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REVIEW

Perioperative, functional, and oncologic outcomes of minimally-invasive surgery for highly complex renal tumors (RENAL or PADUA score ≥ 10): an evidence-based analysis

Xiao-ran Li[1] · Kun-peng Li[1] · Jia-le Zuo[1] · Wei Yang[1] · Hao Tan[1] · Wen-yun Wang[1] · Si-yu Chen[1] · Jun-hai Ma[1] · Jun-sheng Bao[1] · Zhong-jin Yue[1]

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Abstract

The primary objective of the current study is to undertake a comparative analysis of the effectiveness and safety of minimally-invasive partial nephrectomy (MIPN; including laparoscopic and robotic approaches) and open partial nephrectomy (OPN) for the treatment of highly complex renal tumors (defined as PADUA or RENAL score ≥ 10). A comprehensive search was conducted in four electronic databases (PubMed, Web of Science, Embase, and Cochrane Library) to identify relevant studies published in the English language up to April 2023. The current study employed Review Manager 5.4 and encompassed controlled trials of both MIPN and OPN for the treatment of highly complex renal tumors. This study comprised a total of eight comparative trials involving 1161 patients. MIPN demonstrated a significant reduction in length of hospital stay (weighted mean difference [WMD] − 2.08 days, 95% confidence interval [CI] − 2.48, − 1.68; p < 0.00001), blood loss (WMD − 39.86 mL, 95% CI − 75.32, − 4.39; p = 0.03), transfusion rates (odds ratio [OR] 0.30, 95% CI 0.13, 0.71; p = 0.006), and overall complications (OR 0.46, 95% CI 0.31, 0.70; p = 0.0003). However, there were no significant differences between MIPN and OPN in terms of operative time, warm ischemia time, conversion to radical nephrectomy rates, renal functional and oncologic outcomes. This study reveals that MIPN presents several benefits in comparison to OPN, including decreased length of hospital stay, blood loss, transfusion rates, and complications, while still offering renal functional and oncological outcomes that are comparable to those of OPN in patients with highly complex renal tumors.

Keywords Minimally-invasive surgical procedures · Open surgical procedures · Highly complex renal tumors · Outcomes · Meta-analysis

Introduction

Renal cell carcinoma is a malignant tumor that affects a noteworthy proportion of adults, accounting for approximately 3–5% of all cancer cases. It is considered the second most common urological malignancy, and its incidence has been gradually increasing at a rate of around 2% per year [1, 2]. Research has demonstrated that kidney cancers exhibit limited sensitivity to radiation therapy, and also tend to develop resistance to various drugs, thereby imposing significant restrictions on the efficacy of targeted therapy and immunotherapy [3]. Consequently, surgical resection continues to remain the primary mode of treatment for kidney cancer. Partial nephrectomy (PN) offers superior outcomes in terms of preserving renal function compared to radical nephrectomy, while also providing equivalent oncological outcomes [4]. Additionally, PN has been associated with decreased mortality rates for cardiovascular events [5].

The field of surgical technology for PN has undergone significant advancement, transitioning from the traditional open partial nephrectomy (OPN) to laparoscopic partial nephrectomy (LPN), and ultimately to the advanced robotic partial nephrectomy (RPN). However, even with these advancements, performing PN on highly complex renal

✉ Jun-hai Ma
junhaiurology@163.com

✉ Jun-sheng Bao
bjshurol@qq.com

✉ Zhong-jin Yue
yuezhongjing@sina.cn

[1] Department of Urology, Lanzhou University Second Hospital, Lanzhou, China

tumors remains a challenging task, and the possibility of perioperative complications cannot be disregarded [6, 7]. Highly complex renal tumors are typically characterized by a PADUA or RENAL score of ≥ 10 [8, 9], and the efficacy of nephron-sparing treatments for these tumors remains a contentious topic. These tumors are situated deep within the renal parenchyma and are positioned near the midline of the coronal plane of the kidney, presenting complex anatomical structures that are in close proximity to the kidney's collection system [10]. Despite the significance of these challenges, research in this area remains insufficient, especially with regards to minimally invasive partial nephrectomy (MIPN). While there have been several studies comparing the perioperative and functional outcomes of MIPN and OPN for highly complex renal tumors, many of these studies were limited to a single medical center or a single highly-skilled surgeon. This presents a gap in research, as a broader range of comparative studies is necessary to gain a more comprehensive understanding of the advantages and disadvantages of these surgical approaches.

Consequently, the objective of this study is to synthesize the data from comparative studies and assess the effectiveness and safety of MIPN and OPN in treating highly complex renal tumors. The outcomes of this study are intended to serve as a comprehensive guide for clinical decision-making, aiding physicians in choosing the most appropriate surgical approach for their patients.

Methods

This study adhered to the guidelines outlined in the 2020 version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [11, 12] and underwent registration in the PROSPERO registry (ID: CRD42023424308).

Literature search strategy, study selection and data collection

A rigorous and comprehensive search was conducted across several databases, including PubMed, Embase, Web of Science, and Cochrane Library, with data collection concluding in April 2023. The search terms were formulated as follows: ((Robotic PN OR Robot-assisted PN) AND (Laparoscopic PN) AND (Renal cancer OR Renal tumor OR Renal carcinoma OR Renal mass OR Kidney cancer) AND (Highly complex)). To enhance the comprehensiveness of the search, we also conducted a manual search of pertinent references and abstracts, thereby broadening the search scope and minimizing the possibility of missing relevant studies.

We utilized the PICOS approach to delineate the inclusion criteria: P (patients): All patients were diagnosed with highly complex renal tumors, defined as having a PADUA or RENAL score of ≥ 10 [8, 9]; I (intervention): patients who underwent either RPN or LPN; C (comparator): the comparator was OPN; O (outcome): studies measured various outcomes, including perioperative, complications, renal function, and oncologic outcomes; S (study type): eligible studies encompassed prospective studies, randomized controlled trials (RCTs), cohort studies, retrospective studies, or case–control studies. The exclusion criteria were as follows: (1) studies of editorial comments, reviews, case reports, and unpublished works (2) lack of available data for the meta-analysis, and (3) non-comparative studies.

Two authors independently conducted data extraction from each qualified literature. (1) general information pertaining to the manuscript. (2) characteristics of the study population. (3) perioperative effectiveness parameters. (4) renal functional and oncologic outcomes. Any discrepancies or inconsistencies identified in the collected data were resolved through a consensus with a third reviewer.

To gauge the quality of the literature, the studies included in the analysis underwent a meticulous assessment utilizing the "risk of bias in non-randomized studies of interventions" (ROBINS-I) tool [13]. The evaluation was carried out independently by two reviewers (X.L. and K.L.), who rigorously scrutinized the studies for any potential biases, including confounding factors or other sources of systematic error. Any discrepancies or disagreements that arose during the evaluation process were resolved through a thorough discussion.

Statistical analysis

For the purpose of data analysis in this study, we utilized the Cochrane Collaborative RevMan 5.4 software. We used the odds ratio (OR) and weighted mean difference (WMD) to measure dichotomous and continuous outcomes, respectively, and provided 95% confidence intervals (CI) for all outcomes. To determine the heterogeneity among the studies, we used the I^2 test [14]. Due to the expected presence of between-trial heterogeneity, we used the random-effects model for all analyses, and statistical significance was determined by a p-value of less than 0.05. For outcomes that exhibited significant heterogeneity ($I^2 > 75\%$), we conducted sensitivity analyses to identify the source of between-study heterogeneity and to assess the robustness of our findings. Nevertheless, sensitivity analyses could not be performed for outcomes based on three or fewer studies. To evaluate the potential publication bias of the studies, we utilized the funnel plot.

Subgroup analysis

We conducted a subgroup analysis based on various factors, including surgical approaches, age, sample size, country/region, and PADUA or RENAL score.

Results

Baseline characteristics

In the initial electronic search, a total of 178 articles were identified, with 24 remaining after eliminating duplicates. Upon screening titles and abstracts, eight retrospective studies comprising 1161 patients (630 MIPN vs. 531 OPN) were deemed eligible for inclusion in this meta-analysis, as depicted in Fig. 1 [15–22]. Notably, three of the included studies were multi-institutional [19, 21, 22], and two employed a pair-matched method [15, 17]. These studies were conducted in diverse countries, including China, Italy, USA, and Korea, and were published between 2014 and 2022. Detailed baseline patient characteristics are presented in Tables 1 and 2. Moreover, Table 3 provides a comprehensive summary of tumor stage and histopathological results.

The statistical analysis demonstrated non-significant differences in various parameters, including age ($p = 0.90$), left side ($p = 0.75$), BMI ($p = 0.30$), and preoperative eGFR ($p = 0.39$) between two groups (Table S1).

Assessment of quality

The current meta-analysis conducted a rigorous assessment of eight selected studies, wherein seven studies were observed to have exhibited a moderate level of risk in terms of bias, while only one study was found to have demonstrated a significantly low risk of bias [16]. Moreover, all the studies conducted a comparative analysis (Table S2).

Outcome analysis

Perioperative effectiveness

The meta-analysis comprised seven studies that analyzed operative time. The results revealed no significant difference in operative time between the MIPN and OPN groups ($p = 0.19$; seven studies) [15, 16, 18–22]. Additionally, subgroup analysis showed no significant difference in operative time between RPN and LPN when compared to OPN ($p = 0.86$; $p = 0.13$). Nevertheless, the MIPN group

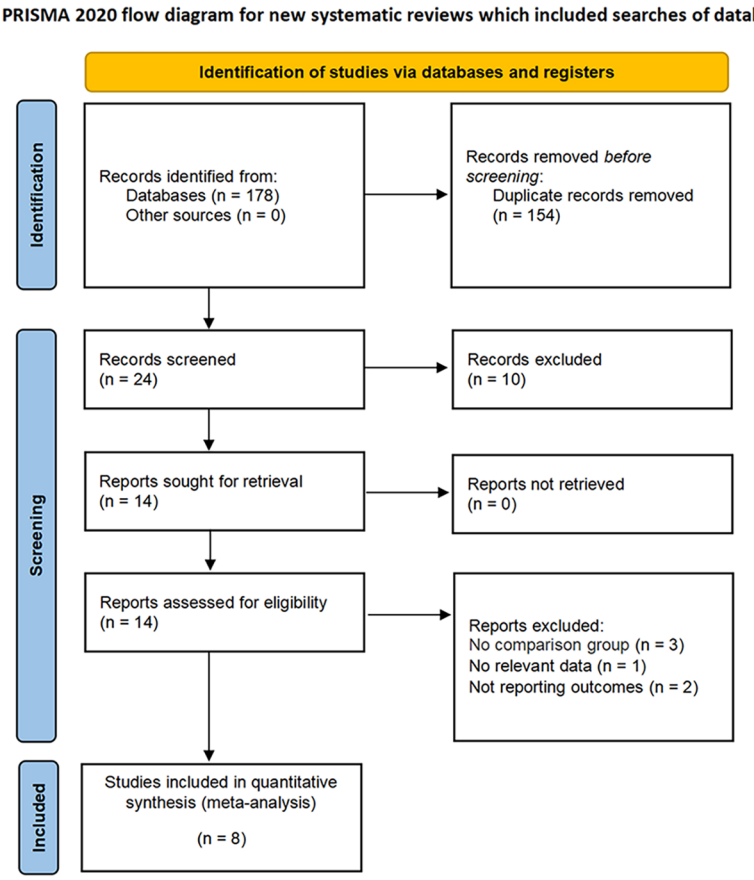

Fig. 1 PRISMA flow diagram for the systematic review

Table 1 The trials included in the systemic review

Reference	Year	Country	Propensity scoring analysis	Center	Patients		Age (years)		Male/female		BMI (kg/m^2)	
					MIPN	OPN	MIPN	OPN	MIPN	OPN	MIPN	OPN
Liu	2022	China	Yes	Single-center	97	44	57 (9.26)	54.5 (8.52)	66/31	29/15	24.5 (3.19)	26.10 (5.41)
Li	2021	China	No	Single-center	20	20	57.6 (11.5)	58.5 (12.15)	12/8	14/6	NA	
Yu	2021	China	Yes	Single-center	66	66	52.16 (8.43)	53.46 (8.51)	36/30	37/29	24.6 (3.1)	25 (2.9)
Chiancone	2021	Italy	No	Single-center	72	21	60.15 (10.39)	59.19 (10.6)	42/30	12/9	26.3 (1.9)	26.8 (1.5)
Mari	2021	Italy	No	Multi-institutional	77	188	63.9 (13.19)	64.1 (13.19)	57/20	116/72	26.1 (3.33)	25.5 (3.7)
Kim	2019	Korea	No	Single-center	85	64	53 (13.33)	52 (14.82)	55/30	42/22	24.7 (3.41)	24.8 (2.67)
Garisto	2018	USA	No	Multi-institutional	203	76	59.8 (12.1)	60.7 (11.2)	125/78	44/32	31 (6.8)	31.2 (6.1)
Zargar	2014	USA	No	Multi-institutional	10	52	61.3 (10.7)	61.5 (11.4)	NA		30 (5.4)	31.7 (6.6)

MIPN minimally-invasive partial nephrectomy, *OPN* open partial nephrectomy, *BMI* body mass index; mean (SD)

Table 2 The trials included in the systemic review

Reference	Tumor site (Lt/Rt)		Tumor diameter (cm)		Preoperative eGFR (ml/min/1.73 m)		PADUA or RENAL score		Surgical approach	Follow-up duration (months)
	MIPN	ONU	MIPN	ONU	MIPN	ONU	MIPN	ONU		
Liu	60/37	25/19	NA		100 (24.78)	92.07 (30.69)	RENAL score:10		LPN vs OPN	54
Li	11/9	10/10	6.8 (1.6)	6.6 (1.9)	NA		RENAL score:10		LPN vs OPN	NA
Yu	32/34	33/33	2.76 (0.86)	2.8 (0.76)	75.12 (10.24)	75.86 (10.36)	PADUA score:10		LPN vs OPN	NA
Chiancone	38/34	11/10	NA		NA		PADUA score: 10:38 (52.8%); 11: 28 (38.9%); 12: 6 (8.3%)	PADUA score: 10:11 (52.4%); 11: 8 (38.1%); 12: 2 (9.5%)	LPN vs OPN	NA
Mari	NA		<4: 36; 4–7:34; ≥7: 7	<4: 96; 4–7:73; ≥7:19	81.9 (26)	83.7 (20.37)	PADUA score: 10:73; 11: 48; 12: 23; 13:1	PADUA score: 10:94; 11: 69; 12: 23; 13:2	LPN vs OPN	48
Kim	49/36	36/28	4.3 1.7)	3.1 (1.85)	87.1 (17.78)	83.3 (18)	Median (IQR); RENAL score: 10.2 (10.0–10.0)	Median (IQR); RENAL score: 10.1 (10.0–10.0)	RPN vs OPN	15–53
Garisto	86/117	38/38	5 (1.81)	5.2 (2)	81 (22.96)	77 (30.37)	Median (IQR); RENAL score: 10 (10–10)	Median (IQR); RENAL score: RENAL score: 10 (10–10)	RPN vs OPN	25
Zargar	NA		4.15 (2.15)	4.3 (1.56)	NA		RENAL score:10		RPN vs OPN	4–19.6

MIPN minimally-invasive partial nephrectomy, *OPN* open partial nephrectomy; mean (SD)

Table 3 Oncologic outcomes

Reference	Tumor stage		Tumor pathology	
	MIPN	OPN	MIPN	OPN
Liu	pT1b:94; pT2a:3; pT2b:0	pT1b:41; pT2a:2; pT2b:1	Clear cell: 89; papillary: 4; chromophobe: 4	Clear cell: 37; papillary: 5; chromophobe: 2
Li	All are cT1 and cT2		NA	
Yu	All are cT1 and cT2		NA	
Chiancone	cT1a:5; cT1b:14; cT2a:2	cT1a:16; cT1b:49; cT2a:7	NA	
Mari	pT1a:26; pT1b:33; pT2:2; pT3a:8	pT1a:79; pT1b:52; pT2:3; pT3a:18	Clear cell: 45; papillary: 9; chromophobe: 8; others: 6	Clear cell: 117; papillary: 19; chromophobe: 12; others: 6
Kim	cT1a:36; cT1b:35; cT2a:14	cT1a:42; cT1b:16; cT2a:6	Clear cell: 65; papillary: 1; chromophobe: 10; others: 9	Clear cell: 50; papillary: 3; chromophobe: 3; others: 8
Garisto	cT1a:67; cT1b:112; cT2a:20; cT2b:4	cT1a:18; cT1b:42; cT2a:11; cT2b:5	Clear cell: 128; papillary: 23; chromophobe: 14; others: 14	Clear cell: 46; papillary: 11; chromophobe: 7; others: 3
Zargar	All are cT1 and cT2		NA	

MIPN minimally-invasive partial nephrectomy *OPN* open partial nephrectomy

had a shorter hospital stay compared to the OPN group (WMD -2.08 days, 95% CI −2.48, −1.68; p < 0.00001) [15–22]. Subgroup analysis revealed that both RPN and LPN had shorter hospital stays than OPN (RPN: WMD −2.00 days, 95% CI −2.24, −1.76; p < 0.00001; LPN: WMD −2.30 days, 95% CI −3.11, −1.50; p < 0.00001). Moreover, the analysis demonstrated that no significant difference in warm ischemia time between MIPN and OPN (p = 0.28) [15–17, 19–22]. The subgroup analysis indicated that RPN and OPN did not significantly differ in terms of warm ischemia time (p = 0.52). However, LPN was associated with a longer warm ischemia time than OPN (WMD 6.13 min, 95% CI 0.62, 11.64; p = 0.03) (Fig. 2).

The results of a meta-analysis comparing MIPN and OPN showed that MIPN was associated with significantly lower estimated blood loss volumes than OPN (WMD −39.86 mL, 95% CI −75.32, −4.39; p = 0.03) [15–22]. However, subgroup analysis revealed that no statistically significant differences were observed between RPN and LPN when compared to OPN (p = 0.18; p = 0.13). In addition, MIPN was found to be associated with a lower transfusion rate than OPN (OR 0.30, 95% CI 0.13, 0.71; p = 0.006) across five studies [18–22]. Nonetheless, no significant differences were observed in the subgroup analysis of RPN and LPN (p = 0.10; p = 0.11) (Fig. 3). Furthermore, the cumulative analysis indicated that there was no significant difference in the prevalence of conversion to radical nephrectomy rates between MIPN and OPN (four studies; p = 0.39) (Fig. 4) [15, 17, 18, 21].

Complications

The cumulative analysis demonstrated no significant difference in the incidence of intraoperative complications (four studies; p = 0.90) [19–22]. Similarly, there was no significant difference in the incidence of major complications between MIPN and OPN (p = 0.08, six studies) [15, 18–22]. Nonetheless, MIPN was associated with a lower incidence of overall complications compared to OPN (OR 0.46, 95% CI 0.31, 0.70; p = 0.0003; eight studies). The overall complication rates were 19.4% (122 out of 630 cases) in the MIPN group and 29.6% (157 of 531 cases) in the OPN group. The subgroup analysis indicated that both RPN and LPN had a lower incidence of overall complications compared to OPN (RPN: OR 0.58, 95% CI 0.38, 0.87; p = 0.008; LPN: OR 0.32, 95% CI 0.15, 0.71; p = 0.005) (Fig. 5) [15–22].

Renal functional and oncologic outcomes

Five studies reported a decline in eGFR. However, the pooled analysis did not demonstrate any statistically significant differences in the decline of eGFR between the MIPN and OPN groups (p = 0.99) (Fig. 4) [15, 17, 19–21].

The comparison between the MIPN and OPN groups did not yield any statistically significant differences in terms of PSM based on six studies (p = 0.81) [15, 18–22]. The prevalence of local recurrence exhibited no significant disparity in two studies (p = 0.89) (Fig. 6) [20, 21]. Moreover, the comprehensive analysis demonstrated no substantial variance in overall survival (OS) between the two groups (two studies; p = 0.93) [15, 20]. Similarly, pooled analysis revealed no significant distinction in recurrence-free survival (RFS) between the MIPN and OPN groups (p = 0.22) (Fig. 7) [15, 20].

Subgroup analysis

We conducted a meticulous subgroup analysis by stratifying the data based on age, region, sample size, and PADUA or RENAL score. The analysis encompassed key outcomes

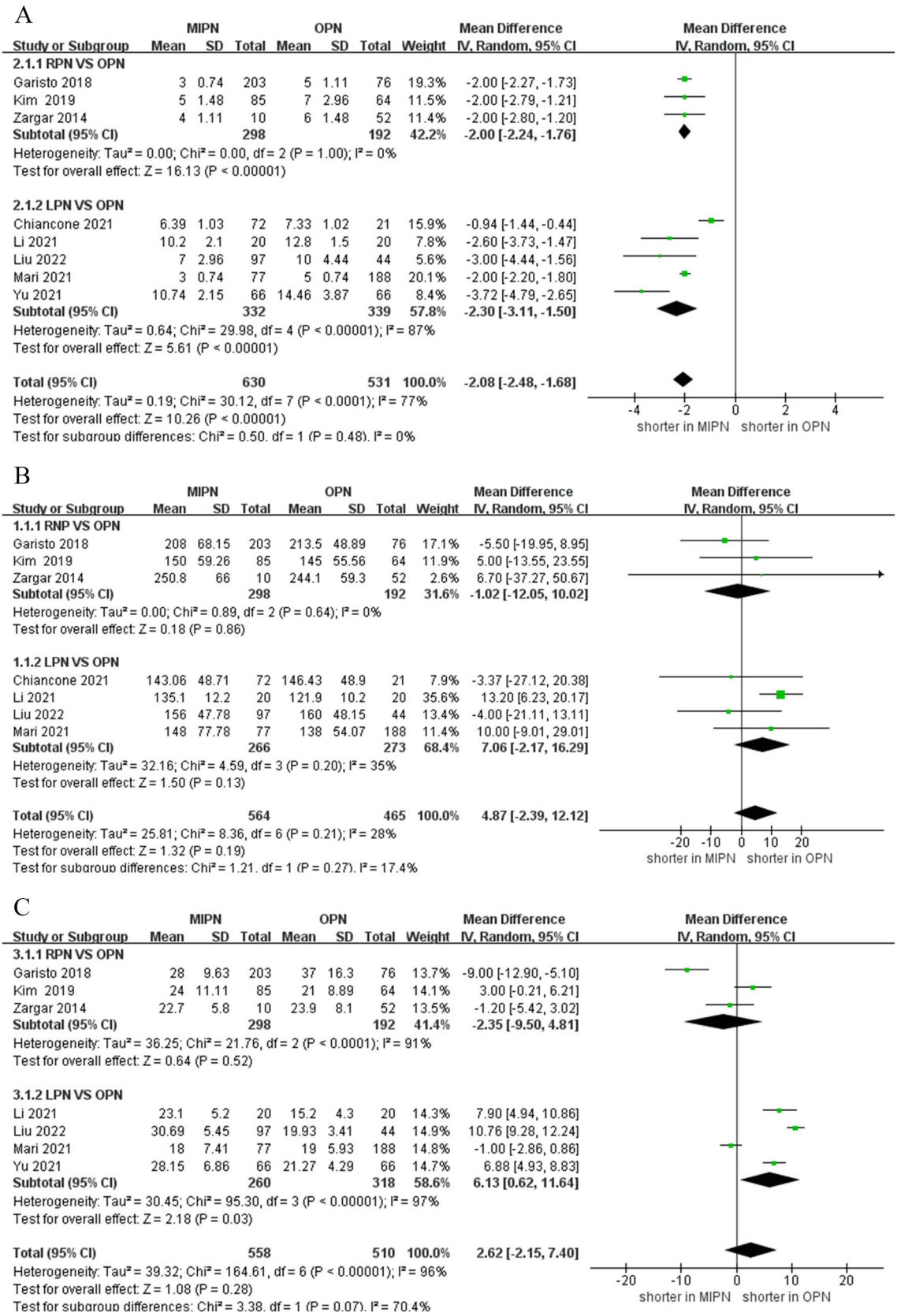

Fig. 2 Forest plots of perioperative outcomes **A** operative time, **B** length of hospital stay, **C** warm ischemia time

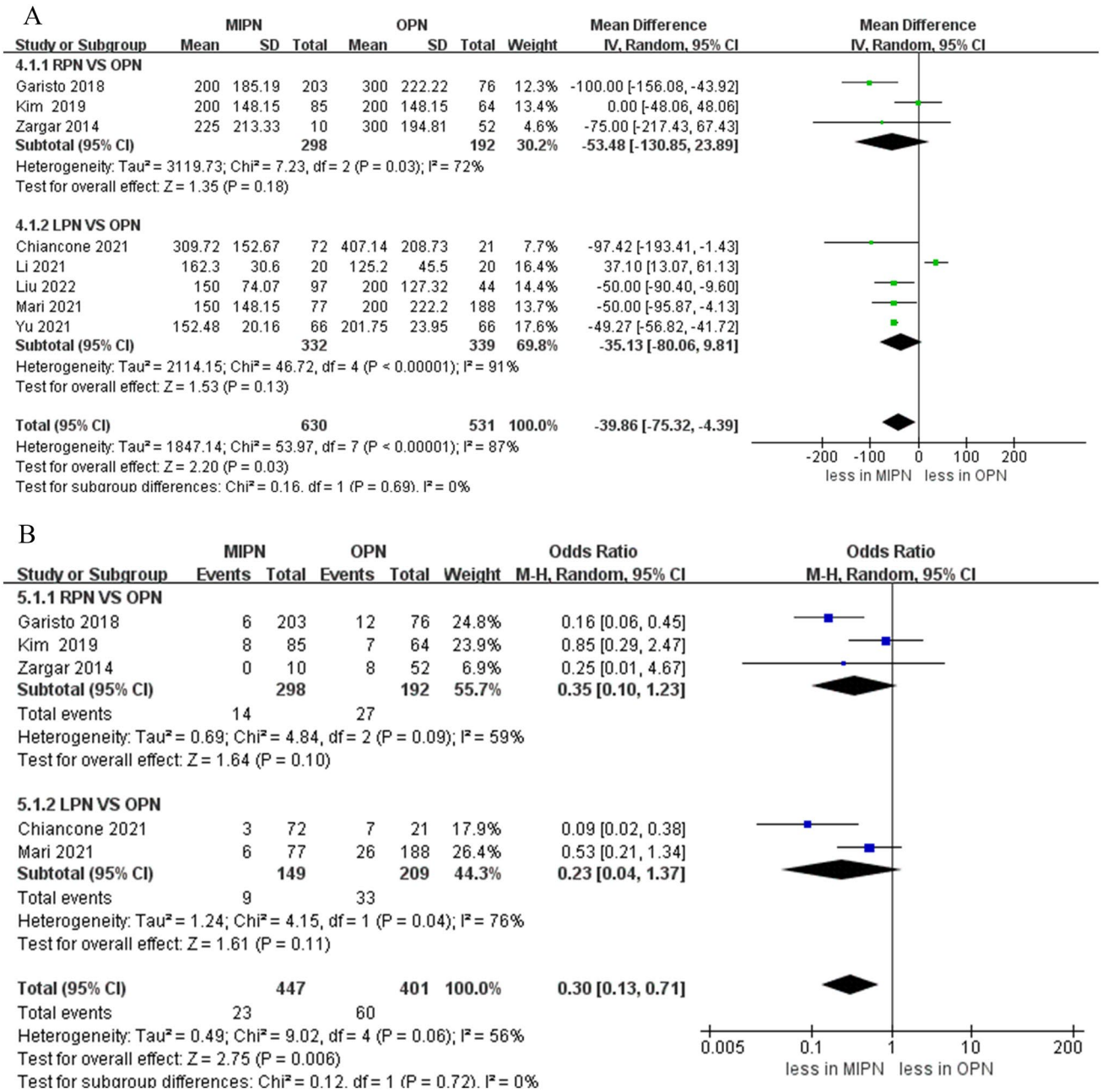

Fig. 3 Forest plots of perioperative outcomes **A** blood loss, **B** transfusion rates

such as operative time, length of stay, blood loss, warm ischemia time, overall complications, and PSM (Table 4).

The sample size emerged as the primary contributor to heterogeneity in operative time. Within the subgroup of sample size < 100, patients who underwent MIPN were observed to experience significantly longer operative time compared to those who underwent OPN ($p = 0.005$). However, no significant difference was observed within the subgroup of sample size ≥ 100 ($p = 0.97$). Notably, the subgroup analysis revealed that MIPN patients across all subgroups exhibited a shorter length of hospital stay than those who underwent OPN.

The interstudy heterogeneity with respect to blood loss was found to be influenced by both sample size and region. Specifically, within the subgroup of studies with a sample size greater than or equal to 100, MIPN was associated with a significantly lower blood loss when compared to OPN ($p < 0.00001$). However, within the subgroup of studies with a sample size less than 100, no significant difference in blood loss was observed between the two groups

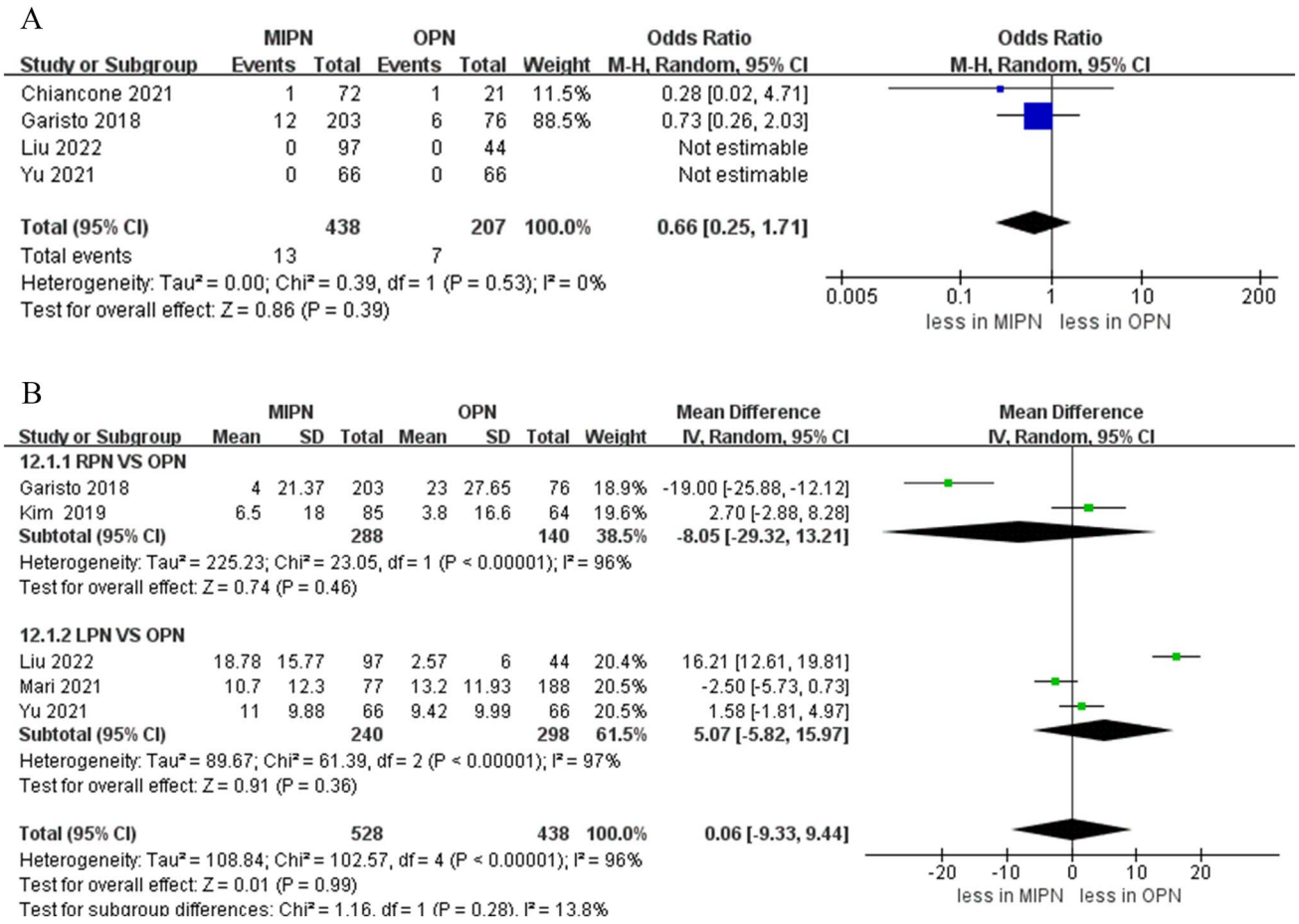

Fig. 4 Forest plots of perioperative and renal functional outcomes **A** conversion to radical nephrectomy rates, **B** eGFR decline

(p = 0.53). Furthermore, within the Non-Asian subgroup, patients who underwent MIPN demonstrated significantly lower blood loss when compared to those who underwent OPN (p < 0.00001), whereas no significant difference was observed within the Asian subgroup (p = 0.54).

Our analysis identified age as a significant source of heterogeneity for warm ischemia time. Specifically, in the subgroup with a mean age of < 60 years, MIPN was associated with longer warm ischemia time compared to OPN (p < 0.00001), while in the subgroup with a mean age of ≥ 60 years, no significant difference was observed (p = 0.15). The heterogeneity observed for overall complications was primarily influenced by sample size. It is worth noting that in the subgroup of studies with sample sizes ≥ 100, a significantly lower incidence of overall complications was observed in the MIPN group than in the OPN group (p < 0.0002). Conversely, in the subgroup of studies with sample sizes < 100, no significant difference was detected between the two groups (p = 0.33). Additionally, the subgroup analysis did not reveal any significant difference in PSM between all MIPN subgroups and OPN.

Heterogeneity

The majority of the findings indicated a tendency towards low to moderate heterogeneity. Despite the inclusion of studies of intermediate and high caliber, significant variability was identified in five of the outcomes examined (length of hospital stay, $I^2 = 77\%$; warm ischemia time, $I^2 = 96\%$; blood loss, $I^2 = 87\%$; OS, $I^2 = 88\%$; RFS, $I^2 = 92\%$).

Sensitivity analysis

In this study, the presence of discernible heterogeneity in parameters such as the length of hospitalization, warm ischemia time, and blood loss necessitated a sensitivity analysis to identify the root cause of the heterogeneity and assess the strength and stability of the study results. The outcomes of this analysis revealed that there was no significant variation in the level of heterogeneity, indicating that the underlying source of heterogeneity in operative time, duration of hospitalization, and blood loss remained stable throughout the study.

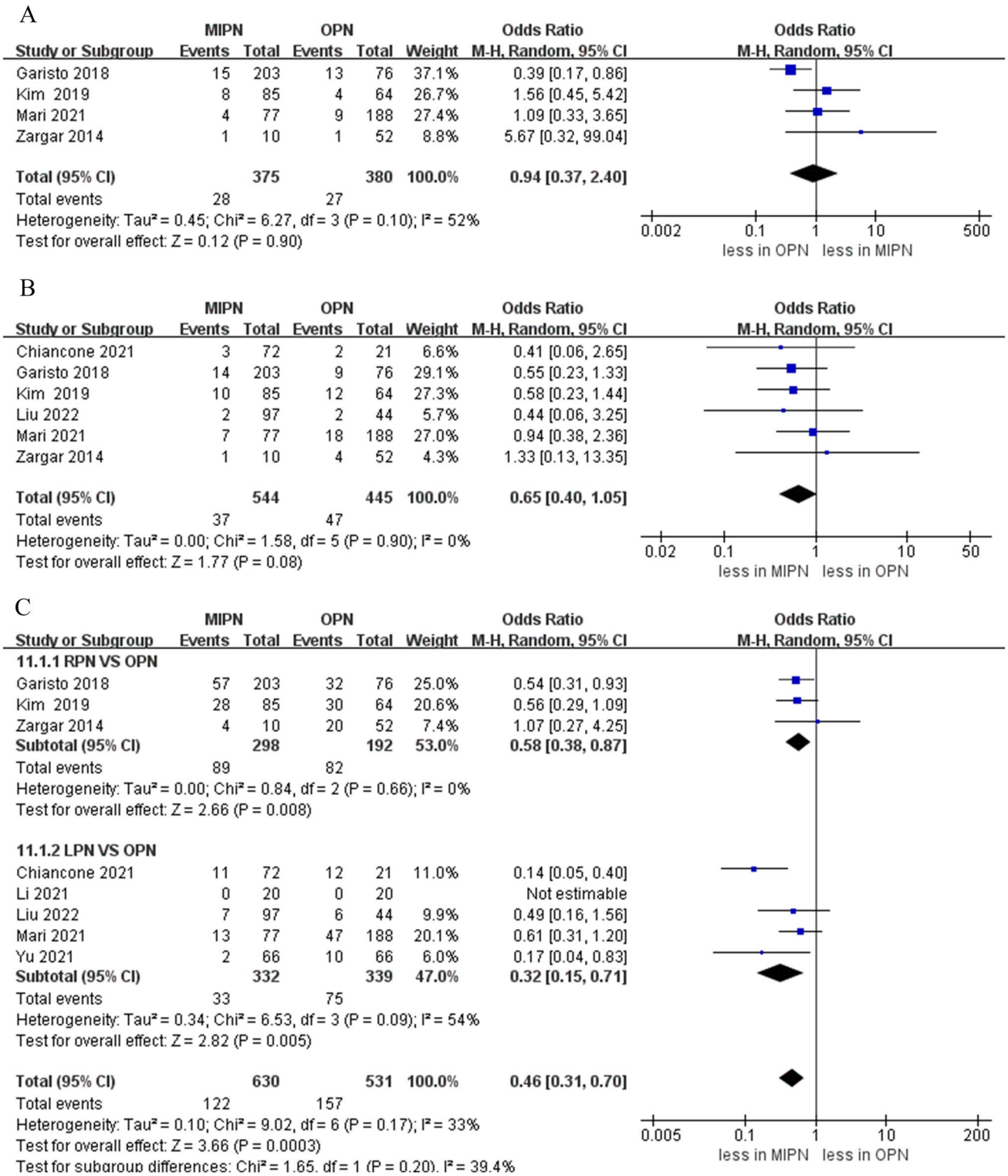

Fig. 5 Forest plots of complication **A** intraoperative complications, **B** major complications, **C** overall complication

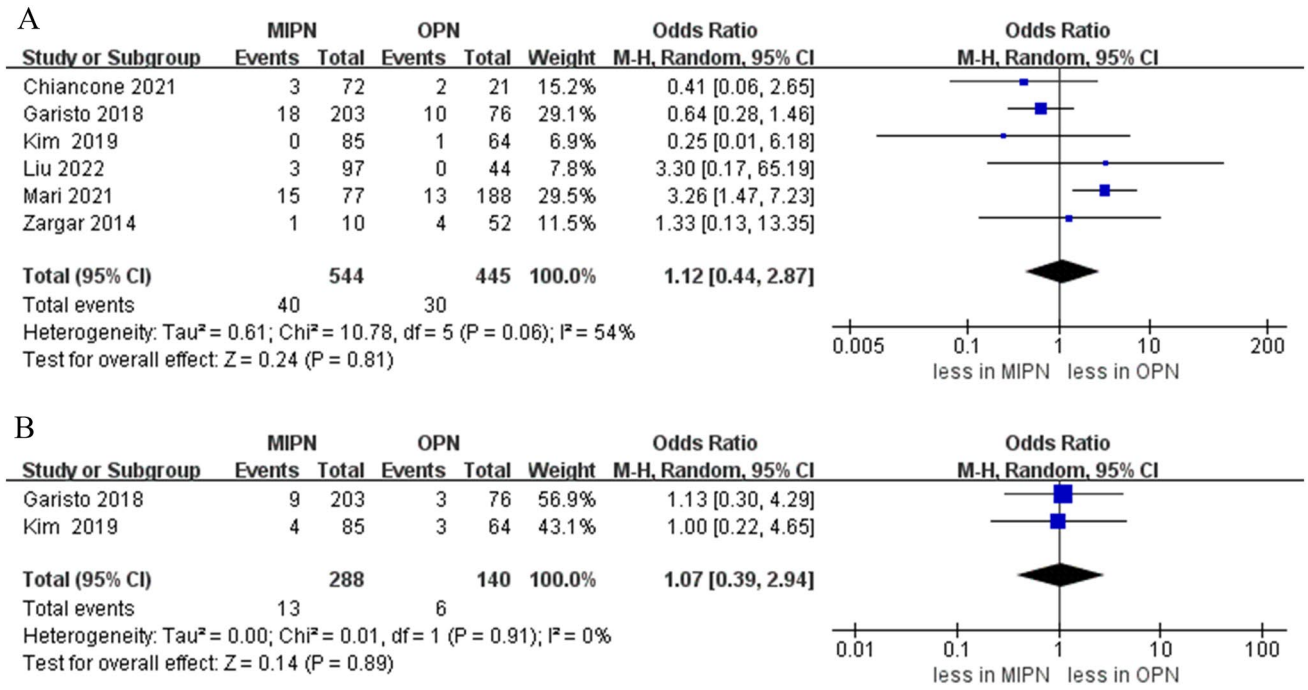

Fig. 6 Forest plots of oncologic outcomes **A** PSM, **B** local recurrence

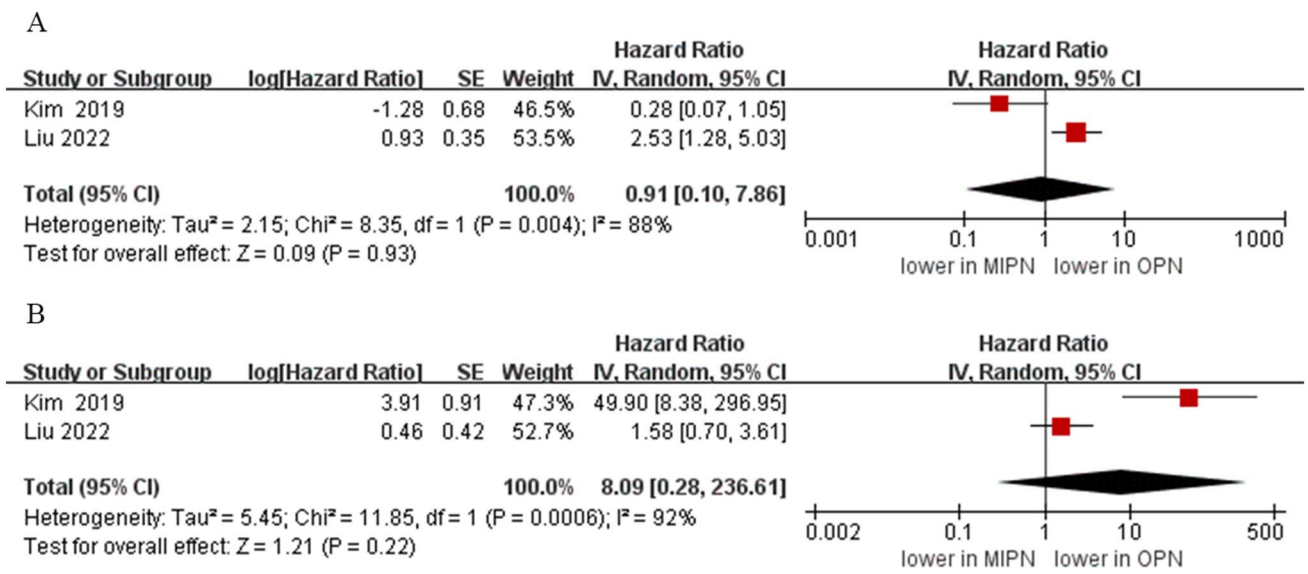

Fig. 7 Forest plots of oncologic outcomes **A** overall survival, **B** recurrence-free survival

Publication bias

In order to determine the possibility of publication bias in the studies, we performed an analysis on operative time, length of stay, blood loss, and overall complications. Our results indicated that the distribution of the studies displayed a nearly symmetrical pattern, indicating a low likelihood of publication bias (Fig. S1).

Discussion

This study represents the first attempt to evaluate the efficacy of MIPN in the management of highly complex renal tumors. Furthermore, several noteworthy findings arising from this analysis warrant additional scrutiny and discussion.

Table 4 Subgroup analysis of outcomes for MIPN and OPN

Group	Subgroups	Studies (n)	MD/OR (95% CI)	I^2 (%)	*P*
Operative time					
Age	Mean age < 60 years	3	7.17 (− 3.37, 17.70)	45	0.18
	Mean age ≥ 60 years	4	− 0.12 (− 10.20, 9.95)	0	0.98
Sample size	Sample size < 100	3	11.77 (5.16, 18.38)	0	0.005
	Sample size ≥ 100	4	0.16 (− 8.33, 8.65)	0	0.97
Country/region	Asian	3	7.17 (− 3.37, 17.70)	45	0.18
	Non-Asian	4	− 0.12 (− 10.20, 9.95)	0	0.98
PADUA or RENAL score	RENAL score ≥ 10	5	4.08 (− 5.49, 13.65)	47	0.40
	PADUA score ≥ 10	2	4.78 (− 10.07, 19.62)	0	0.53
Length of stay					
Age	Mean age < 60 years	4	− 2.77 (− 3.57, − 1.96)	55	< 0.00001
	Mean age ≥ 60 years	4	− 1.76 (− 2.17, − 1.34)	81	< 0.00001
Sample size	Sample size < 100	3	− 1.76 (− 2.75, − 0.76)	80	0.0006
	Sample size ≥ 100	5	− 2.22 (− 2.59, − 1.85)	65	< 0.00001
Country/region	Asian	4	− 2.77 (− 3.57, − 1.96)	55	< 0.00001
	Non-Asian	4	− 1.76 (− 2.17, − 1.34)	81	< 0.00001
PADUA or RENAL score	RENAL score ≥ 10	5	− 2.05 (− 2.29, − 1.82)	0	< 0.00001
	PADUA score ≥ 10	3	− 2.10 (− 3.14, − 1.05)	92	< 0.0001
Blood loss					
Age	Mean age < 60 years	4	− 15.78 (− 66.03, 34.48)	94	0.54
	Mean age ≥ 60 years	4	− 73.42 (− 105.85, − 41.00)	0	< 0.00001
Sample size	Sample size < 100	3	− 33.41 (− 137.02, 70.20)	78	0.53
	Sample size ≥ 100	5	− 48.29 (− 69.14, − 27.45)	44	< 0.00001
Country/region	Asian	4	− 15.78 (− 66.03, 34.48)	94	0.54
	Non-Asian	4	− 73.42 (− 105.85, − 41.00)	0	< 0.00001
PADUA or RENAL score	RENAL score ≥ 10	5	− 30.26 (− 86.73, 26.60)	86	0.29
	PADUA score ≥ 10	3	− 49.58 (− 57.01, − 42.15)	0	< 0.00001
Warm ischemia time					
Age	Mean age < 60 years	4	7.32 (4.20, 10.44)	87	< 0.00001
	Mean age ≥ 60 years	3	− 3.60 (− 8.51, 1.30)	85	0.15
Sample size	Sample size < 100	2	3.48 (− 5.44, 12.39)	92	0.44
	Sample size ≥ 100	5	2.77 (− 3.75, 8.30)	97	0.46
Country/region	Asian	4	7.32 (4.20, 10.44)	87	< 0.00001
	Non-Asian	3	− 3.60 (− 8.51, 1.30)	85	0.15
PADUA or RENAL score	RENAL score ≥ 10	5	2.43 (− 4.33, 9.19)	96	0.48
	PADUA score ≥ 10	3	2.93 (− 4.79, 10.66)	97	0.46
Overall complication					
Age	Mean age < 60 year	4	0.47 (0.27, 0.81)	0	0.007
	Mean age ≥ 60 years	4	0.47 (0.24, 0.90)	58	0.02
Sample size	Sample size < 100	3	0.36 (0.05, 2.75)	81	0.33
	Sample size ≥ 100	5	0.53 (0.38, 0.74)	0	0.0002
Country/region	Asian	4	0.47 (0.27, 0.81)	0	0.007
	Non-Asian	4	0.47 (0.24, 0.90)	58	0.02
PADUA or RENAL score	RENAL score ≥ 10	3	0.57 (0.39, 0.83)	0	0.004
	PADUA score ≥ 10	5	0.27 (0.09, 0.80)	68	0.02
PSM					
Age	Mean age < 60 years	2	0.97 (0.08, 12.32)	26	0.98
	Mean age ≥ 60 years	4	1.13 (0.38, 3.39)	68	0.82
Sample size	Sample size < 100	2	0.66 (0.15, 2.79)	0	0.57
	Sample size ≥ 100	4	1.32 (0.38, 4.57)	67	0.66

Table 4 (continued)

Group	Subgroups	Studies (n)	MD/OR (95% CI)	I^2 (%)	*P*
Country/region	Asian	2	0.97 (0.08, 12.32)	26	0.98
	Non-Asian	4	1.13 (0.38, 3.39)	68	0.82
PADUA or RENAL score	RENAL score ≥ 10	4	0.73 (0.35, 1.51)	0	0.39
	PADUA score ≥ 10	2	1.39 (0.19, 10.18)	75	0.75

The findings of this study revealed no significant disparity in operative time between patients who underwent MIPN and those who underwent OPN. While previous studies have suggested that the utilization of robotic platforms may require repeated docking or patient repositioning, potentially leading to prolonged operative time [23], the subgroup analysis in our study surprisingly demonstrated no significant difference in the operative duration between RPN and OPN. Moreover, it is worth noting that all robotic procedure was carried out by highly experienced operators with extensive expertise in the field of minimally-invasive surgery. This aspect may contribute to the outcome, as skill and proficiency of the surgeon are known to have a significant impact on the success and efficiency of the surgical procedure. The study results indicated that patients who underwent MIPN had a significantly shorter length of hospitalization compared to those who underwent OPN. The decreased hospital stay in the MIPN group can be attributed to the potential benefits of robotic and laparoscopic surgeries, including reduced trauma, faster recovery of intestinal function, and lower incidence of complications associated with prolonged bed rest. However, it is essential to note that differences in healthcare systems and insurance policies across various regions may result in variations in hospitalization durations [24, 25].

Furthermore, the analysis revealed no significant discrepancy in warm ischemia time between patients who underwent MIPN and those who underwent OPN. However, patients who underwent LPN had a longer warm ischemia time than those who underwent OPN. Previous studies have recommended keeping the warm ischemia time below 25 or 30 min to prevent potential harm to renal function [26, 27]. Interestingly, four studies have reported that the ischemia time in the LPN group was less than 30 min. Considering these results, the warm ischemia time observed in LPN seems to be a viable option for treating highly renal tumors. However, it is crucial to conduct further investigations with more extensive sample sizes and extended follow-up periods to confirm these findings more conclusively.

Minimally-invasive surgery offers a significant advantage in reducing blood loss. With the aid of robotic and laparoscopic vision imaging systems, surgeons are able to expand their view during dissection, allowing for improved visualization of vascular anatomy and more precise maneuvers. Additionally, the establishment of a pneumoperitoneum through minimally-invasive surgery serves to effectively mitigate venous hemorrhages that may occur during dissection [28, 29]. MIPN has been linked to a lower transfusion rate in comparison to OPN. However, upon conducting a subgroup analysis of RPN and LPN, no significant differences were observed. This could potentially be due to insufficient literature incorporated in the subgroup analysis. Furthermore, the transfusion rates observed in both MIPN and OPN may also be influenced by the surgeon's level of expertise and the blood transfusion guidelines followed by the hospital. Consequently, additional research is imperative to ascertain if MIPN provides superior benefits in terms of transfusion rate for highly complex renal tumors.

The assessment of complications was a crucial aspect of our study, and we utilized the Clavien–Dindo grading system for this purpose [30]. The cumulative analysis revealed no statistically significant difference in the incidence of intraoperative complications between MIPN and OPN. However, the major complications group exhibited a marginal difference with a p-value of 0.08. In addition, MIPN was found to be associated with a lower incidence of overall complications when compared to OPN. The findings suggest that MIPN surgery offers superior safety and facilitates the expeditious restoration of patients' gastrointestinal and other physiological functions after the procedure. The following factors may account for the main results. Firstly, measures were taken to minimize bleeding during the surgery to guarantee an unobstructed surgical view and prevent injury to surrounding tissues or the need for prolonged drainage. Additionally, efforts were made to minimize complications arising from extended bed rest and hospitalization, thereby fostering a conducive environment for the prompt recuperation of patients [31].

The results of the meta-analysis did not reveal any significant statistical differences in the decline of eGFR between the MIPN and OPN groups. Nevertheless, when comparing renal function outcomes between the two groups, an important consideration lies in preoperative renal function and the number of preserved kidneys. Emerging evidence suggests that these factors have a substantial impact on long-term renal function outcomes. Conversely, the role of warm ischemia time appears

relatively minor in influencing these outcomes [32, 33]. Therefore, this finding should be interpreted with caution.

Oncologic outcomes are considered crucial benchmarks of surgical quality. The PSM rates between MIPN and OPN groups were 7.35% and 6.74%, respectively. Nevertheless, a study found that PSM rates range from 0 to 3.7% for complex renal tumors (RENAL score > 9) [34]. Therefore, it is necessary to conduct further investigations with larger sample sizes and longer follow-up durations to establish the findings more conclusively. Despite the cumulative analysis revealing no significant differences in local recurrence, OS, and RFS between two groups, there are several crucial considerations to bear in mind when evaluating the oncologic outcomes between the two groups. Firstly, the constraint of limited follow-up duration in the majority of the studies, alongside the limited number of studies, poses a significant challenge to establishing conclusive findings. Consequently, it is imperative to conduct additional research employing larger sample sizes and longer follow-up periods to verify the oncologic outcomes of MIPN. Finally, the dearth of available literature precludes definitive determination of the cancer-specific survival between the two groups.

Other important issue required in-depth discussion. The single-port (SP) robotic platform was recently developed by Intuitive Surgical, which enables "true" single site surgery without extra ports. Li et al. [35] demonstrated that the SP robotic platform was less invasive than a multiport robotic system in radical prostatectomy. Furthermore, Kim et al. [36] identified that SP robot-assisted PN was associated with a shorter operation time when compared to multiport robot-assisted PN, and they suggested that SP robotic system is particularly beneficial for managing complex renal tumors. Therefore, more studies from different institutions are essential to determine which surgical method is best suited for the complex renal tumors.

While the analysis conducted had intermediate to high quality, there were still certain limitations that need to be acknowledged. Firstly, all the studies included were retrospective and lacked the rigor of RCTs, which leaves room for inherent selection biases to have potentially influenced the findings. Secondly, it is worth noting that the lack of a subgroup analysis based on the surgical approach, such as transperitoneal and retroperitoneal, may have resulted in slight discrepancies in the outcomes. Finally, despite conducting a meticulous subgroup analysis by stratifying the data based on the PADUA or RENAL score, it is important to note that a pooled analysis was performed solely on studies that utilized RENAL and PADUA scores ≥ 10, which may have introduced subtle heterogeneity into the results.

Conclusions

The present study indicates that MIPN is a safe and effective approach that offers better outcomes than OPN for managing highly complex renal tumors, with advantages such as reduced hospitalization time, lower blood loss, and a lower incidence of complications. Moreover, MIPN showed comparable outcomes in terms of renal function and oncological outcomes when compared to OPN. However, to strengthen the evidence base and affirm the veracity of the findings, further extensive and meticulous research is indispensable, encompassing a larger sample size and comprehensive data from high-volume medical centers.

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Author contributions Author contributions LX: Protocol development, data collection and management, methodology, data analysis and writing original draft. LK: Protocol development, data collection, data analysis, study supervision and writing original draft. ZJ: Protocol development, management and writing original draft. YW: Data analysis, methodology and writing original draft. TH: Data management and writing original draft. WW: Data management, methodology and writing original draft. CS: Data analysis, methodology and writing original draft. MJ: Protocol development, management, visualization and writing original draft. BS: Protocol development, management, visualization and writing original draft. YZ: Protocol development, visualization and writing original draft.

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Availability of data and material Raw data available at request.

Declarations

Conflict of interest All the Authors have nothing to declare.

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