



How far has robot-assisted partial nephrectomy reached?

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Nephron-sparing surgery is the standard treatment for small renal mass (SRM). Nephron-sparing surgery has evolved from an open to a minimally invasive technique. Robot-assisted partial nephrectomy (RAPN) is the latest technique in this field and is reported to be safe and feasible, showing oncologically and functionally superior or compatible results compared with open and laparoscopic partial nephrectomy for SRM. This is not limited to only SRM but also applies to large and complex renal masses and other challenging situations. RAPN showed good oncological and functional outcomes for $\geq$ clinical T2 renal tumors, complex renal masses (PADUA score ≥ 10 , RENAL score ≥ 10), hilar renal tumors, and multiple renal tumors. In addition, the outcomes of RAPN in these challenging cases were not inferior to those in conventional cases. RAPN could also be applied to a number of challenging cases in which the open technique was considered first. RAPN showed good results in patients with a solitary kidney, horseshoe kidney, and in repeat surgeries. Furthermore, RAPN could be safely performed on obese, elderly, and pediatric patients. Finally, this review evaluates efficiency and utility of RAPN based on the results of challenging cases of renal masses and to project the future of RAPN.

Keywords: Kidney cancer; Nephrectomy; Robotics

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INTRODUCTION

Partial nephrectomy (PN) has been established as the gold standard treatment for clinical T1a renal cell carcinoma (RCC) [1] in place of radical nephrectomy (RN), which was the previously accepted gold standard for localized RCC. PN shows superior oncologic and functional outcomes compared to RN. In particular, in terms of functional outcome, PN showed similar functional effect compared to tumor enucleation [2]. One of the complications that can occur after PN is formation of vascular lesion, and it has been reported that there is no significant adverse effect on renal function even after selective embolization of vascular lesion [3].

Minimally invasive surgery (MIS) has become a contemporary trend. PN, which was initially performed as an open technique, is now mostly performed as laparoscopic partial nephrectomy (LPN) and robot-assisted partial nephrectomy (RAPN), due to numerous advantages these two methods have over open technique [4]. Owing to its advanced surgical approach, RAPN is now a mainstream technique for performing PN, having a shorter warm ischemic time (WIT) and being associated with less frequent conversion to the open technique or RN, better preservation of renal function, and a shorter hospital stay than LPN [5]. In addition, RAPN has a relatively short learning curve compared to LPN [6]. Because of these advantages, RAPN is considered the

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standard treatment for clinical T1a renal tumors. Furthermore, its indications are now being expanded to T1b and T2 tumors with increasing evidence. Due to these advantages, good results have been reported when performing PN using RAPN in cases of complex renal tumors where it is difficult to perform LPN.

Nevertheless, the open technique is still considered a potential surgical treatment for complex tumors and/or challenging situations, and the role of MIS in these challenging situations is passively accepted. In the present article, we highlight the technical advancements in RAPN and the expansion of its role to include complex tumors and challenging situations based on recent studies.

LARGE AND COMPLEX RENAL TUMOR IN RAPN

1. RAPN in $\geq$ T2 renal tumor

The European Association of Urology guidelines strongly recommend PN for patients with T1 tumors. However, the guidelines are passive regarding the applicability of PN in treating T2 tumors [7]. Nevertheless, several studies on localized renal tumors above T2 have reported that RAPN is feasible not only for T1 but also for T2 tumors (Fig. 1). Long et al. [8] reported that RAPN showed good preservation of renal function and acceptable perioperative and oncologic outcomes in treating large renal tumors (>7 cm), suggesting

that RAPN is a safe and effective procedure (WIT of 20.0 min, no patients died, and no local recurrence during a mean follow-up of 31.0 months). In a multicenter analysis conducted by 19 robotic centers, Bertolo et al. [9] reported that RAPN showed acceptable outcomes in the treatment of large renal masses above T2 and that it was safely performed (WIT of 25 min, positive surgical margins [PSMs] in 20 patients [8%], 10 deaths and 25 recurrences/metastases during a follow-up period of 12 months).

Several studies have compared the results of RAPN in small and large tumors. Most studies have reported that, although estimated blood loss (EBL) and WIT are long in large tumors, there is no significant difference between functional and oncological outcomes depending on size.

Petros et al. [10] performed a multi-institutional analysis and compiled data relating to RAPN for renal tumors in patients with tumors >4 cm and ≤ 4 cm. They reported that patients who had tumors >4 cm showed longer WIT than those with tumors ≤ 4 cm (24 vs. 17 min; $p<0.001$), more EBL (200 vs. 150 mL; $p=0.001$), and a higher rate of collecting system repair (72.2% vs. 51.6%; $p=0.006$). However, there was no difference in risk of adverse outcomes between groups (complication rate: 8.4% vs. 3.9%, $p=0.37$; percent decrease in estimated glomerular filtration rate [eGFR] at the final follow-up: 8.6 vs. 3.9%, $p=0.11$; only one local recurrence occurred, which was in a patient with a tumor >4 cm) [10].

Reynolds et al. [11] compared RAPN for renal tumors in

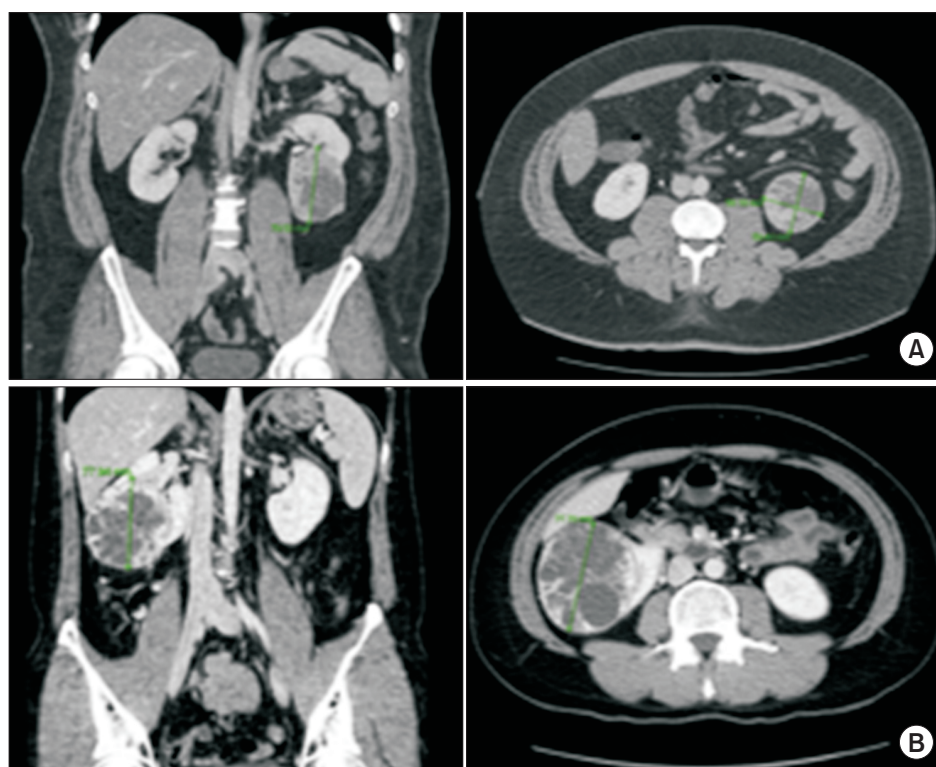


Fig. 1. Large and complex renal tumors. (A) Renal with RENAL score 11xh. (B) Renal with RENAL score 10a.

patients with T1a (n=1,307) and T1b (n=377) tumors. They reported that T1b was associated with longer WIT (18.8 vs 15.0 min; $p<0.001$), higher EBL (150.0 vs 100.0 mL; $p<0.001$), more intraoperative complications (5.6% vs 2.4%; $p=0.034$), and higher incidence of postoperative complications (10.1% vs 5.7%; $p=0.002$). However, there were no differences in the risk of major postoperative complications (3.7% vs 3.6%; $p=0.917$), PSM (3.0 vs 4.6%; $p=0.228$) or percentage change in eGFR at the final follow-up (-12.4% vs -8.5%; $p=0.156$). The authors suggested that RAPN should be considered for T1b tumors when the anatomical and spatial location allows for a feasible procedure [11].

Delto et al. [12] compared RAPN for renal tumors in patients with T1a, T1b, and T2a tumors. RAPN was associated with greater EBL in T2a tumors (T1a for 100 mL, T1b for 150 mL, T2a for 200 mL; p [T2a vs T1a] <0.001 , p [T2a vs T1b]=0.003) and WIT (T1a for 15 min, T1b for 18.1 min, T2a for 19.7 min; p [T2a vs T1a] <0.001 , p [T2a vs T1b]=0.252), and it was not associated with a greater rate of complications compared with T1 tumors (T1a for 10.4%, T1b for 13.2%, T2a for 7.3%; p [T2a vs T1a]=0.793, p [T2a vs T1b]=0.279) or PSM (T1a for 4.5%, T1b for 3.3%, T2a for 4.5%, p [T2a vs T1a] >0.999 , p [T2a vs T1b]=0.539). Renal function preservation rates were equivalent for up to 24 months postoperatively (p [T2a vs T1a]=0.124, p [T2a vs T1b]=0.0467); however, 12-month recurrence-free survival was significantly lower in the T2a group (T1a, 99.6%, T1b for 100%, T2a for 91.7%; p [T2a vs T1a] <0.001 , p [T2a vs T1b]=0.007). The authors suggested that RAPN could be a feasible treatment option for T2a tumors in a selected patient population when performed by experienced surgeons [12].

2. RAPN in complex renal tumor

In PN, size is not the only determining factor for surgical difficulty. Anatomical challenges can arise depending on whether the tumor is exophytic or endophytic and its relationship with the collecting system, renal sinus, and location (anterior, posterior, or polar) (Fig. 1). There are several standardized anatomical classification scoring systems, such as the RENAL nephrometry [13] score and the preoperative anatomical aspects and dimensions included in the PADUA score [14]. If each of the two classes is 10 points or more, it is considered as a high-complexity group. Based on these classifications, there are several reports of high-complexity renal tumors (Table 1) [15-19].

Buffi et al. [15] reported multicentric experience of RAPN in complex renal tumors (PADUA score ≥ 10), showing the feasibility and safety of RAPN in complex renal tumors (WIT: 18.6 min; Clavien–Dindo >2 complications: 13

[5.1%]; PSM: four recurrences [1.9%] during a follow-up of 28 months: one [0.4%] local and two [0.8%] distant). Volpe et al. [16] also reported a short WIT, acceptable major complication rate, and good long-term renal functional outcomes of RAPN for renal tumors, with a PADUA score ≥ 10 (WIT: 16 min; high Clavien–Dindo grade complications: four [9.1%]; no significant differences from the preoperative serum creatinine level at the 6-month follow-up [96.4 vs 89.3 $\mu\text{mol/L}$; $p=0.09$]).

To evaluate outcomes of PN, a trifecta is generally used and is defined as WIT <25 min, negative surgical margins, and no intraoperative or postoperative major complications (Clavien–Dindo grade ≥ 3) [20]. Koukourikis et al. [17] reported a 43.2% trifecta achievement rate of RAPN in high-complexity tumors (PADUA score ≥ 10). Nevertheless, it showed excellent long-term functional and oncologic outcomes over a median follow-up period of 58 months (87% eGFR preservation, 93.6% recurrence-free survival, and 96.7% overall survival rates), and RAPN was suggested to be a safe and effective treatment option [17]. Abdel Raheem et al. [18] reported a 37.5% trifecta achievement rate for a PADUA score of ≥ 10 after RAPN. However, long-term oncological and functional outcomes seem to be equivalent to a PADUA score <10 with 46.5-month follow-up (renal functional outcomes [$p>0.05$], overall survival [$p=0.314$], cancer-specific survival [$p=0.228$] and cancer-free survival [$p=0.532$], and suggest that high-complexity tumors can be successfully handled via the robotic approach [18].

In addition, Hennessey et al. [19] reported that RAPN is a safe approach for selected patients with RENAL nephrometry scores of 10 or more, showing good results (WIT: 23 min, 3.2% PSM, no recurrences during a follow-up of 125 months). However, significant differences were observed between 3 months postoperative and preoperative creatinine levels (77 and 93 $\mu\text{mol/L}$, respectively; $p<0.001$) and eGFR (79 and 64 mL/min/1.73 m², respectively; $p<0.001$) [19].

There is a study compared the results of RAPN in non-complex and complex tumors. Wakita et al. [21] investigated not only the size but also the complexity of RAPN. They compared the results of RAPN for patients with RENAL nephrometry scores ≥ 10 and non-complex renal tumors. They analyzed 299 patients who underwent RAPN for non-complex renal tumors and 49 patients who underwent RAPN for complex tumors. There were no differences in oncological outcomes, although more postoperative complications and decreased renal function were observed in complex tumors than in non-complex tumors. Specifically, the WIT was significantly longer in the complex tumor group (21 vs. 26 min; $p<0.01$). Major perioperative complications, defined as Clavien–Dindo classification ≥ 3 , were significantly more fre-

Table 1. Studies on RAPN in complex renal tumor

Study	Age (y), median (IQR)	Complexity (%)	WIT (min), median (IQR)	EBL (mL), median (IQR)	PSM (%)	Complications (%)	Recurrence (%)	Metastasis (%)
Buffi et al. [15]	62 (54–69)	PADUA 10, 43.5	17 (14–21)	150 (80–250)	3.4	Clavien–Dindo ≥ 2 , 3.3	-	-
		PADUA 11, 33.3	18 (15–22)	150 (100–225)	0	Clavien–Dindo ≥ 2 , 6.2	-	-
		PADUA 12–13, 23.1	21 (18–27)	200 (120–300)	1.9	Clavien–Dindo ≥ 2 , 11.9	-	-
Volpe et al. [16]	65 (60–73.8)	PADUA 10, 54.5	16 (13.8–18)	150 (80–200)	4.5	Clavien–Dindo 1, 11.4	-	-
		PADUA 11, 38.7				Clavien–Dindo 2, 2.3		
		PADUA 12, 6.8				Clavien–Dindo 3, 9.1		
Koukourikis et al. [17]	53 (45–62)	PADUA 10, 41.9	25 (21–31)	250 (150–400)	7.0	Clavien–Dindo ≥ 3 , 0.6	3.5	1.8
		PADUA 11, 35.5	27 (23.5–31)	200 (100–475)	5.8	Clavien–Dindo ≥ 3 , 0	1.9	3.8
		PADUA 12–13, 22.6	28 (23–34.5)	250 (100–500)	23.5	Clavien–Dindo ≥ 3 , 2.9	0	3.1
Abdel Raheem et al. [18]	51 (44–61)	PADUA ≥ 10 , 41	26 (22–32)	360 (200–550)	9.9	Clavien–Dindo ≥ 2 , 13.3	2.5	-
Hennessey et al. [19]	57 (50.5–70.5)	RENAL ≥ 10 , 12.4	23 (18.5–29)	200 (50–265)	3.2	Overall complications, 6.4	-	-

RAPN, robot-assisted partial nephrectomy; IQR, interquartile range; WIT, warm ischemic time; EBL, estimated blood loss; PSM, positive surgical margin.

quent in the complex tumors group than in the non-complex tumor group (5.7% vs. 16.3%; $p=0.018$). Postoperative preservation of eGFR at one year was significantly inferior in the complex tumor group (84.2% vs. 74.5%; $p<0.001$); however, at 3 (83.5% vs. 77.7%; $p=0.22$) and 5 (79.5% vs. 76.0%; $p=0.20$) years postoperatively, no significant differences were observed between the two groups. The PSM rates were 0% and 0.3% in the complex and non-complex tumor groups, respectively. There were no significant differences in recurrence-free survival between the two groups ($p=0.11$) [21].

3. RAPN in renal hilar tumor

It is difficult to locate tumors in the renal hilum (Fig. 2). Hilar tumors are classified based on the RENAL score, in addition to other scoring systems. These lesions may prove particularly challenging because of the possibility of injury to the main vessels, bleeding, and difficulty in reconstruction. The recurrence rate of hilar tumors is reportedly higher than that of non-hilar tumors [22]. Thus, even experienced surgeons should consider performing RN. However, several studies have suggested that RAPN is a feasible approach for the assessment of hilar tumors (Table 2) [23–26].

Sunaryo et al. [23] reported the results of a multi-institutional analysis of 263 patients with hilar tumors after

RAPN. They suggested that hilar renal tumors should be considered for RAPN as it shows acceptable results. Compared with non-hilar tumors, hilar tumors were associated with longer operative times (186 vs. 161 min; $p<0.001$), WIT (18 vs. 15 min; $p<0.001$), greater EBL (150 vs. 100 mL; $p<0.001$), eGFR decline at discharge ($\Delta=3.9\%$, $p=0.035$), and eGFR decline per month up to 36 months post-RAPN ($\beta=-0.25$; $p=0.017$). In the multivariable analysis, hilar tumors were only associated with a 10% increase in operative time ($p\leq 0.001$), and there were no differences in WIT, EBL, complication rate, or recurrence free survival [23]. Tyagi et al. [24] compared trifecta outcomes after RAPN for hilar versus non-hilar tumors. Trifecta was achieved in only 14/41 patients in the hilar group (34.1%), as compared to 24/41 (58.5%) in the nonhilar group ($p=0.027$). However, they reported that the hilar location of the tumors was not an independent predictor of overall complications (odds ratio [OR]: 6.37, 95% confidence interval [CI]: 0.5–69.4, $p=0.4$), and trifecta (OR: 0.38, 95% CI: 0.14–1.0, $p=0.051$) [24].

Miyake et al. [25] compared RAPN and open partial nephrectomy (OPN) for hilar tumors. They showed a WIT of 23.0 ± 7.5 min for RAPN and a WIT of 20.3 ± 9.1 min for OPN for hilar tumors, but there was no significant difference ($p=0.37$). Neither were there any significant differences in

Table 2. Studies on RAPN in renal hilar tumor

Study	Age (y), mean (range) or mean $\pm$ SD	Tumor size (cm), mean (range) or mean $\pm$ SD	Operation time (min), mean (range) or mean $\pm$ SD	WIT (min), mean (range) or mean $\pm$ SD	EBL (mL), mean (range) or mean $\pm$ SD	PSM (%)	Complications (%)	Decrease in postoper- ative eGFR (%), mean (range) or mean $\pm$ SD
Sunaryo et al. [23]	58.2 (26–83)	3.7 (1.1–12.0)	186 (156–230)	18 (14–23)	100 (50–200)	3.61	Major complications (4.72)	-16.78 (-30.02 to -2.71)
Tyagi et al. [24]	49.4 $\pm$ 12.9	4.7 $\pm$ 1.7	166.2 $\pm$ 51	28.8 $\pm$ 8.3	201.5 $\pm$ 175	6.25	Overall complication (14.5)	-8.6 $\pm$ 23.7
Miyake et al. [25]	63.3 $\pm$ 13.2	3.0 $\pm$ 0.9	263.0 $\pm$ 63.5	23.0 $\pm$ 7.5	57.5 $\pm$ 96.9	0	Clavien–Dindo $\geq$ 2 (0)	-10.4 $\pm$ 7.0
Hinata et al. [26]	62.6 (38–85)	3.2 (1.3–6.5)	146 (46–318)	20.2 (7–70)	138.6 (1–1,500)	1.9	Clavien–Dindo $\geq$ 2 (4.8)	-

RAPN, robot-assisted partial nephrectomy; SD, standard deviation; WIT, warm ischemic time; EBL, estimated blood loss; PSM, positive surgical margin; eGFR, estimated glomerular filtration rate.

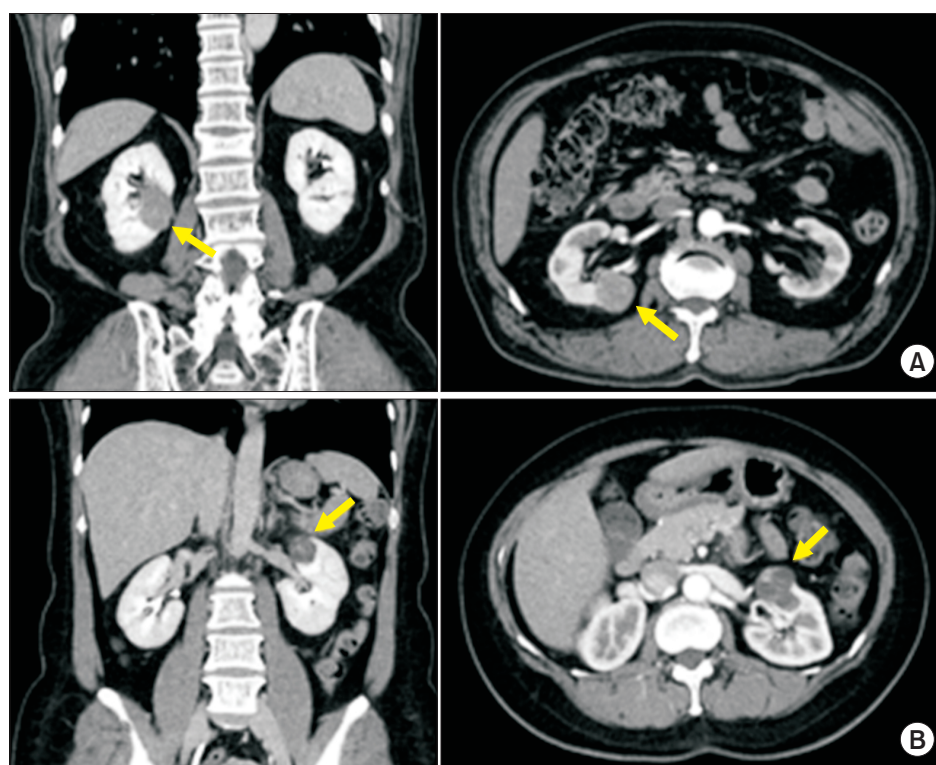


Fig. 2. (A) Posterior renal hilar tumor on CT image. (B) Anterior renal hilar tumor on CT image. CT, computed tomography.

the incidence of postoperative complications ($p=0.25$) or the percentage decrease in the eGFR at 4 weeks after surgery ($p=0.87$) between the two groups. They suggested that RAPN is a less invasive surgical option for renal hilar tumors [25]. Hinata et al. [26] compared RAPN and LPN for hilar tumors in a prospective multi-institutional study. They showed superiority of RAPN over LPN for hilar tumors in terms of WIT, with a 20.2 minutes WIT for RAPN, compared with 27.7 minutes for LPN (95% CI: 16.7–21.8; $p<0.0001$) [26].

4. RAPN in multiple renal tumor

PN for multiple renal tumors is challenging because

of the anatomical approach and positional changes for a single tumor, which differ from those of PN. Treatment with minimally invasive PN is more challenging than open techniques. However, experienced surgeons implementing minimally invasive PN for multiple renal tumors have been reported several times (Table 3) [27–29].

In 2009, Boris et al. [27] reported their initial experience of removing 24 tumors from the unilateral kidney in nine patients, with up to four tumors removed per patient. Given their observations, they suggested that RAPN is feasible for multiple ipsilateral tumors (size: 2.3 cm, WIT: 29.6 min), with no intraoperative complications, no loss of renal units, and

one conversion to open surgery [27]. Furthermore, Yang et al. [28] recently showed the feasibility of sequential clamping of segmental renal arteries in RAPN for multiple ipsilateral renal tumors in 11 patients (size: 3.3 cm, RENAL score: 5.7, total clamping time for a single case: 37.5 min, insignificant reduction [9.3%] of postoperative eGFR, no PSM, and no recurrence or metastasis during a follow-up period of 5.4 months). However, Maurice et al. [29] reported that multiple tumor excisions in the ipsilateral kidney are associated with increased morbidity, emphasizing the need for caution in implementing RAPN for multiple tumors. The number of excised ipsilateral masses during RAPN was significantly associated with complications (20.2% for ≤ 2 excisions vs. 42.9% for >2 excisions; $p=0.037$) [29].

5. RAPN for renal tumor in solitary kidney

Although LPN has been performed by experts in patients with a solitary kidney as an MIS, OPN is considered the 'gold standard' treatment for tumors in a solitary kidney because LPN has a longer WIT, higher rate of complications, and higher rates of dialysis. RAPN can be considered an alternative to open and laparoscopic techniques, as it shows oncological outcomes comparable to LPN and OPN, functional outcomes comparable to OPN, and better functional outcomes compared to LPN in general cases (Table 4) [30-33].

Hillyer et al. [30] reported that RAPN is a feasible treatment option for solitary kidneys, as it reliably preserves renal function, low surgical morbidity, and oncological outcomes (WIT: 17 min; intraoperative complication rate: 7.7%, postoperative complication rate: 11.5%, recurrence rate: 3.8%,

Table 3. Studies on RAPN in multiple renal tumor

Study	Number of cases	Age (y), mean (range) or %	Number of tumors, mean (range) or number	RENAL score, mean (range) or mean $\pm$ SD	Tumor size (cm), mean (range) or mean $\pm$ SD	Operation time (min), mean (range) or mean $\pm$ SD	WIT (min), median (IQR), mean [range] or mean $\pm$ SD	EBL (mL), mean (range) or mean $\pm$ SD
Boris et al. [27]	9	50 (26–69)	2.7 (2–4)	-	2.3 (0.5–5.5)	257 (195–330)	29.6 (19–48) ^a	360 (100–500)
Yang et al. [28]	12	62.7 (42–77)	2.2 (2–3)	5.7 (4–10) ^b	2.7 (1.4–5.8)	91.7 (72–155)	37.5 [32.0–52.0]	150 (50–350)
Maurice et al. [29]	35	<60, 54.3 60–69, 22.9 ≥ 70 , 22.9	2	6.4 $\pm$ 1.9	2.7 $\pm$ 1.5	194 $\pm$ 54	16 $\pm$ 12	184 $\pm$ 203
	14	<60, 57.1 60–69, 28.6 ≥ 70 , 14.3	3	7.4 $\pm$ 1.7	3.4 $\pm$ 1.5	240 $\pm$ 101	24 $\pm$ 17	330 $\pm$ 353

RAPN, robot-assisted partial nephrectomy; SD, standard deviation; WIT, warm ischemic time; IQR, interquartile range; EBL, estimated blood loss.

^a:66% patients required hilar clamp.

^b:Maximum for each patient.

Table 4. Studies on RAPN for renal tumor in solitary kidney

Study	Age (y), median (IQR) or mean $\pm$ SD	RENAL score, median (IQR) or %	Tumor size (cm), median (IQR)	WIT (min), median (IQR) or mean $\pm$ SD	EBL (mL), median (IQR)	PSM (%)	Decreased eGFR (%), median (IQR) or mean $\pm$ SD
Hillyer et al. [30]	66 (60–71)	6 (5–7)	4.3 (2.9–5)	17 (12–28)	225 (100–437)	3.8	-15.8 (-21.4 to -4.5)
Zargar et al. [31]	61.3 $\pm$ 10.7	RENAL score 4–8, 6 (2)	2.5 (2.35)	15 (9)	200 (300)	6.7	-17.9 $\pm$ 22.7
		RENAL score 9–12, 9.5 (1)	4.15 (2.9)	22.7 $\pm$ 5.8	225 (288)	10	-19.7 $\pm$ 23.7
Panumatrassamee et al. [32]	63 (59–69)	RENAL score 4–6, 53 RENAL score 7–9, 27 RENAL score 10–12, 20	3.2 (2.5–5.3)	15 (0–24)	150 (100–300)	0	-23 (-28 to 6)
Arora et al. [33]	64 (56–72)	6 (5–9)	2.3 (1.8–3.7)	15.5 (8.75–20.0)	150 (100–350)	5.4	-7 (16.3)

RAPN, robot-assisted partial nephrectomy; IQR, interquartile range; SD, standard deviation; WIT, warm ischemic time; EBL, estimated blood loss; PSM, positive surgical margin; eGFR, estimated glomerular filtration rate.

PSM, and no significant change in percentage in eGFR after surgery [$p=0.13$]. Zargar et al. [31] compared RAPN and OPN in solitary kidneys with low RENAL nephrometry scores and reported that RAPN showed perioperative and short-term functional outcomes comparable to OPN (no significant difference between the treatment modalities in overall intraoperative/postoperative complications, transfusion rate, and PSM rates, no difference in eGFR preservation beyond 1 month [OPN 80.51% vs. RAPN 81.29%]).

Panumatrassamee et al. [32] compared RAPN and LPN in solitary kidneys and reported that RAPN has advantages in terms of OT (225 vs. 171 min; $p=0.02$), WIT (19 vs. 15 min; $p=0.04$), and hospital stay (4 vs. 3 d; $p=0.03$) compared with LPN. One study also suggested that RAPN is a safe and effective treatment option in a solitary kidney, as it showed 'trifecta' outcomes in solitary kidney. Thirty-eight of 66 patients (57.6%) achieved trifecta outcomes, with a mean WIT of 15.5 min, a 24.1% overall complication rate, Clavien–Dindo grade $\leq$ II complications rate of 16.3%, and a PSM rate of 5.4% [33].

6. RAPN for renal tumor in horseshoe kidney

Surgery for tumors in a horseshoe kidney is another challenging procedure because of the unique anatomical features, such as high variability of the vascular structure; presence of an isthmus, which could cause decreased mobility of the kidney; and abnormal renal pelvic and ureteral passage. However, several such cases have been reported to date. RAPN with tumors in a horseshoe kidney was first reported in 2017 [34], and several successful procedures involving various tumor locations have been reported [35–38]. It is important to establish a detailed three-dimensional preoperative image to determine the optimal approach (trans- or retroperitoneal) and strategy, owing to the unique anatomy of the horseshoe kidney.

7. RAPN in salvage treatment

Repeat surgery is more difficult to perform than conventional surgery due to adhesions caused by the previous surgery and it is associated with higher morbidity and long-term risk of requiring renal replacement therapy [39,40]; therefore open techniques are considered first. For this reason, MIS is not considered for repeat surgeries; however, there are several reports of RAPN being used for repeat surgery.

Autorino et al. [41] first reported the results of repeat RAPN performed in nine patients. They suggested that while technically more demanding, repeat RAPN can be safely and effectively performed (RENAL nephrometry score: 7, WIT: 17.5 min, no intraoperative complications, no significant difference between mean preoperative and lat-

est postoperative eGFR [70.5 vs. 63.5 mL/min/1.73 m²; $p>0.05$], and all surgical margins were negative) [41]. Watson et al. [42] compared 98 patients with initial RAPN and 26 patients with repeat RAPN; although repeat RAPNs showed more EBL (500 vs. 900 mL; $p=0.01$), longer length of stay (8 vs. 10 d; $p=0.01$), and higher rate of urine leak (3.1% vs. 19.2%; $p=0.01$), renal function preservation was comparable (preoperative and 3-month eGFR: -4.7 vs. -5.21%, respectively; $p=0.41$); therefore, they suggested that repeat RAPN is a safe and feasible procedure [42].

RAPN IN SPECIAL PATIENTS

Besides abnormalities in the anatomy of the kidney or its surrounding structures, each surgery may present unique difficulties depending on specific patient characteristics, which can also affect surgical outcomes. Obesity, old age, and young age are representative examples. Nevertheless, RAPN can be considered even in such unusual situations. Below, we discuss some studies showing that RAPN can show a favorable outcome, even in unique situations.

1. RAPN in obese patients

Obesity can directly or indirectly increase the risk of perioperative morbidity due to obesity-related comorbidities [43,44]. In addition, obesity is related to greater EBL and operation time, as it makes open urological surgery more difficult [45,46]. RAPN provides a technical advantage over other techniques, and good results have been reported in patients with obesity (Table 5) [47–49].

Malkoc et al. [47] compared the results of OPN and RAPN in obese patients (defined as body mass index >30 kg/m²) with small renal masses. They reported superiority of RAPN in intraoperative blood transfusion (1.1% vs 10%; $p=0.01$), median operating time (180 vs. 207 min; $p<0.01$), median ischemia time (19.5 vs 27 min; $p<0.01$), and overall complication rate (15.8% vs 31.7%; $p<0.01$) compared with OPN [47].

Abdullah et al. [48] compared RAPN between non-obese and obese patients (body mass index >30 kg/m²) and reported that RAPN for non-obese patients was superior in terms of the median operating time (176 vs. 165 min; $p=0.002$) and median (150 vs. 100 mL; $p=0.002$), but there was no difference in the rate of intraoperative and postoperative complications ($p=0.985$, $p=0.346$). Rosen et al. [49] compared non-obese and obese patients (body mass index >30 kg/m²). Similarly, they reported that heavier patients required longer operative times (166–196 vs. 155 min; $p<0.001$), but there was no difference in WIT ($p=0.873$) or complication rates ($p>0.05$) [49].

Table 5. Studies on RAPN in obese patients

Study	Age (y), mean±SD, median (IQR) or mean [range]	BMI, kg/m ² , median (IQR)	RENAL score, median (IQR), mean±SD or mean [range]	Tumor size (cm), median (IQR) or mean [range]	Operation time (min), median (IQR) or mean [range]	WIT (min), median (IQR) or mean [range]	EBL (mL), median (IQR) or mean [range]	PSM (%) (Clavien–Dindo ≥3)	Complications (Clavien–Dindo ≥3) (%)	Change in eGFR (%), median (IQR)
Malkoc et al. [47]	54.9±11.4	Overall 33.4 (31.4–39)	7 (5–8)	2.5 (2–3)	180 (150–210)	19.5 (15–25)	150 (75–210)	4	5.6	83.8 (75.7–93.7)
		30–34.9								
		60.4%								
		35–39.9								
		21.5%								
		≥40								
		18.1%								
Abdullah et al. [48]	59 (51–65)	33.8 (31.6–38.0)	7.3±1.9	2.9 (2.0–4.0)	176 (142–212)	19 (15–24)	150 (100–250)	3.5	4.4 (Clavien–Dindo >3)	-12.26 (-24.5–0.2)
Rosen et al. [49]	62 [17–87]	25–29.99	7 [4–12]	2.8 [0.4–19.0]	166.0 [76.0–345.0]	15.2 [0.0–51.0]	100 [7–1,500]	5.1	6.0	-
		34.3%								
	61 [24–89]	30–39.99	7 [4–12]	3.0 [0.5–15.0]	175.0 [81.0–400.0]	16.0 [0.0–52.0]	100 [5–2,500]	6.3	5.1	-
		35.8%								
	57 [23–79]	≥40	7 [4–12]	3.0 [0.8–10.8]	196.0 [103.0–436.0]	15.1 [0.0–51.0]	100 [20–1,500]	3.7	4.2	-
		9.4%								

RAPN, robot-assisted partial nephrectomy; SD, standard deviation; IQR, interquartile range; BMI, body mass index; WIT, warm ischemic time; EBL, estimated blood loss; PSM, positive surgical margin; eGFR, estimated glomerular filtration rate.

2. RAPN in elderly patients

Currently, PN is preferred for localized renal masses in most patients; however, its applicability has not been established in elderly patients. This is because pre-existing medical comorbidities and complications related to the procedure are higher in older patients than in younger patients. However, RAPN is known to have fewer complications and better operative outcomes than OPN and LPN [50]. Because of these characteristics, RAPN has been implemented in elderly patients, and several related studies have been conducted.

Vartolomei et al. [51] reported long-term oncological and functional outcomes of RAPN in elderly patients. The median patient age was 74 years (IQR, 72–76.5 y), and most of the patients (67.3%) had low PADUA score. The complication rate was 15.4%, and most of the patients (50%) had a Clavien–Dindo score of 2. The trifecta achievement rate was 71.2%, and trifecta failure was associated with PADUA score ($p=0.02$) and tumor diameter ($p=0.04$). The preoperative and postoperative mean creatinine levels were 0.97 mg/dL (range 0.38–2.31 mg/dL) and 1.01 mg/dL (range 0.44–2.39 mg/dL), respectively ($p=0.33$). The disease-free survival, overall survival, and cancer-specific survival were 89.33%, 90.06%, and 94.4%, respectively. These results suggest that RAPN is feasible and safe for elderly patients and that it has good long-term oncological outcomes [51].

Veccia et al. [52] compared RAPN with robot-assisted radical nephrectomy (RARN) in elderly patients with large renal masses. After propensity matching, the mean age was 71.3 years in the RARN and 73.0 in the RAPN group, and the mean RENAL score was 9.6 in the RARN and 8.6 in the RAPN group. EBL (200 vs. 100 mL; $p<0.001$) and rate of overall complications (38% vs. 23%; $p=0.05$) were higher in the RAPN group; however, there was no difference in major complications ($p=0.678$). The RAPN group showed higher eGFR levels (55.4 ± 22.6 vs. 45.7 ± 15.7 mL/min; $p=0.016$) and lower eGFR variation (9.7 vs. 23.0 mL/min; $p<0.001$) at the final follow-up. Procedure type was not associated with recurrence free survival (hazard ratio [HR]: 0.47; $p=0.152$) or overall mortality (HR: 0.22; $p=0.084$). Veccia et al. [52] suggested that RAPN in elderly patients with large renal masses provided acceptable surgical and oncological outcomes, allowing for better functional preservation than RARN.

3. RAPN in pediatric patients

Pediatric surgery is a challenging environment for surgeons because of the smaller scale. However, robotic surgery is reported to be feasible and safe in children [53], and several studies of RAPN in pediatric patients have been conducted.

Lee et al. [54] reported the results of RAPN for nine pediatric patients. The mean age and weight of patients were 7.2 kg (range: 0.5–16.5 kg) and 34.8 kg (range: 8.1–104.0 kg), respectively. The mean operative time was 275 minutes, and the mean EBL was 49 mL. Overall, the patients had a mean hospitalization duration of 2.9 days. All patients had normal remaining renal moieties, as confirmed by Doppler ultrasonography. The only complication was an asymptomatic urinoma, which was discovered on ultrasound. These results demonstrated the safety and feasibility of RAPN in children [54].

Ballouhey et al. [55] compared RAPN and OPN in children under 15 kg. RAPN showed better outcomes than OPN in terms of hospital stay (6.3 d, range: 5–8 d vs. 3.4 d, range: 1–7 d; $p<0.001$) and postoperative pain control in terms of total morphine equivalent intake (0.52 vs. 1.08 mg/kg/day; $p<0.001$). There were no significant differences in operating time, complication rate, or renal outcome. The authors suggested that RAPN in small children offers renal outcomes comparable to those of standard open surgery [55].

ADVANCED TECHNIQUES IN RAPN

1. Single-port (SP) RAPN

Intuitive Surgical recently released a new second-generation single-site robotic platform, the da Vinci SP system, which received FDA approval in 2018 [56]. The SP system has been successfully employed in many urological surgeries, with studies indicating that it allows for shorter hospital stays, decreased postoperative pain, and improved wound cosmesis [57,58]. Several studies also suggest that the SP system could be adaptable to RAPN, showing comparable or superior outcomes when compared with conventional multi-port (MP) RAPN.

Okhawere et al. [59] reported a longer mean ischemia time in the SP group (18.29–10.49 vs. 13.79–6.29 min; $p<0.001$) compared to the MP group. However, other variables such as EBL, length of hospital stay, operative time, PSM, and any complication rate were similar between the two groups [59]. Glaser et al. [60] found the mean operative time for SP cases was 183.9 ± 63.5 and 208.6 ± 65.0 minutes for MP cases ($p=0.12$). They also reported that the rate of conversion to RN was 3.8% for SP cases vs. 9.6% for MP cases ($p=0.37$). The majority of patients were discharged on the first postoperative day (67.9%), irrespective of the operative approach ($p=0.60$) [60].

Harrison et al. [61] highlighted the benefits of the SP system. They reported that the SP cohort had lower median opioid use on postoperative day 1 (4.6 vs. 9.8 morphine milligram equivalents, $p=0.0209$) and during the cumulative

hospital stay (5.1 vs. 9.3 morphine milligram equivalents, $p=0.0357$). The SP system also resulted in a shorter median length of stay (1.4 vs. 1.6 days, $p=0.0045$). There were no significant differences in operative time, EBL, WIT, transfusions received, or PSM [61].

One study compared transperitoneal (TP) and retroperitoneal (RP) approaches for RAPN with the SP system. Bang et al. [62] found no significant difference in WIT (727.41–561.18 s for TP and 698.56–299.23 s for RP, $p=0.812$) or console time (67.97–24.06 min for TP and 69.71–28.66 min for RP, $p=0.724$). Postoperative renal function, calculated from diethylenetriamine pentaacetic acid kidney scans, was 103.33 mL/min/1.73 m² for TP and 101.33 mL/min/1.73 m² for RP ($p=0.214$). And at 90 days post-surgery, it was 90.36 mL/min/1.73 m² for TP and 87.74 mL/min/1.73 m² for RP ($p=0.592$) [62].

2. Three-dimensional (3D) technology in RAPN

Most RAPN cases that represent a considerable challenge are due to unusual anatomy or complexity. As imaging techniques advance, a high level of anatomical information can be achieved, although preoperative consultation is mostly performed by CT or MRI, which are two-dimensional imaging modalities [63]. On the other hand, 3D imaging can provide spatial depth perception that cannot be accomplished by two-dimensional imaging; accordingly, 3D technology is applied to RAPN nowadays. Several studies have been conducted on RAPN using the 3D technology.

Kim et al. [64] reported that the use of a 3D-printed transparent kidney model reduced the console time by 20% compared with conventional RAPN (64.6 vs. 78.5 min; $p=0.001$). Michiels et al. [65] suggested that 3D-image guided RAPN could lower the risk of complications and improve perioperative clinical outcomes, as it showed improved results in terms of major complications (3.8% vs. 9.5%; $p=0.04$), eGFR variation (-5.6% vs. -10.5%; $p=0.002$), and trifecta achievement rate (55.7% vs. 45.1%; $p=0.005$). Furthermore, a study demonstrated that perfusion-region-3D virtual models allow maximizing the efficacy of selective clamping and minimizing renal function impairment. Amparore et al. [66] reported that the mean split renal function decreased by 11.3%, 7.7%, and 1.7%, and the estimated renal plasmatic flow decreased by 18.9%, 9.9%, and 6.0% after global, selective, and superselective clamping, respectively ($p=0.004$, $p=0.02$).

3D technology is expected to not only improve perioperative outcomes by providing specific anatomical information before RAPN but also to have a positive influence on the learning curve and increase accessibility and expertise in RAPN in the future.

CONCLUSIONS

The results of these studies suggest that RAPN can be established as a representative surgical method for MIS with excellent oncological and functional outcomes. Moreover, many studies have suggested that RAPN can even be considered under special circumstances in which open techniques would typically be considered first because of the difficulty in accessing MIS. In most cases, RAPN is the best surgical method for achieving nephron-sparing surgery. These special procedures are performed by experienced surgeons, and likewise should be performed by experts in actual surgical situations. These studies are limited by their relatively short follow-up durations due to RAPN being a recent innovation; however, the results of the available studies so far have shown that RAPN can play a substantial role as a mainstream treatment for PN. Furthermore, new robotic systems are being developed and introduced, and it is expected that they will be able to overcome limitations such as the application of cold ischemic times that cannot be applied at present. With these advances, the use of RAPN is expected to expand in the future, overcoming technological limitations and achieving better results.

CONFLICTS OF INTEREST

The authors have nothing to disclose.

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AUTHORS' CONTRIBUTIONS

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