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Three-dimensional Models for Individualized Preoperative Planning of Robot-assisted Partial Nephrectomy in Patients with Horseshoe Kidneys: A European Multicenter Case Series (YAU RCC-UroCCR)

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Abstract

Renal tumors in horseshoe kidneys (HSKs) present unique surgical challenges because of complex vascular anatomy, limited organ mobility, and the proximity of critical structures. We report a European multicenter case series of 24 patients with HSK tumors who underwent robot-assisted partial nephrectomy that was planned with patient-specific three-dimensional (3D) virtual models. Reconstructions were generated from multiphase computed tomography scans, which allowed detailed vascular mapping and tailored ischemia strategies. The median tumor size was 5.4 cm, with a median of three renal arteries per patient. A clampless approach was achieved in 12 cases (50%), including five with anatomic devascularization via ligation of tumor-specific segmental arteries. When clamping was required (n = 12), the median warm ischemia time was 23 min. There were no conversions to open surgery and no local recurrences. Major complications occurred in two patients (8.3%) and the median decline in estimated glomerular filtration rate was −5.0 ml/min/1.73 m^2 at last follow-up. Trifecta outcomes (negative surgical margin, no major complications, and renal function ≥90% of the baseline value) were achieved in 50% of cases. This series highlights the role of 3D surgical planning in

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Selective clamping
Three-dimensional modeling
Vascular management

optimizing vascular control, facilitating nephron-sparing techniques, and preserving renal function in these anatomically highly complex procedures.

1. Case series

Renal tumors arising in horseshoe kidneys (HSKs) are rare [1] and surgically demanding because of aberrant vascular anatomy, limited renal mobility, and the presence of an isthmus across the midline [2,3]. While partial nephrectomy (PN) is feasible in this setting, meticulous planning is required. Three-dimensional (3D) reconstructions based on multiphase computed tomography (CT) scans can provide detailed anatomic information to guide vascular and surgical strategies.

We conducted a retrospective, multicenter study across European tertiary referral centers. Patients were eligible if they had renal tumors in HSKs treated with robot-assisted PN (RAPN) and preoperative high-resolution 3D models available for surgical planning; patients with automatically generated 3D renderings were excluded. Data were extracted from the UroCCR database (CNIL DR 2013-206; NCT03293563) and the institutional registries of participating centers. 3D models were generated using validated segmentation platforms from multiphase CT scans with fine-slice acquisition (0.6–1.5 mm). Despite software heterogeneity across centers, anatomic rendering was consistently reliable and intraoperative findings were highly concordant with the preoperative models. Reconstructions were systematically reviewed to identify vascular anatomy and anticipate ischemia management, and were displayed intraoperatively on the robotic console for cognitive navigation.

The cohort comprised 24 patients who were predominantly male (83%), with a median age of 65 yr and median body mass index of 29.6 kg/m^2. Comorbidities were common (median Charlson Comorbidity Index 3), and nearly half of the patients had undergone prior abdominal surgery. Tumors were complex (median RENAL score 9, median PADUA score 10), with isthmus involvement in three cases. Two patients had tumor thrombus in the renal vein and another had extension into the inferior vena cava. Detailed characteristics are summarized in Table 1.

The vascular anatomy was highly variable, with a median of three renal arteries (range 1–7). Clamping strategies were adapted according to vascular complexity and tumor location. A clampless approach was used in 12 patients (50%), including five with anatomic devascularization via ligation of tumor-specific segmental arteries, which allowed selective control of tumor perfusion without ischemia to the healthy parenchyma. Total clamping was used in ten patients (42%) and selective clamping in two (8.3%), with median warm ischemia time of 23 min (interquartile range [IQR] 21.5–26; Table 2).

Tumor enucleation was the predominant surgical technique (67%), followed by formal resection (25%) and heminephrectomy (8.3%). In two patients, a concomitant pyelotomy was performed for management of large calculi. Hemostatic agents were used in 58% of procedures, intraoperative ultrasound in 54%, and indocyanine green fluorescence in 17%. These adjuncts were used at the discretion of the surgeon, in addition to 3D guidance.

Median operative time was 240 min, estimated blood loss 500 ml, and hospital stay 4 d. Severe complications (Clavien–Dindo grade ≥3) occurred in two patients: one postoperative urinary fistula was managed conservatively with ureteral stenting and percutaneous drainage, and one postoperative arterial bleeding required reintervention in a patient who underwent total clamping. Notably, no major hemorrhagic events occurred among the 12 patients treated with a clampless approach. The overall complication rate was 29%. No conversions to open surgery or radical nephrectomy were necessary (Table 3).

Functional and oncological outcomes were favorable. Median eGFR had declined by −2.2 ml/min/1.73 m^2 (IQR −8.0 to 0.1) at discharge, and by −5.0 ml/min/1.73 m^2 (IQR −12.2 to 0.0) at last follow-up (median 21 mo). Pathology revealed pT1 disease in 21%, pT2 in 17%, and pT3 in 58% of cases. Histological subtypes included clear-cell renal cell

Table 1 – Patient and tumor characteristics (n = 24)

Parameter	Result
Median age, yr (IQR)	65 (59–74)
Male, *n* (%)	20 (83)
Median BMI, kg/m^2 (IQR)	29.6 (25.2–32.1)
Charlson comorbidity index, *n* (%)	
0	1 (4.2)
1	2 (8.3)
2	4 (17)
≥3	17 (71)
Median eGFR at Dx, ml/min/1.73 m^2 (IQR)	76.0 (53.4–86.0)
Previous abdominal surgery, *n* (%)	11 (46)
Preoperative biopsy, *n* (%)	4 (17)
Multiple synchronous tumors, *n* (%)	3 (13)
Split pyelum, *n* (%)	7 (29)
Tumor location, *n* (%)	
Left	12 (50)
Right	11 (46)
Isthmus	1 (4.2)
Hilar location, *n* (%)	11 (46)
cT stage, *n* (%)	
cT1	14 (58)
cT2	6 (25)
cT3	4 (17)
Median tumor diameter, cm (IQR)	5.4 (4.0–7.0)
RENAL score, *n* (%)	
4–6	3 (12)
7–9	12 (50)
10–12	9 (38)
PADUA score, *n* (%)	
5–7	3 (12)
8–9	5 (21)
10–14	16 (67)

BMI = body mass index; Dx = diagnosis; eGFR = estimated glomerular filtration rate; IQR = interquartile range.

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Table 2 – Vascular anatomy and ischemia management in the series of 24 patients

Parameter	Result
Number of arteries to HSK, *n* (%)	
≤2	8 (33)
3	8 (33)
4	4 (17)
≥5	4 (17)
Clamping technique, *n* (%)	
Total	10 (42)
Selective	2 (8.3)
Off clamp	12 (50)
Number of arteries clamped, *n* (%)	
1	6/12 (50)
2	5/12 (42)
3	1/12 (8)
Median warm ischemia time, min (IQR)	23 (21.5–26.0)

HSK = horseshoe kidney; IQR = interquartile range.

Table 3 – Surgical, functional, and oncological outcomes in the series of 24 patients

Parameter	Result
Resection technique, *n* (%)	
Enucleation	16 (67)
Resection	6 (25)
Heminephrectomy	2 (8.3)
Hemostatic agent, *n* (%)	14 (58)
Floseal	6/14 (43)
Surgicel	1/14 (7.1)
Tachosil	7/14 (50)
Indocyanine green use, *n* (%)	4 (17)
Intraoperative ultrasound, *n* (%)	13 (54)
Median operative time, min (IQR)	240 (150–300)
Median estimated blood loss, ml (IQR)	500 (160–750)
Complications, *n* (%)	7 (29)
Severe (grade ≥3)	2 (8.3)
Median length of stay, d (IQR)	4 (3–5)
Positive margin status, *n* (%)	2 (8.3)
pT stage, *n* (%)	
pT1	5 (21)
pT2	4 (17)
pT3	13 (54)
Data not available	2 (8.3)
Histological subtype, *n* (%)	
Clear-cell renal cell carcinoma	15 (62)
Papillary renal cell carcinoma	3 (13)
Chromophobe renal cell carcinoma	3 (13)
Neuroendocrine carcinoma	2 (8.3)
Oncocytoma	1 (4.2)
Trifecta criteria met, *n* (%)	12 (50)
Median GFR, ml/min/1.73 m^2 (IQR)	
At discharge	63.0 (43.3–80.1)
At last follow-up	66.7 (40.1–76.0)
Median change in GFR, ml/min/1.73 m^2, (IQR)	
At discharge	−2.2 (−8.0 to 0.1)
At last follow-up	−5.0 (−12.2 to 0.0)

GFR = glomerular filtration rate; IQR = interquartile range.

carcinoma (63%), papillary renal cell carcinoma (13%), chromophobe renal cell carcinoma (13%), neuroendocrine carcinoma (8.3%), and oncocytoma (4.2%). Positive surgical margins were observed in two patients (8.3%). At a median follow-up of 20 mo (IQR 6.8–29.5), no local or distant recurrences were observed. One patient died from non–cancer-related causes, resulting in recurrence-free and cancer-specific survival rates of 100%. Trifecta criteria—defined as negative surgical margins, the absence of major complications, and preservation of renal function (≥90% of the preoperative eGFR [4])—were met in 50% of cases.

Representative cases highlighting distinct 3D reconstruction platforms and vascular strategies are shown in Figure 1. A complete visual series of 3D reconstructions for all the patients is provided in Supplementary Figure 1.

2. Discussion

This multicenter experience highlights how 3D planning and intraoperative guidance can refine surgical strategies during RAPN for HSKs. Vascular control strategies were defined during preoperative planning based on 3D reconstructions, which allowed accurate identification of tumor-specific arterial branches and anticipation of selective or clampless approaches. It would be difficult to achieve this degree of vascular planning using standard imaging techniques alone.

Our findings align with prior reports on 3D-assisted RAPN. Amparore et al [5] showed that perfusion-based 3D models facilitated selective ischemia planning, while Porpiglia et al [6] demonstrated that hyperaccuracy reconstructions increased the feasibility and safety of selective clamping for complex tumors. Michiels et al [7] reported better trifecta outcomes in a multicenter matched analysis of 3D-guided RAPN. Together, these studies support the role of 3D technology as a valuable adjunct in nephron-sparing surgery for anatomically complex kidneys.

Importantly, our entire cohort was treated using robotic surgery, which provides enhanced magnification, dexterity, and stability. This uniform use of the robotic platform likely contributed to the safety and reproducibility of nephron-sparing surgery in HSKs. In contrast, in the large HSK series by Roussel et al [8], nearly half of the procedures were performed using an open approach, which may have limited the adoption of refined vascular strategies and contributed to a higher nonconservative resection rate. Although complication rates were relatively similar between the two cohorts, the combination of robotics and 3D guidance in our study appears to optimize surgical precision and perioperative control.

Beyond safety, 3D assistance in RAPN may also enhance functional outcomes. In our series, heminephrectomy was required in only two cases, and nephron-sparing surgery was feasible in the vast majority. This compares favorably to the heminephrectomy rate of 12.5% reported by Roussel et al [8], along with an additional 25% of wedge or nonconservative resections. Despite similar tumor complexity between the two cohorts, the median decline in renal function in our study (−5.0 ml/min/1.73 m^2 at last follow-up) was lower than that reported in the original Roussel series. This suggests a real clinical impact of integrating 3D surgical planning into the management strategy for HSK tumors. The combination of 3D reconstruction and robotic surgery may thus enhance parenchymal preservation and translate to better long-term renal function and overall quality for nephron-sparing surgery. The margin positivity rate of 8.3% in our series aligns with previous PN data for HSKs, and the absence of local recurrences during follow-up further supports the oncological adequacy of RAPN in this complex setting. Comparisons with the cohort described by Roussel et al [8] should be viewed with caution, as their

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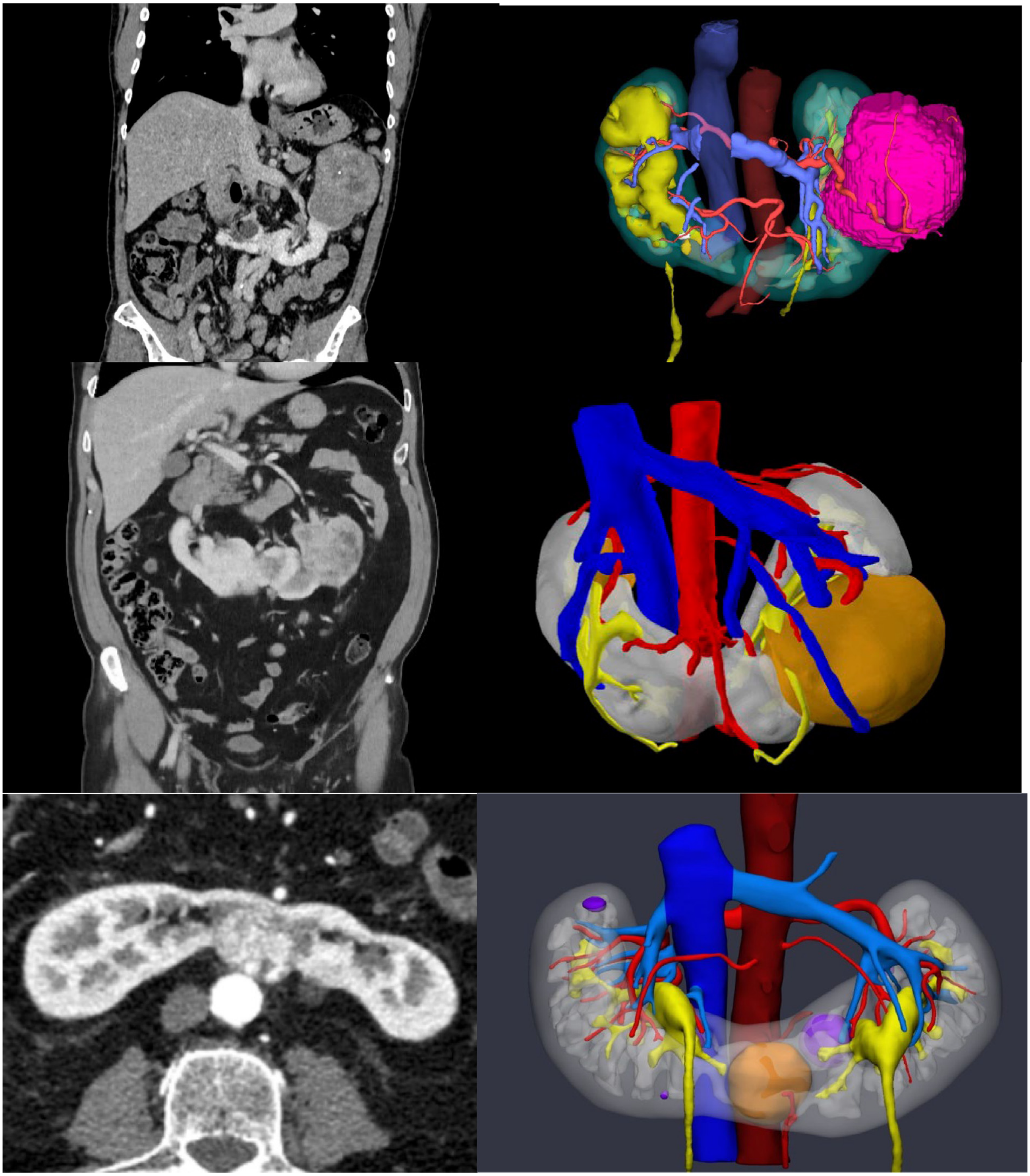

Fig. 1 – Representative three-dimensional models from three participating centers, each illustrating a different segmentation and rendering technology. For each case, the preoperative computed tomography scan is shown on the left, and the corresponding reconstruction on the right. The models show key anatomic structures, including the renal parenchyma, the tumor, the arterial and venous vasculature, and the collecting system.

predominantly open approach limits direct comparability; our analysis is therefore purely descriptive.

The heterogeneity of the vascular anatomy observed in our series (up to 7 arteries) underlines the value of 3D assistance. Anticipating such variability was critical for tailoring clamping strategies and probably reduced the risk of intraoperative surprises. Notably, severe complications remained limited despite the high anatomic complexity, which reinforces the safety of this approach in expert hands.

Several limitations must be acknowledged. The retrospective design and lack of a comparative cohort without 3D modeling limit our ability to draw definitive causal conclusions. The relatively small number of cases may also affect statistical robustness, although this limitation is

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inherent to the rarity of HSK tumors. All procedures were performed in high-volume referral centers with access to 3D technologies, which may restrict the generalizability of our findings. Finally, variability in imaging protocols, segmentation tools, and intraoperative display (static vs dynamic) could have influenced the consistency of 3D guidance across centers.

Future perspectives include integration of augmented reality and real-time image fusion for navigation, which could further improve anatomic orientation and precision [9–11]. Advances in artificial intelligence may also allow automated segmentation and standardization of 3D workflows, which could support broader adoption. Ultimately, collaborative platforms and consensus guidelines will be required to ensure reproducibility and widespread implementation of 3D-assisted nephron-sparing surgery in complex cases such as HSKs.

Conflicts of interest: The authors have nothing to disclose.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.euo.2026.02.010.

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