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RESEARCH

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Robotic partial nephrectomy and three-dimensional reconstruction in solitary kidneys: surgical and functional outcomes

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This article belongs to the Special Issue: Robot-assisted surgery vs. laparoscopy surgery; which is better?

Abstract

Background: Partial nephrectomy represents an absolute indication in patients with a solitary kidney, where preservation of renal function must be balanced against oncologic control. Robot-assisted partial nephrectomy has expanded the feasibility of nephron-sparing surgery in complex tumors, while patient-specific three-dimensional reconstruction has emerged as a planning tool. This study evaluated the impact of robotic surgery and three-dimensional reconstruction on perioperative and functional outcomes in patients with a solitary kidney.

Methods: We retrospectively analyzed all solitary kidney patients who underwent partial nephrectomy between 2020 and 2024 at a tertiary referral center. Perioperative, oncologic, and renal functional outcomes (median follow-up: 12.0 months) were assessed according to surgical approach (robotic *vs.* open/laparoscopic). The impact of three-dimensional reconstruction was also explored. Acute kidney injury was defined according to Kidney Disease: Improving Global Outcomes criteria.

Results: Twenty-seven solitary kidney patients were analyzed. Nineteen patients underwent robot-assisted partial nephrectomy. Robotic surgery was associated with shorter hospital stay (median 4 *vs.* 8 days; $P = 0.009$), lower conversion to radical nephrectomy (0% *vs.* 37.5%; $P = 0.019$), and lower peak postoperative creatinine (1.6 *vs.* 4.7 mg/dL; $P = 0.036$). Acute kidney injury occurred in 59.3% of patients overall. Four patients treated robotically underwent three-dimensional-assisted planning; these cases had the highest tumor complexity scores in the cohort. Three-dimensional reconstruction was used selectively in the most anatomically complex cases; its independent association with perioperative outcomes could not be reliably assessed given the small subgroup.

Conclusion: Robot-assisted partial nephrectomy in solitary kidney patients appears to offer perioperative advantages over open/laparoscopic approaches. Due to the small sample size, these findings should be considered preliminary and hypothesis-generating. Three-dimensional reconstruction appears to support surgical planning in anatomically complex tumors rather than demonstrating independent improvement in renal outcomes.

Keywords: Solitary kidney, partial nephrectomy, three-dimensional reconstruction, renal function, nephron-sparing surgery

Introduction

Renal cell carcinoma accounts for approximately 2–3% of all malignancies worldwide, with over 430,000 new cases annually [1]. Partial nephrectomy is recommended as the standard treatment for localized renal cell carcinoma whenever technically feasible, offering oncologic outcomes comparable to those of radical nephrectomy while preserving renal function [2-6].

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In patients with a solitary kidney, partial nephrectomy represents an absolute indication, as radical nephrectomy would result in end-stage renal disease and the need for dialysis or transplantation [2, 7]. However, partial nephrectomy in this setting is technically demanding and associated with increased risk of acute kidney injury and long-term renal impairment [8, 9].

Robot-assisted partial nephrectomy has expanded the indications for nephron-sparing surgery by improving visualization and dexterity [10, 11]. In parallel, patient-specific three-dimensional reconstructions have been introduced to improve anatomical understanding and surgical planning in complex tumors [12-15].

This study aimed to evaluate the impact of robotic surgery on perioperative and renal functional outcomes in patients with a solitary kidney treated at a referral institution. The role of three-dimensional reconstruction was also explored.

Methods

Study design and population

This retrospective observational study included solitary kidney patients undergoing partial nephrectomy for renal tumors between 2020 and 2024 at a referral institution.

Demographic, clinical, and tumor variables included age, sex, body mass index, American Society of Anesthesiologists score, Charlson comorbidity index, hypertension, diabetes, preoperative creatinine, tumor size, and Preoperative Aspects and Dimensions Used for an Anatomical classification score [16]. Follow-up duration was calculated from the date of surgery to the last available clinical or biochemical evaluation.

Surgical variables

Perioperative data included surgical approach (robotic *vs.* open/laparoscopic), the use of intraoperative ischemia, estimated blood loss, operative time, conversion to radical nephrectomy, length of stay, surgical margin status, and complications (Clavien–Dindo classification [17]). Acute kidney injury was defined according to Kidney Disease: Improving Global Outcomes criteria [18].

Statistical analysis

Continuous variables were reported as medians and interquartile ranges, given the non-normal distribution of most variables, as assessed by visual inspection of histograms and Shapiro–Wilk testing. Categorical variables were expressed as absolute frequencies and percentages. Comparative analyses were performed according to 1) surgical approach (robotic *vs*. open/laparoscopic) and 2) use of three-dimensional reconstruction. For continuous variables, differences between groups were assessed using the Mann–Whitney *U* test. Categorical variables were compared using the χ^2 test or Fisher's exact test, as appropriate, based on expected cell frequencies. All tests were two-sided, and statistical significance was set at $P < 0.05$. Statistical analyses were performed using SPSS version 29.0.

Table 1. Baseline characteristics of the study population.

Variable	Overall (n = 27)
Age, years	61.5 (57.0–70.3)
Male sex, n (%)	16 (59.3%)
Body mass index, kg/m²	27.1 (24.6–30.9)
ASA score ≥ 3, n (%)	13 (48.1%)
Charlson comorbidity index	5 (4–6)
Hypertension, n (%)	18 (66.7%)
Diabetes, n (%)	3 (11.1%)
Preoperative creatinine, mg/dL	1.23 (1.07–2.04)
Tumor size, cm	2.9 (2.4–5.0)
PADUA score	8 (7.3–10.0)
Three-dimensional reconstruction, n (%)	4 (14.8%)

Notes: Values are median (interquartile range) unless otherwise specified. PADUA: Preoperative Aspects and Dimensions Used for an Anatomical classification.

Results

Twenty-seven patients with a solitary kidney undergoing partial nephrectomy were included in the analysis. The median follow-up for the entire cohort was 12.0 months (interquartile range: 3.0–24.0). The median age was 61.5 years, and 59.3% of patients were male. Tumors had a median tumor diameter of 2.9 cm, with a median Preoperative Aspects and Dimensions Used for an Anatomical classification score of 8, reflecting an overall intermediate anatomical complexity (Table 1). A robotic approach was adopted in 19 patients (70.4%), while 8 patients (29.6%) underwent open (n = 6) or laparoscopic (n = 2) surgery (Table 2).

Within the robotic cohort, four patients (14.8% of the overall population) underwent preoperative three-dimensional reconstruction–assisted planning. These cases had the highest PADUA scores in the cohort (Figure 1).

Conversion to radical nephrectomy occurred exclusively in the open/laparoscopic group (3 out of 8 patients, 37.5%), whereas none occurred in patients treated robotically.

Regarding functional outcomes, according to the Kidney Disease Improving Global Outcomes criteria, acute kidney injury was observed in 16 patients (59.3%) overall. Specifically, Stage 1 occurred in 8 patients (29.6%), Stage 2 in 2 patients (7.4%), and Stage 3 in 6 patients (22.2%). When stratified by surgical approach, acute kidney injury was observed in 47.4% (9/19) of robotic cases compared with 87.5% (7/8) in the open/laparoscopic group (P = 0.09). Peak postoperative serum creatinine levels were significantly lower in the robotic group (median 1.6 mg/dL) compared to the open/laparoscopic group (median 4.7 mg/dL; P = 0.036). At last follow-up, creatinine values remained numerically lower in patients treated robotically (1.4 mg/dL *vs*. 3.9 mg/dL), although this difference did not reach statistical significance (P = 0.07).

Discussion

Table 2. Perioperative outcomes according to surgical approach.

Variable	Robotic (*n* = 19)	Open/Lap (*n* = 8)	*P*-value
Conversion to radical nephrectomy, *n* (%)	0 (0%)	3 (37.5%)	0.019
Operative time, min	150 (110–190)	165 (120–210)	NS
Estimated blood loss, mL	150 (50–400)	300 (100–700)	NS
Intraoperative ischemia used, *n* (%)	7 (36.8%)	1 (12.5%)	NS
Positive surgical margins, *n* (%)	1 (5.3%)	1 (12.5%)	NS
Acute kidney injury, *n* (%)	9 (47.4%)	7 (87.5%)	0.09
Length of stay, days	4 (3–6)	8 (6–10)	0.009

Note: NS: not significant.

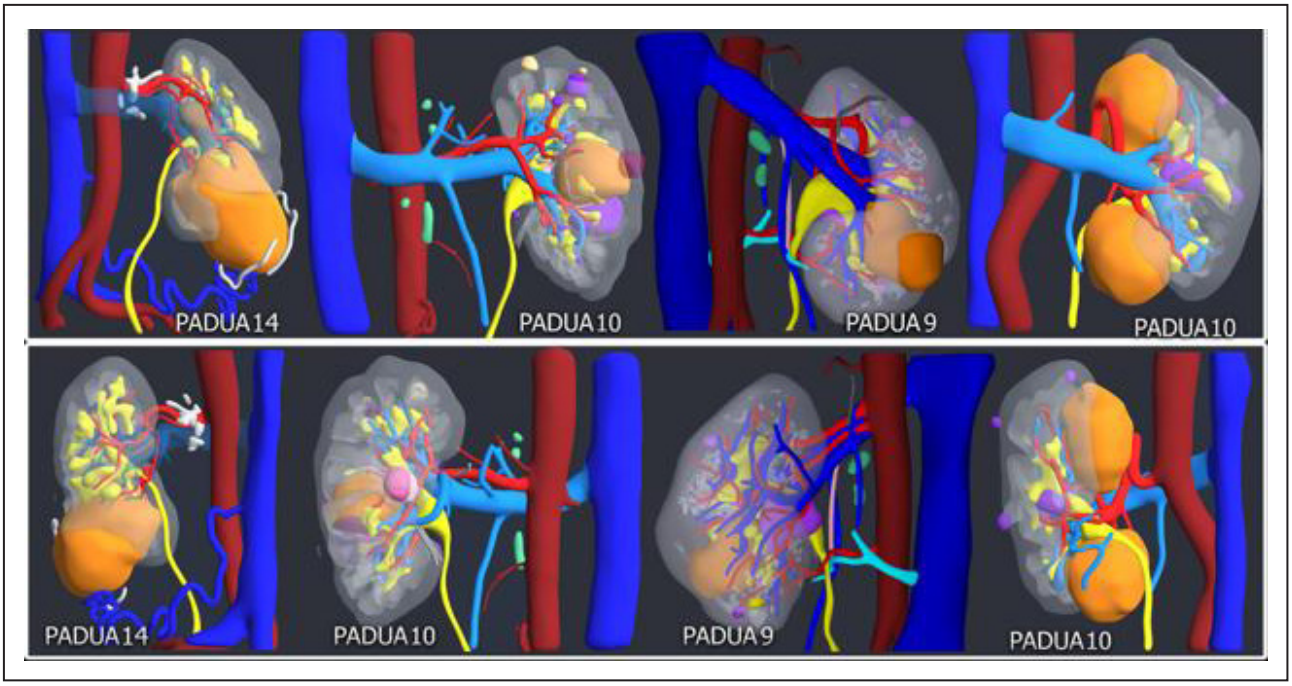


Figure 1. **Three-dimensional reconstructions of the four solitary kidney cases treated with robotic partial nephrectomy**. The upper panel illustrates the anterior (front) views, while the lower panel shows the posterior (back) views. In both perspectives, the tumors' anatomical complexity is clearly evident, consistent with the high PADUA scores observed in these cases. The following color code was used to represent the anatomical structures: orange for the tumor; red for the arterial vasculature; blue for the venous vasculature; yellow for the collecting system; purple for renal cysts; and semi-transparent white for the healthy renal parenchyma. The reconstructions highlight the spatial relationships between the tumor, renal parenchyma, segmental vascular and calyceal structures, supporting preoperative planning in anatomically challenging scenarios.

Partial nephrectomy in patients with a solitary kidney remains one of the most challenging scenarios in urologic oncology, as the clinical consequences of renal functional loss are particularly relevant in the absence of contralateral reserve. Our single-center experience confirms that robot-assisted partial nephrectomy can be performed with acceptable perioperative morbidity, low conversion rates in experienced hands, and, importantly, preservation of renal function in the majority of patients.

Although several intraoperative strategies have been proposed to minimize permanent renal injury, including cold ischemia and off-clamp techniques [19-22], the optimal approach remains debated. In our cohort, we focused on evaluating the overall impact of the surgical approach. Minimizing perioperative morbidity is critical in solitary kidney patients [23]. Previous large series have demonstrated that open surgery is associated with an increased risk of overall complications compared with minimally invasive approaches [24, 25].

These findings are highly relevant in the context of solitary kidneys. Although the patients evaluated had primarily bilateral kidneys, the underlying mechanisms—reduced tissue trauma, improved visualization, enhanced dexterity, and more precise renorrhaphy—are equally applicable to the solitary kidney setting. In our cohort, conversion to radical nephrectomy occurred exclusively in the open/laparoscopic group, and peak postoperative creatinine levels were significantly lower in the robotic group. Moreover, acute kidney injury occurred less frequently in robotic cases, showing a trend toward significance. These data suggest that the advantages of robotic technology observed in complex renal masses in patients with bilateral kidneys translate into at least comparable, if not greater, benefits in the solitary kidney population.

From a pathophysiological perspective, major complications such as hemorrhage, urinary fistula, or prolonged

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drainage may induce additional renal stress, systemic inflammatory response, or secondary ischemic events, all of which may contribute to deterioration of residual renal function. Therefore, minimizing perioperative complications is not only a matter of surgical quality but also of long-term nephron preservation.

Two further principles emerge consistently from the literature and are reinforced by our findings. First, preoperative risk stratification remains fundamental. Baseline renal function and comorbidity burden (including diabetes and vascular disease) are consistently associated with renal outcomes and should guide surgical counseling and strategy selection. Second, parenchymal-sparing precision is likely more impactful than the mere duration of ischemia. The volume of functional parenchyma preserved—influenced by resection technique, excisional accuracy, and renorrhaphy strategy—is a major determinant of postoperative renal function [26, 27]. Advanced planning tools, including three-dimensional reconstructions, may enhance the understanding of segmental vascular anatomy and tumor relationships, thereby facilitating selective clamping and precise resection [12].

Alternative strategies, such as percutaneous cryoablation or active surveillance, may be appropriate for selected small renal masses and frail patients [28, 29]. Cryoablation avoids hilar ischemia and has low perioperative morbidity, but oncologic durability differs from that of partial nephrectomy, and careful shared decision-making is particularly critical in solitary kidney patients, where functional and oncologic trade-offs are more consequential [30].

Our study shares limitations common to retrospective series. First, the sample size is extremely small (27 patients), with an evident indication bias. Second, the control group merged open (n = 6) and laparoscopic (n = 2) cases; while methodologically suboptimal given their different perioperative profiles, this was necessary to allow any statistical comparison against the robotic cohort. Third, three-dimensional planning was utilized in only 4 patients, limiting the robustness of comparisons regarding its independent impact. Finally, the median follow-up of 12.0 months is relatively short, preventing definitive conclusions regarding long-term oncologic safety. Consequently, our findings must be interpreted as preliminary, exploratory, and hypothesis-generating.

In summary, while ischemia management remains relevant, it should be interpreted within a broader risk-adapted framework that prioritizes baseline renal function, maximization of preserved parenchyma, and minimization of perioperative complications. The consistent association between open surgery and higher complication rates further supports the preferential adoption of robotic technology whenever feasible—a principle that appears particularly compelling in the solitary kidney setting.

Despite the inherent limitations of this analysis, our findings, contextualized within the available evidence, support a risk-adapted paradigm: prioritizing baseline renal function and parenchymal preservation during surgical planning; considering the use of robotic technology to maximize renal unit preservation and reduce perioperative morbidity; and adopting three-dimensional technologies to enhance the quality and precision of surgical planning.

Conclusions

Based on our preliminary, exploratory data, robot-assisted partial nephrectomy in solitary kidney patients is technically feasible, oncologically safe, and functionally sustainable in experienced centers. Robotic surgery offers perioperative advantages over open/laparoscopic approaches. Three-dimensional reconstruction enhances surgical planning in complex cases but does not independently alter renal outcomes. Prospective multicenter studies are needed to further define the role of advanced imaging technologies in precision nephron-sparing surgery.

Declarations

Author contributions: Made substantial contributions to conception and design of the study: Roggero L, Bertolo RG, Antonelli A; performed data acquisition: Ditonno F, Pettenuzzo G, Montanaro F, Caudana F, Quagliato MV; performed data analysis and interpretation: Veccia A, Cerruto MA; drafted the work: Roggero L, Bertolo RG.

Availability of data and materials: The datasets generated during the current study are available from the corresponding author on reasonable request.

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Conflicts of interest: All authors declared that there are no conflicts of interest.

Ethical approval and informed consent: The study was performed in accordance with the Declaration of Helsinki and approved by the Comitato Etico Territoriale Area Sud-Ovest Veneto (CET-ASOV). An informed consent to participate in the study was obtained from all participants.

Consent for publication: Not applicable.

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