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Intelligent Software and Personalized 3D Planning for Nephron-Sparing Surgery in Pediatric Renal Tumors

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Abstract

Renal tumors account for approximately 6% of all childhood malignancies, with nephroblastoma (Wilms' tumor) being the most common subtype, predominantly affecting children aged 2 to 5 years. Less frequent entities include congenital mesoblastic nephroma, cystic nephromas, and renal cell carcinoma (RCC) in adolescents. While radical nephrectomy remains the standard treatment for unilateral Wilms' tumor, nephron-sparing surgery is preferred in selected cases such as bilateral disease, solitary kidneys, or genetic predisposition syndromes. Volume rendering and three-dimensional reconstruction are two examples of advanced imaging and modelling technologies that have become useful tools for enhancing preoperative planning and surgical accuracy. This study presents the clinical experience of three pediatric renal tumor cases managed with personalized 3D planning and intelligent software solutions: an infant with an NTRK-rearranged tumor, a 6-year-old child with nephroblastoma, and a 17-year-old adolescent with RCC. The methodology for 3D model generation, including MRI/CT segmentation and VR visualization, is described, along with the impact of these technologies on surgical outcomes. Comparative analysis with recent international literature over the past three years is provided. Key parameters such as resection margin status and functional outcomes are examined, alongside discussion of the approach's limitations, including small sample size and resource intensity. The findings support the potential of 3D technologies to enhance surgical planning and optimize nephron-sparing interventions in pediatric renal oncology.

Keywords: Nephroblastoma, Nephron-sparing surgery, 3D planning, Artificial intelligence, Pediatric oncology, Surgical simulation

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Introduction

Pediatric renal tumors account for approximately 5–7% of all childhood cancers (Somers *et al.,* 2025). Wilms' tumor (nephroblastoma) is the most common histologic type, representing 90–95% of primary renal neoplasms in children (Pastore *et al.*, 2006). Peak incidence occurs between 2 and 5 years of age, with a slight female predominance overall; bilateral tumors are twice as common in girls (Kotagal & Geller, 2019). Data from large population-based registries, such as the Surveillance, Epidemiology, and End Results (SEER) program, show that incidence rates vary across racial and ethnic groups - highest in African American populations and lowest in Asian cohorts (Treece, 2020). Recent analyses suggest that incidence among some subgroups (Black males, Hispanic males, and Asian females) may be rising, possibly reflecting improved healthcare access, genetic diversity, or epigenetic factors (Grover *et al.*, 2019).

The spectrum of pediatric renal tumors extends beyond nephroblastoma to include several rare entities with distinct clinical and molecular features **(Table 1)** (Jain *et al.*, 2021). Congenital mesoblastic nephroma typically presents in early infancy and has a favorable outcome after complete surgical resection (Simkhada *et al.*, 2023). Clear cell sarcoma of the kidney, malignant rhabdoid tumor of the kidney, and renal cell carcinoma

(RCC) occur less frequently and carry variable prognoses (Friesenbichler *et al.*, 2021). Pediatric RCC accounts for approximately 2–6% of childhood renal tumors and has distinct molecular subtypes, including MiT family translocation-associated RCCs, which are increasingly identified by advanced immunohistochemical and genomic profiling (Beek *et al.*, 2023). The recognition of NTRK-rearranged renal tumors (such as cellular mesoblastic nephroma with NTRK fusions) has expanded the diagnostic spectrum and opened new possibilities for targeted therapy with TRK inhibitors (Surrey & Davis, 2022).

Table 1. Spectrum of Pediatric Renal Tumors and Relative Frequency

Tumor Type	Approximate Frequency	Peak Age	Key Molecular Features
Wilms' tumor (nephroblastoma)	90-95 %	2-5 years	WT1, WT2, CTNNB1, AMER1
Congenital mesoblastic nephroma	3-5 %	<1 year	ETV6-NTRK3 fusion
Clear cell sarcoma of the kidney	2-4 %	1-4 years	BCOR internal tandem duplication
Malignant rhabdoid tumor of the kidney	1-2 %	<2 years	SMARCB1 inactivation
Renal cell carcinoma	2-6 %	Adolescence	MiT family translocations, ALK rearrangements
Other rare entities	<1 %	Variable	Variable

The management of pediatric renal tumors has changed substantially over recent decades through the work of international study groups (Romao *et al.*, 2024). Historically, unilateral Wilms' tumor was treated with radical nephrectomy followed by adjuvant chemotherapy (Artunduaga *et al.*, 2023). Current protocols use refined risk stratification and include histologic response to preoperative chemotherapy as a key prognostic factor (Vujanić *et al.*, 2018). Although nephrectomy remains standard for most unilateral cases, nephron-sparing surgery (NSS) is now preferred in selected scenarios: bilateral Wilms' tumor (about 5% of cases), tumors in a solitary kidney, and patients with genetic syndromes that predispose to metachronous contralateral disease (WAGR, Denys-Drash, and Beckwith-Wiedemann syndromes) (Malek *et al.*, 2020). The rationale for NSS in these children goes beyond immediate cancer control - it preserves long-term renal function and reduces the risk of end-stage renal disease, dialysis, or transplantation (Balis *et al.*, 2021).

Performing NSS in children requires careful preoperative assessment of tumor anatomy, especially the relationship between the tumor and segmental arteries, veins, and the pelvicalyceal system (Banerjee *et al.*, 2024). Standard cross-sectional imaging (CT and MRI) provides two-dimensional views that often miss the three-dimensional complexity of tumor-vessel interfaces, limiting the surgeon's ability to plan optimal margins and predict residual parenchymal volume (Ardicli *et al.*, 2025). In young children, these limitations are worse because patient motion, respiratory variation, and the need for sedation can compromise image quality (Amparore *et al.*, 2022).

To address this, advanced digital technologies are increasingly used for preoperative planning in complex pediatric oncology cases (Banerjee *et al.*, 2024). Three-dimensional reconstruction techniques (volume rendering, cinematic rendering) generate patient-specific anatomical models from DICOM data. Surgeons can interactively explore these models, simulate different resection strategies, and estimate the volume of parenchyma that would remain after surgery (Ardicli *et al.*, 2025). Augmented reality (AR) and virtual reality (VR) platforms immerse the surgical team in a virtual environment where holographic models can be examined before entering the operating room (Amparore *et al.*, 2022; Padma *et al.*, 2023; Temirbekova *et al.*, 2024). Physical 3D printing of patient-specific models has also been used for surgical planning and family education (Banerjee *et al.*, 2024).

At the same time, artificial intelligence (AI) and machine learning are being studied to improve diagnostic accuracy and workflow efficiency in renal tumor assessment (Distante *et al.*, 2023). Deep learning architectures (convolutional neural networks (CNNs) and transformer-based models) have achieved high accuracy in distinguishing renal tumor subtypes on multimodal CT and MRI datasets (Anush *et al.*, 2023). Radiomics (high-throughput extraction of quantitative imaging features) can predict histologic subtype, tumor grade, and molecular characteristics non-invasively, helping with preoperative risk stratification (Lomer *et al.*, 2025). When combined with 3D modeling, AI-based segmentation automates organ and tumor delineation, reduces inter-observer variability, and speeds up the path from image acquisition to a usable clinical model (Kim & Hong, 2022).

Despite growing evidence supporting these technologies, their use in pediatric renal oncology varies widely across institutions. Published experience with integrated 3D planning and AI-assisted workflows in diverse tumor types, including NTRK-rearranged neoplasms, Wilms' tumor, and adolescent RCC, remains limited (Valls-Esteve *et al.*, 2023). This study reports the experience of a specialized pediatric uro-oncology center with personalized 3D technologies in three patients who had renal tumors of different histologic origins (Perwitasari *et al.*, 2023; Sonbol *et al.*, 2023; Saputra *et al.*, 2024). We aim to show how combining three-dimensional visualization, virtual resection planning, and AI-assisted image analysis can improve surgical planning for nephron-sparing interventions in pediatric renal tumors and to put these findings into the context of recent international literature (Amparore *et al.*, 2022; Kim & Hong, 2022; Valls-Esteve *et al.*, 2023; Banerjee *et al.*, 2024; Ardicli *et al.*, 2025).

Materials and Methods

Study Design and Patient Population

This single-center retrospective study included three children with renal tumors who underwent preoperative 3D planning. All patients were admitted to the pediatric uro-oncology department between 2022 and 2024. The cohort consisted of: (1) an NTRK-rearranged tumor in a 10-month-old infant, (2) stage IV nephroblastoma (Wilms' tumor) in a 6-year-old child, and (3) renal cell carcinoma (RCC) in a 17-year-old adolescent (Babaei *et al.*, 2023; Kusumawardani *et al.*, 2023; Doddapanen *et al*., 2024; Joungtrakul & Smith, 2024; Shaji *et al*., 2024). The study followed the ethical standards of the institutional research committee and the principles of the Declaration of Helsinki. Written informed consent for anonymized clinical data and imaging was obtained from the patients' legal guardians (World Medical Association, 2002).

Imaging Acquisition

All patients underwent preoperative cross-sectional imaging of the kidneys. Depending on the clinical indication, either contrast-enhanced CT or MRI was used. For MRI, we added a non-contrast magnetic resonance angiography (MRA) sequence to better visualize the renal parenchymal vasculature (Zhang *et al.*, 2018). All images were acquired with standardized parameters to ensure sufficient spatial resolution for 3D reconstruction. Image data were stored in DICOM format.

Three-Dimensional Reconstruction and Segmentation

DICOM datasets were imported into MedVision AI (a medical imaging software platform) for volumetric analysis and 3D reconstruction. Semi-automated segmentation isolated the renal parenchyma, tumor, arteries, veins, and the pelvicalyceal system (van der Beek *et al.*, 2022). The workflow combined automatic thresholding with manual correction by an experienced radiologist to ensure precise tissue boundaries. This allowed layer-by-layer visualization and detailed examination of the tumor's relationship with adjacent critical structures.

The resulting 3D models were reviewed for anatomical accuracy by a multidisciplinary team (radiologist and pediatric urologic surgeon). Accuracy was verified by comparing the segmented boundaries with the original cross-sectional images. Discrepancies were resolved by consensus and, when needed, by refining the segmentation (Alansari *et al.*, 2025).

Clinical Application of 3D Models

We used the digital 3D models in several ways (García & Jaramillo, 2023; Maiti *et al.*, 2023; Shenoy *et al.*, 2023; Sindhu *et al.*, 2023; Chauhan & Angadi, 2024; Nkosi *et al.*, 2024; Weber *et al.*, 2024). First, they were loaded into the MedVision AI interactive viewer, where surgeons could manipulate, rotate, and virtually dissect the models to understand each patient's anatomy before surgery. Second, surgeons completed structured questionnaires (Likert scales and free-text comments) rating the models' usefulness for surgical planning, spatial orientation, and predicting intraoperative challenges (Bernhard *et al.*, 2016). Third, in selected cases, we performed virtual resection on the 3D models to simulate different surgical approaches and estimate residual parenchymal volume (RPV) after tumor excision. Virtual RPV was calculated as a percentage of total parenchymal volume and later compared with actual postoperative measurements (Khondker *et al.*, 2023).

Surgical Interventions and Perioperative Management

All procedures were aimed at nephron preservation when technically feasible and oncologically safe. Two patients underwent partial nephrectomy (tumor resection with parenchymal suturing); one patient with RCC required radical nephrectomy because of technical complexity that precluded safe partial resection. Surgical approach (open or laparoscopic) was chosen based on tumor characteristics, patient anatomy, and surgeon preference (Pisano *et al*., 2023; Shaheen *et al.*, 2023; Hima *et al.*, 2024).

All patients received standard adjuvant therapy according to established pediatric oncology protocols, including chemotherapy and, when indicated, radiation therapy, based on risk stratification and histopathology (World Medical Association, 2002).

Outcome Assessment

We evaluated two primary outcomes: (1) radicality of resection (negative surgical margins, defined as no tumor cells at the margin), and (2) preservation of renal function, assessed by serial postoperative imaging and, when applicable, differential radionuclide renal perfusion studies. For the RCC patient, effective renal clearance was measured at baseline and at one-year follow-up (van der Beek *et al.*, 2023).

Because this was a small case series, we did not perform a formal statistical analysis. Instead, we used descriptive analysis and qualitatively compared our findings with previously published studies to contextualize the results.

Data Availability

The datasets generated and analyzed in this study are not publicly available because of patient privacy and institutional data protection policies. They can be obtained from the corresponding author on reasonable request and with appropriate institutional approvals.

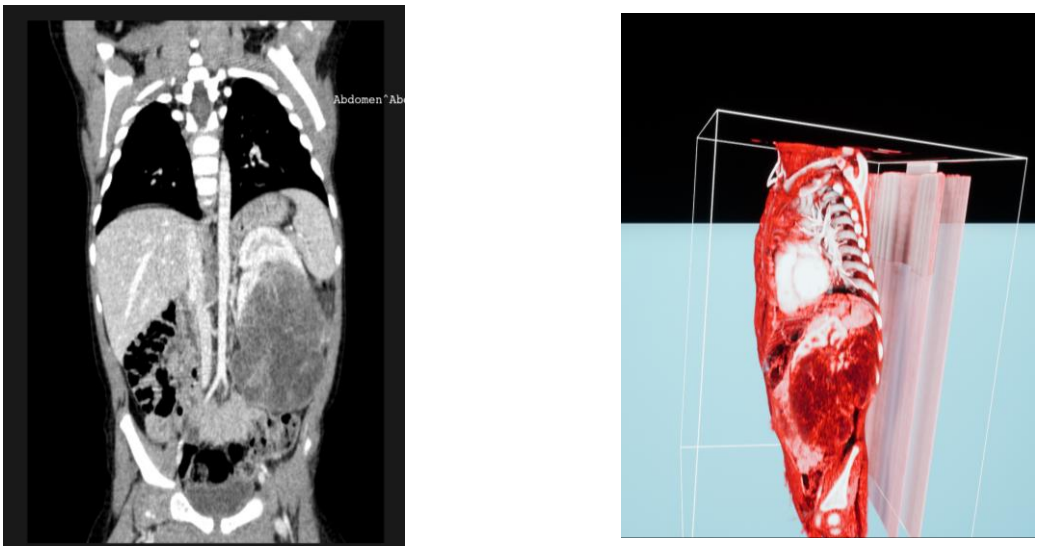
Results and Discussion

Preoperative 3D modeling and additional software-based assessments enabled surgeons to gain a more comprehensive understanding of the individual tumor and kidney anatomy in each patient.

Clinical Case 1 (NTRK-Rearranged Tumor)

A 10-month-old infant presented with a large right renal mass. Histology showed a cellular mesoblastic nephroma with *NTRK* gene rearrangement. The 3D model revealed a central tumor location with proximity to the hilar vessels. Virtual resection planning estimated that approximately 85% of the parenchyma would be preserved after tumor excision. This closely matched the actual postoperative volume (virtual residual parenchymal volume 84.5%). The procedure was performed laparoscopically, following nephron-sparing principles **(Figure 1).** Postoperative assessment

confirmed negative resection margins and preserved renal function.



a) b)

Figure 1. CT scan of the kidney and corresponding 3D model of the NTRK-rearranged tumor (segmentation of renal parenchyma and vessels). The model facilitated resection planning aimed at maximal parenchymal preservation.

Clinical Case 2 (Nephroblastoma, 6 Years)

A 6-year-old boy presented with an extensive unilateral nephroblastoma without metastases. He received neoadjuvant chemotherapy per protocol, followed by an MRI with MR angiography. The imaging data and 3D model allowed the surgeon to visualize the segmental arteries and assess the depth of tumor invasion into the parenchyma **(Figure 2).** 70% of the renal tissue was expected to be preserved during virtual resection. Approximately two-thirds of the kidney was saved during a partial nephrectomy. The residual parenchymal volume matched the prediction, according to postoperative MRI. Compared with conventional 2D planning, the 3D model gave a more accurate representation of tumor boundaries - consistent with the absence of positive surgical margins. A neural network-based AI assistant produced results that agreed with the histologic findings **(Figure 3).**

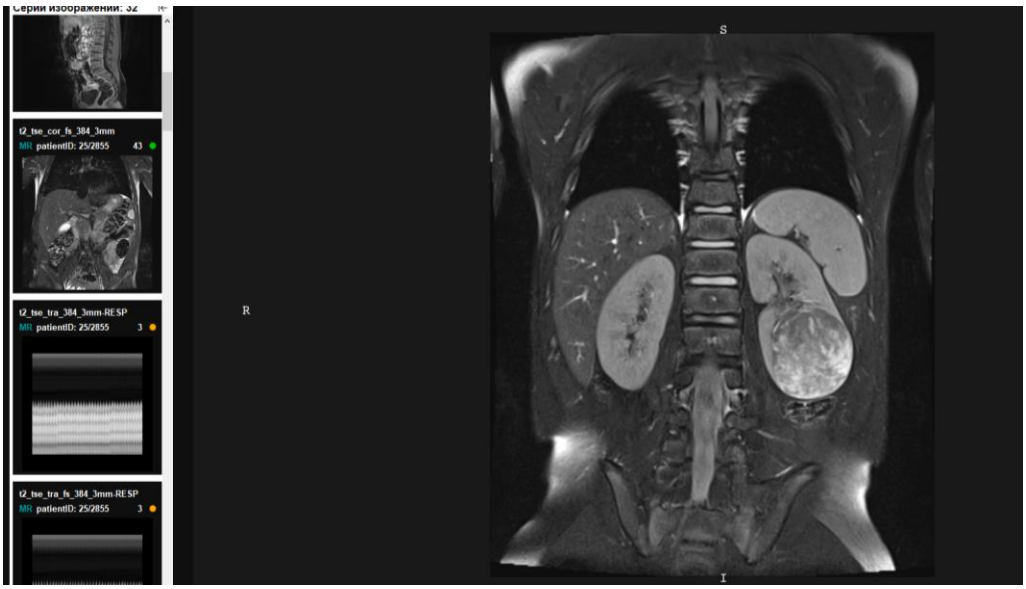


Figure 2. MRI of the left kidney in Patient 2 (Wilms' tumor).

Figure 3. Neural network output - nephroblastoma.

Clinical Case 3 (RCC, 17 Years)

A 17-year-old adolescent presented with an incidentally detected nodular tumor in the upper pole of the left kidney. CT and biopsy confirmed papillary renal cell carcinoma (RCC). A 3D model from CT segmentation showed an eccentric tumor location with enough distance from the hilar vessels to make partial resection feasible. Virtual resection predicted preservation of 90% of the parenchyma. During laparoscopic surgery, the tumor was successfully removed with a nephron-sparing approach. Postoperative histology confirmed the same RCC subtype with negative margins. Longitudinal assessment of renal function by differential radionuclide renal perfusion showed nearly unchanged values (effective clearance: 64 mL/min at baseline; 62 mL/min at one year), indicating successful nephron preservation.

Comparison with Published Data

Our outcomes are consistent with the best available reports. For example, a large retrospective study from the Netherlands that also used 3D models for nephron-sparing surgery (NSS) planning reported a reduction in unexpected positive margins from 18.8% to 3.7% after implementing 3D planning. In our series, no positive margins occurred in any case. In addition, the virtual assessment of residual parenchymal volume closely matched the actual postoperative volume.

Our results show that personalized 3D planning has clear advantages in managing pediatric renal tumors. These findings align with a growing body of recent international literature supporting the use of three-dimensional visualization technologies for preoperative planning in nephron-sparing surgery (NSS) (Manning *et al.*, 2018; Mittal *et al.*, 2023).

Impact of 3D Modeling on Surgical Outcomes

Several groups have systematically evaluated how 3D modeling affects surgical outcomes. A large retrospective cohort study from a national pediatric oncology center in the Netherlands included 43 NSS procedures and found that preoperative 3D planning was associated with a sharp drop in unexpected positive margin rates—from 18.8% without 3D models to 3.7% with 3D-based planning (Fitski *et al.*, 2025). These numbers closely match our experience, where none of the three cases had positive margins. The Dutch series also reported good functional outcomes with no decline in renal function after NSS, supporting the parenchymal preservation we observed in our patients: our virtual resection estimates of residual renal volume were highly consistent with actual postoperative measurements (Fitski *et al.*, 2025).

Beyond Margin Control: Navigation and Precision

Advanced visualization technologies also help with intraoperative navigation and surgical precision. Other researchers have described complete workflows that combine MR angiography, image segmentation, and augmented reality (AR) for pediatric renal tumors (Sirota *et al.*, 2019; La Barbera *et al.*, 2023). They reported that holographic models and 3D-printed reconstructions are time-efficient and user-friendly in clinical settings, improving spatial understanding of complex tumor-vessel relationships

(Pokharkar *et al.*, 2025). These technologies enhance the surgeon's ability to visualize segmental arterial anatomy and assess the depth of parenchymal invasion—benefits we also observed in our cases, especially for the centrally located NTRK-rearranged tumor and the Wilms tumor with complex vascular involvement (Wellens *et al.*, 2019).

Educational and Communication Value

There is also growing evidence for the educational and communication value of 3D technologies. Patient-specific printed models improve how well patients and families understand the diagnosis and the proposed surgical plan (van der Zee *et al.*, 2022). Although we did not directly measure this in our series, it highlights the broader potential of these tools for informed consent and shared decision-making in pediatric oncology (Esposito *et al.*, 2021).

Artificial Intelligence in Renal Tumor Diagnostics

Alongside advances in 3D visualization, artificial intelligence (AI) is being studied as a complementary tool for renal tumor diagnosis. A recent systematic review and meta-analysis of AI-based CT analysis for renal tumors reported promising diagnostic performance: pooled estimates from externally validated AI algorithms gave 80% sensitivity and 90% specificity for distinguishing malignant renal lesions (Knudsen *et al.*, 2024). Another clinically validated deep learning framework for kidney cancer detection showed that AI assistance cut radiologists' reporting time by an average of 33%, while improving sensitivity for detecting renal lesions and increasing inter-radiologist agreement (Lin *et al.*, 2023). These findings suggest that AI-based image analysis could support 3D planning workflows by automating tumor segmentation, aiding preoperative risk stratification, and reducing inter-observer variability in radiological assessment (Mühlbauer *et al.*, 2021).

Comparison with International Best Practices

The surgical outcomes in our series fall within the range of internationally reported best practices. Besides the Dutch experience, other centers have documented favorable results after centralizing pediatric oncology care and systematically implementing 3D modeling (Morrison *et al.*, 2020). A multicenter initiative involving specialized pediatric institutions showed that structured preoperative assessment with three-dimensional tools improves surgical precision and reduces complication rates in complex NSS cases (Zarfati *et al.*, 2025). The reduction in positive margin rates seen in these studies correlates strongly with better resection planning, reinforcing the idea that detailed preoperative visualization leads directly to better intraoperative execution (Checcucci *et al.*, 2021).

Limitations and Considerations

That said, several points deserve attention. The existing literature, like our own experience, comes mainly from retrospective series with relatively small sample sizes, reflecting the rarity of pediatric renal tumors and the selective use of NSS. A pathological review of Wilms tumor nephrectomy specimens suggested that, by strict oncologic criteria, about one in four children undergoing upfront surgery for unilateral disease might be anatomically suitable for a nephron-sparing approach (Murphy & Davidoff, 2023). This finding points to both the potential for wider use of NSS and the need for precise preoperative selection—exactly the kind of task for which 3D modeling is well suited (Hild *et al.*, 2024).

Summary of Findings

Our findings, together with those from other specialized centers, support the conclusion that careful preoperative modeling improves the surgeon's understanding of individual tumor anatomy and helps plan the best resection. This approach achieves maximal parenchymal preservation while ensuring complete tumor removal—the fundamental dual goal of nephron-sparing surgery. Thus, three-dimensional models and virtual simulation are increasingly seen as valuable tools for preparing organ-preserving procedures in pediatric renal oncology (Bramlet *et al.*, 2024).

Multidisciplinary Collaboration

A key factor for successful implementation remains multidisciplinary collaboration among surgeons, radiologists, and medical imaging specialists. Creating accurate and clinically useful 3D models requires seamless integration of expertise across these fields—from optimal image acquisition protocols to precise segmentation and interpretation (Checcucci *et al.*, 2020). Institutions that have successfully adopted these technologies emphasize that structured multidisciplinary workflows are essential to turn technological capability into better patient outcomes (Libes *et al.*, 2023).

Conclusion

Personalized 3D planning and modern intelligent software have real potential to improve the management of pediatric renal tumors. Our experience, consistent with recent international evidence, shows that augmented reality, virtual resection, and three-dimensional modeling allow more accurate preoperative assessment. They may also lower the risk of incomplete resection while maximizing parenchymal preservation. In our cases, these technologies boosted surgical confidence and improved the quality of the interventions.

Despite these promising results, wider adoption will require more clinical experience and standardized modeling protocols. Differences in segmentation techniques, software platforms, and reporting frameworks currently make it hard to compare outcomes across institutions. Consensus guidelines are needed for this rapidly evolving field.

In the future, integrating 3D technologies and artificial intelligence into routine treatment protocols could move pediatric renal oncology toward more precise, individualized strategies. AI-driven automation of tumor segmentation, predictive modeling of surgical outcomes, and real-time intraoperative guidance are logical next steps.

To conclude, although nephron-sparing surgery for Wilms tumor and other pediatric renal malignancies remains indicated only in selected cases, today's digital tools are steadily expanding what is

surgically possible. With structured training of surgical teams and centralized coordination of expertise, these innovations are likely to become a standard part of high-technology oncologic surgery. Their systematic use can reduce complication rates and preserve long-term renal function in young patients — improving both cancer control and quality of life.

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Ethics statement: This study was conducted in accordance with the ethical standards of the institutional research committee and with the principles of the Declaration of Helsinki (2013 revision). The study represents a retrospective analysis of clinical cases, and all patient data were processed in compliance with applicable data protection regulations, including the General Data Protection Regulation (GDPR) principles. Patient confidentiality was maintained throughout the study by anonymizing all clinical data, images, and 3D models, with removal of all personal identifiers before analysis and publication.

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