, efficiency, and confidence in reading renal CT scans, thereby bridging the gap between theoretical learning and practical clinical application.

Materials and methods

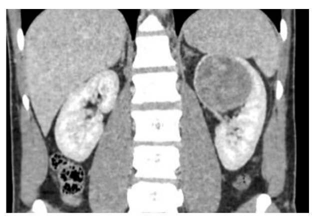
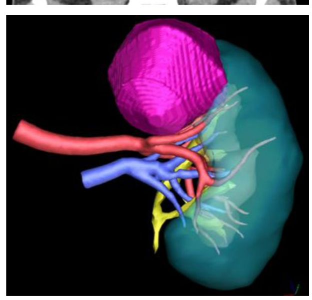
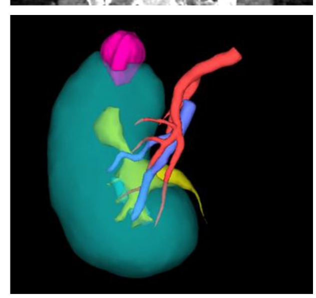
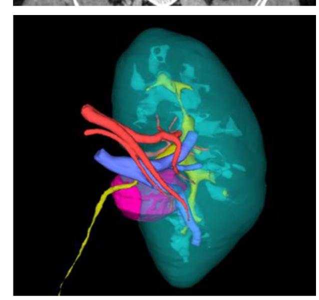
Production of educational tools

We selected three distinct kidney tumor cases from patients who underwent robotic partial nephrectomy in our urology department to demonstrate a range of anatomical and tumor complexities (Table 1). These three cases were intentionally selected to represent low-, intermediate-, and high-complexity renal tumors. This exploratory pilot design ensured feasibility and methodological standardization before expanding to a larger sample. All patients were enrolled in the prospectively maintained French Research Network on Kidney Cancer Database, UroCCR (CNIL DR 2013 – 206; NCT03293563), after providing informed consent.

The CT scans of these cases were anonymized and chosen to represent varying anatomical complexities and tumor complexity scores. Using the Synapse 3D® software (FUJIFILM®) with the kidney analysis® application, the CT scans were segmented by a urologist to create detailed 3D models encompassing the tumor, healthy renal cortex, arterial and venous vasculature, and the urinary system (Table 1). These models were cross-verified against the original CT scans and refined for anatomical accuracy by a senior urologist and a senior radiologist.

The segmented 3D models were exported as *.STL files and processed for 3D printing. The models were printed using the J750® 3D printer (Stratasys), chosen for its high-resolution, multi-material printing capability (photopolymer material jetting technology [21]). Translucent resin was utilized for the renal cortex to provide visibility of hilar structures (Fig. 1). The accuracy of the 3D-printed

Table 1 Detailed characteristics of patients and tumors in the selected cases

	Patient 1	**Patient 2**	**Patient 3**
Age (years)	40	37	44
Sex	Male	Female	Male
Side of the affected kidney	Left	Right	Left
Tumor diameter (cm)	6	2.2	3.8
Tumor localization	Upper pole Posterior Internal rim	Upper pole Anterior External rim	Equatorial Posterior Internal rim
Hilar	Yes	No	Yes
Sinusal contact	Yes	No	Yes
Contact with urinary tract	Yes	No (> 7 mm)	Yes
Exophytic / Endophytic	> 50% endophytic	Mainly exophytic	> 50% endophytic
RENAL score	10ph	4a	9ph
PADUA score	11p	6a	10p
Complexity	High	Low	Medium
Particularity	-	-	3 renal arteries
CT scan			
Virtual 3D models of the kidney (Synapse 3D® software - FUJIFILM®)			

models was revalidated against the original CT scans by two urologists and a senior radiologist.

Development of questionnaires

Questionnaires were created for each case, incorporating items from the PADUA and RENAL complexity scores. Additionally, two urologists and a radiologist developed six supplementary questions per case, focusing on anatomical specifics with clinical implications relevant to trainees' understanding of kidney and tumor radiological anatomy. Each correctly answered item from the complexity score and the supplementary questions was awarded one point, resulting in a potential total of 17 points per case, across three cases.

Study population

The study involved fifth-year medical students undergoing a two-month clinical rotation in our urology department. All participants had previous exposure to CT-scan visualization and interpretation through their precedent clinical rotations.

Study protocol

Medical students from three different rotation periods were invited to participate. Following a lecture on renal tumors, radiological descriptions, and surgical implications, students were randomized into three groups: 7 were assigned to the "CT-only" (CT) group, 9 to the "3D virtual model" (3DV) group, and 7 to the "3D printed model" (3DP) group. This slight difference in group size resulted from voluntary participation across three consecutive student rotations. Non-parametric statistical tests (Mann-Whitney) were used to account for these small and unequal sample sizes, as detailed in the Statistical Analysis section.

Each group interpreted the same anonymized CT scans of the selected kidney tumor cases.

Initially, participants completed a baseline questionnaire assessing their medical, radiological, and urological experience (Supplementary Material 1). For each case, students filled out a dedicated questionnaire while being timed for each section (RENAL score and anatomical questions) (Supplementary Material 2).

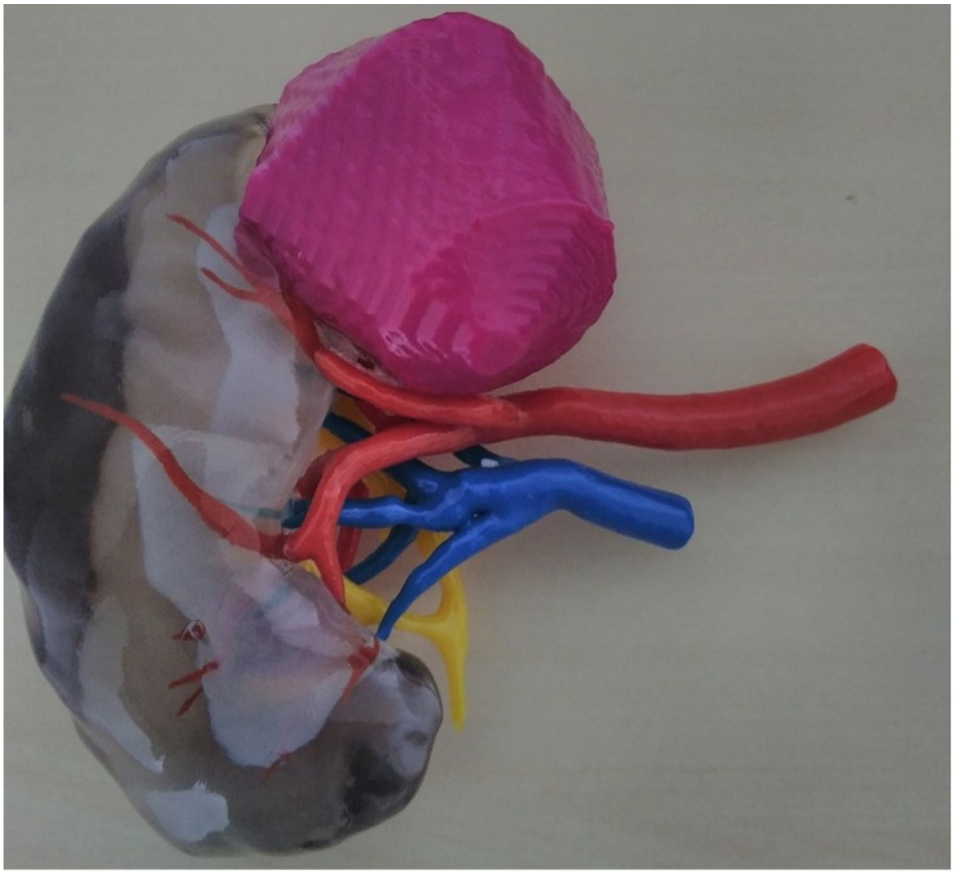


Fig. 1 Printed 3D model of the kidney with tumor, arterial and venous vasculature, and urinary system (using the J750® 3D printer - Stratasys)

All students used the same standardized computer and CT scan viewer. The 3D virtual model group had access to a segmented 3D model on the same computer, which they could manipulate while viewing the CT scan. The 3D-printed model group had physical models they could handle during the interpretation process.

Following the exercise, a comprehensive feedback session was conducted where students reviewed the correct complexity scores and anatomical answers. This session included demonstrations on CT scan analysis and utilization of both virtual and physical 3D models as learning aids. All participants, including those in the CT-only group, participated in this session.

Finally, students completed an anonymized satisfaction questionnaire evaluating their perception and satisfaction with the 3D-printed models as educational tools for understanding kidney malignancies and their effectiveness in radiology teaching (Supplementary Material 3).

Statistical analysis

All statistical analyses were performed using Prism® (version 8.0, GraphPad®, San Diego, CA). Given the small sample size and unequal group distribution, non-parametric tests (Mann-Whitney) were used for all comparisons. Accuracy scores from the questionnaires were compared across groups, and time-to-completion for each case-related questionnaire was analyzed similarly.

Results

A total of 69 CT scan lecture sessions were performed by 23 fifth-year medical students enrolled in this study. The students were randomized into three groups: 7 were assigned to the "CT-only" (CT) group, 9 to the "3D virtual model" (3DV) group, and 7 to the "3D printed model" (3DP) group. Each student individually completed three questionnaires corresponding to the three selected clinical cases and their respective CT scans, 3D virtual models, and 3D printed models. Additionally, all 23 students completed satisfaction and course evaluation questionnaires, as well as the personal experience questionnaire.

All participants were in their fifth year of medical studies and there were no statistically significant differences in the personal experience or self-assessment of CT-scan interpretation abilities between the groups (Table 2).

A total of 69 case questionnaires were available for analysis (Fig. 2). The median accuracy of the complexity

Table 2 Students' characteristics – results from the « personal experience » questionnaire

	CT *N* = 7	3DV *N* = 9	3DP *N* = 7	*p* value
Year of medical studies, mean (SD)	5 (0)	5 (0)	5 (0)	NS
Number of OR days attended, median [IQR]	6 [4;10]	7 [5;9]	8 [6;9.5]	NS
Have attended a partial nephrectomy, n (%)	5 (71.4)	7 (77.8)	5 (71.4)	NS
Have seen a real human kidney during a surgery, n (%)	6 (85.7)	9 (100)	7 (100)	NS
Number of renal complexity scores already completed, median [IQR]	0 [0;0]	0 [0;0]	0 [0;0]	NS
Approx. number of CT-scans visualized, median [IQR]	50 [35;90]	50 [20;80]	50 [30;95]	NS
Self-assessment of ability: (1–10), median [IQR]				
To interpret an arterial phase CT-scan	6 [5;6.5]	5 [5;7]	4 [3;5]	NS
To interpret a urinary phase CT-scan	6 [5.5;6]	5 [4;6]	5 [4.5;5.5]	NS
To characterize a kidney tumor on a CT-scan	5 [4;6]	6 [4;7]	4 [3;4.5]	NS

CT: Computed Tomography only group, 3DV: 3D virtual model group, 3DP: 3D printed model group, OR: Operating room, NS: Not Significant

score was 91% [IQR 82; 91] in the 3DV group, and 91% [IQR 73; 100] in the 3DP group, compared to 73% [IQR 64; 82] in the CT-only group. The accuracy of complexity score completion was significantly higher in both the 3DP and 3DV groups compared to the CT group ($p < 0.05$). No statistically significant difference was found between the 3DV and 3DP groups.

The mean time for completing the complexity scores was longer in the CT-only group (11 min ± 5.3) compared to the 3DV group (9.4 min ± 4.7) and the 3DP group (7.1 min ± 3.5). Time for complexity score completion was significantly shorter in both 3D groups compared to the CT group, but there was no significant time difference between the 3DV and 3DP groups.

The mean total scores (complexity questionnaires + anatomical questions) were 62% (± 13) in the CT-only group, 81% (± 12) in the 3DV group, and 83% (± 14) in the 3DP group. Scores were significantly higher in both the 3DP and 3DV groups compared to the CT group ($p < 0.05$), with no statistically significant difference between the 3DV and 3DP groups.

When comparing additional questions separately from the complexity score completion regarding score results and time for completion between groups, the same statistical significance was observed.

The median satisfaction with the 3D printed model as a radiology education tool was 80% [IQR 70; 87.5] (Fig. 3). Perceived benefits for understanding anatomy were rated at 100% [IQR 92.5; 100], and for aiding further CT readings, the median rating was 80% [IQR 70; 90]. Students suggested that 3D model teaching tools should be developed for other organs and disciplines, with a rating of 90% [IQR 82.5; 100]. The application of these models for nephron-sparing surgery assessment received an appraisal of 85% [IQR 80; 97.5], with a median rating of 90% [IQR 90; 100] for improving understanding of the tumor/kidney relationship. Ultimately, the usefulness of the 3D printed model as a teaching tool was rated at a median of 90% [IQR 90; 100] by the students.

Discussion

Our study demonstrates that 3D printed models can effectively be used to train medical students in understanding CT-based renal anatomy and performing tumor complexity scoring tasks. Additionally, 3D virtual models also proved to be beneficial, indicating that both modalities enhance educational outcomes. These improvements relate to enhanced spatial understanding and task performance rather than acquisition of formal radiological interpretation skills.

Knoedler et al. [13] previously highlighted the educational value of 3D-printed kidney models in helping trainees understand kidney anatomy and tumor complexity scores. Our study extends these findings by not only using 3D models for nephrometry score completion but also integrating them into the process of CT scan interpretation. Similar benefits have been reported in other fields, with randomized or prospective studies confirming the pedagogical impact of 3D-printed models for anatomy learning [4] and for urology residents [22]. This approach aids students in actively searching for answers within the scans, thereby bridging the gap between static anatomical knowledge and dynamic radiological skills. Unlike Knoedler's study, which focused on anatomical understanding for partial nephrectomy, our research addresses a broader educational scope, enhancing CT scan interpretation skills that are universally applicable across medical disciplines.

Given that medical students in their clinical rotations may choose to specialize in different fields, the ability to accurately interpret cross-sectional imaging remains a critical skill for their future practice. Satisfaction survey results suggest that the experience gained using 3D models for kidney tumors can improve students' proficiency in interpreting CT scans beyond urological applications.

Our study provides both qualitative and quantitative evidence supporting the use of 3D-printed models to train medical students, filling a crucial gap in the current literature. Previous research has endorsed the utility of 3D-printed kidney models for surgical planning and anatomical understanding prior to partial nephrectomy, often based on expert opinion surveys [14, 23].

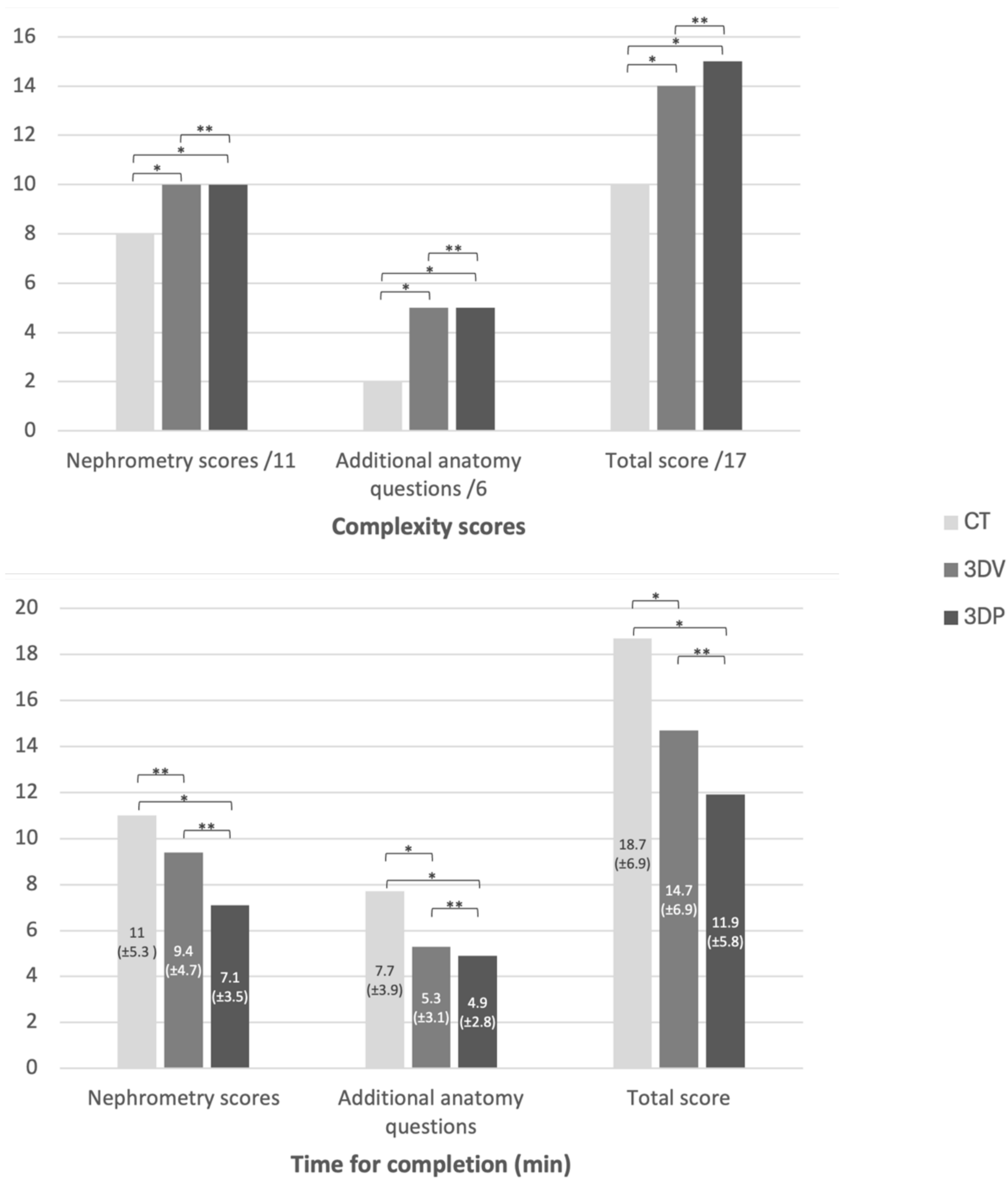


Fig. 2 Results of complexity scores, additional question accuracy, and time to completion for each case

Interestingly, our findings revealed no significant difference in educational outcomes between using 3D-printed and 3D virtual models, in agreement with Moro et al. [7], who demonstrated the effectiveness of virtual reality and augmented reality in medical anatomy education. This result indicates that both 3D-printed and virtual models were equally effective in enhancing students' spatial understanding. For younger, technology-savvy learners, virtual models may therefore provide similar educational benefits at lower cost. This observation aligns with current trends in digital and simulation-based learning, where interactive virtual environments are increasingly integrated into medical education. However, this contrasts with Wake et al.'s findings [24], which indicated that 3D-printed models were more beneficial for patient education compared to virtual ones. This discrepancy could be attributed to generational differences; today's medical students are more adept with technology, including 3D visualization tools, virtual reality or augmented reality, than older patient populations. Thus, for educating technologically adept students, 3D virtual models, being both cost-effective and readily accessible, might be just as advantageous as physical 3D-printed models. Given that virtual models are virtually free to disseminate compared to the $150-$500 cost of 3D-printed models

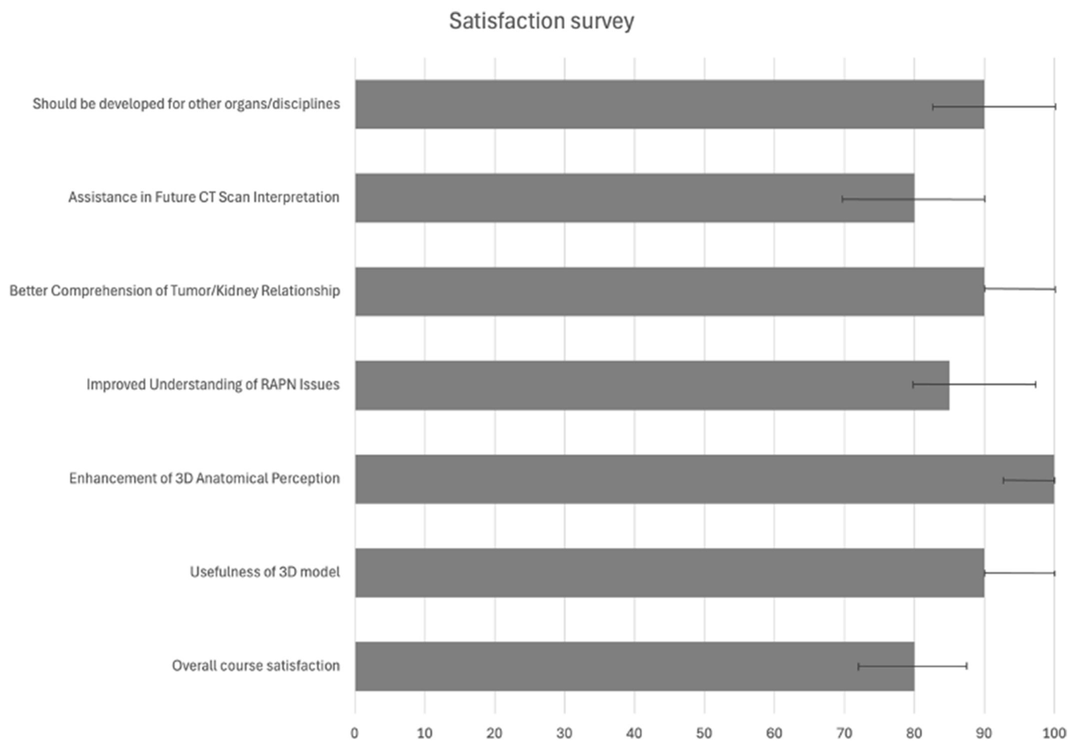


Fig. 3 Satisfaction survey scores evaluating the use of 3D models as educational tools for enhancing radiological anatomy understanding of kidney tumors

[8], their broader adoption in medical education is highly warranted.

Our study parallels the findings of Bernhard et al. [17], who also observed that 3D-printed models significantly enhanced patients' understanding of anatomical relationships and complex structures. This improvement was reflected in their greater overall satisfaction. Moreover, Lee et al. [16] corroborate the practical benefits of personalized 3D kidney models in clinical settings, such as preoperative planning and patient education. Integrating similar models into medical training not only enhances educational outcomes but also aligns with their proven clinical applications, providing a comprehensive skill set for future healthcare professionals. Recent studies, such as those by Yamazaki et al. [22], further validate the educational significance of these models, emphasizing their importance in resident education and training.

The beneficial use of 3D-printed models for educational purposes has been well documented in other disciplines. Ra et al. demonstrated the feasibility and effectiveness of 3D hepatic models for surgical resident education [5], while McMenamin et al. highlighted the cost-effectiveness and ease of use of 3D printed anatomical teaching resources over plastinated specimens [3]. Lim et al.'s randomized study is particularly noteworthy, showing significantly better educational outcomes using 3D printed materials compared to traditional cadaveric resources for teaching external cardiac anatomy [4].

A critical aspect of using 3D printed materials in education is ensuring the anatomical accuracy of the models. This quality control is emphasized in the existing literature and was rigorously maintained in our workflow, as detailed in our previous publication on methodological accuracy [25].

The landscape of medical education is continually evolving, with 3D-printed models playing a crucial role in this transformation. Our findings indicate that medical students significantly benefit from using these models for visualizing and interpreting CT scans of kidney tumors. This methodology should be extended to other organs and medical disciplines to enhance the quality of educational courses. Future research should include randomized controlled trials across various disciplines utilizing different 3D printed models to validate and expand upon our findings.

This study has several limitations. First, it was designed as an exploratory pilot study including only three selected cases representing different levels of tumor complexity, which restricts the generalizability of our findings. The small number of participants and the unequal group sizes further limit statistical power. Moreover, the study did not assess pre- and post-intervention changes in CT interpretation, precluding conclusions about long-term learning. Future work should include a larger and more diverse case set to validate and expand these preliminary results.

Conclusion

This study demonstrates the educational value of both 3D-printed and 3D virtual kidney models for improving anatomical and spatial understanding of renal tumors among medical students. Our results indicate that these models significantly enhance medical students' ability to accurately interpret CT scans of kidney tumors and complete complexity scores with greater precision and efficiency compared to traditional methods. Notably, no significant difference was found between the educational outcomes of using 3D-printed versus 3D virtual models, suggesting that virtual models may serve as a cost-effective and accessible alternative.

The high levels of student satisfaction underscore the educational value of these tools in improving anatomical and radiological understanding. Given the central role of imaging in medical practice, these models are essential for developing critical interpretative skills that are applicable across various specialties. Future integration of 3D models into medical curricula should extend to other organs and disciplines. These models offer a valuable educational approach, bridging the gap between theoretical anatomy and imaging-based understanding, and helping future healthcare professionals develop stronger spatial reasoning skills.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s41205-026-00319-9.

Supplementary Material 1

Author contributions

GM, JCB and CM designed the study.GM supervised the data analysis, and wrote the manuscript.CM, JS, EJ, SR, FB, JCB, GR and FB contributed to data collection, figure preparation and manuscript editing.JCB provided critical revisions and senior oversight.All authors reviewed and approved the final version of the manuscript.

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Data availability

Requests for specific data will be considered by the UroCCR scientific committee following publication of the manuscript for researchers who provide a methodologically sound proposal.

Declarations

Ethical approval

UroCCR (NCT03293563) has received the approval of the Committee for the Protection of Individuals ("Comité de Protection des Personnes Sud-Ouest et Outre-mer III"; decision number DC 2012/108). The study was conducted in accordance with the principles of the Declaration of Helsinki and complied with applicable French regulatory requirements. It is IRB-approved and obtained the CNIL authorization number DR-2013-206. All patients and participants received oral and written information about the objectives and methodology of the project and written consent was obtained.

Competing interests

The authors declare no competing interests.

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