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An updated meta-analysis of the efficacy and safety of robot-assisted laparoscopy hepatectomy and laparoscopic hepatectomy in the treatment of liver tumors

Fuyong Niu, MD[a], Yefei Wang, MD[a], Zhiyuan Bai, MD[a], Zhiqiang He, MD[a], Hailin Wang, MD[a], Furong Li, MD[a,*]

Abstract

Background: To compare the efficacy and safety of robot-assisted laparoscopic hepatectomy (RALH) with laparoscopic hepatectomy (LH) in the treatment of liver tumors.

Methods: A comprehensive search of English-language literature was conducted in PubMed, Embase, Web of Science, and the Cochrane Library from January 2000 to June 2024. Studies comparing RALH and LH for liver tumors were identified, and after qualitative evaluation, a meta-analysis was performed using Stata 16.0 software.

Results: After applying inclusion and exclusion criteria, 42 articles were included, including 29,969 patients, with 5673 in the RALH group and 24,296 in the LH group. The meta-analysis showed that compared with the LH group, surgery time was longer in the RALH group (MD = 55.33; 95% CI: 34.84–75.83; $P < .001$), the conversion to open surgery rate was higher (RR = 1.04; 95% CI: 1.03–1.05; $P < .001$), the total cost was higher (MD = 0.43; 95% CI: 0.14–0.73; $P = .004$), and the tumor diameter was larger (MD = 0.37; 95% CI: 0.24–0.49; $P < .001$). Additionally, the R1 resection rate was higher in the RALH group (RR = 1.04; 95% CI: 1.03–1.06; $P < .001$). However, there were no significant differences between the groups in terms of intraoperative transfusion rate, hepatic hilar occlusion rate, postoperative complications, postoperative hospital stay, mortality rate, malignancy rate, or R0 resection rate ($P > .05$).

Conclusion: Based on current evidence, RALH is safe and effective, although it is associated with higher total costs, increased blood transfusion rates, and longer operative times. However, there were no significant differences between RALH and LH in terms of other outcome indicators, suggesting that both procedures offer similar surgical efficacy and safety. Further clinical randomized controlled trials are needed to confirm these findings.

Abbreviation: AMSTAR = assessing the Methodological quality of systematic reviews, CI = confidence intervals, LH = laparoscopic hepatectomy, MD = mean difference, NOS = Newcastle-Ottawa Scale, PRISMA = preferred reporting items for systematic reviews and meta-analyses, RALH = robot-assisted laparoscopic hepatectomy, RR = relative risk.

Keywords: meta-analysis, robot-assisted laparoscopic hepatectomy, tumors

1. Introduction

In recent years, robot-assisted laparoscopic hepatectomy (RALH) has emerged as a potentially effective alternative to conventional laparoscopic hepatectomy (LH). The advantages of current robotic surgical platforms include 3-dimensional visualization and improved instrument flexibility, which may aid in navigating the complex liver anatomy and performing intricate surgical reconstructions. Furthermore, the use of an ergonomic surgical console may reduce surgeon fatigue during long and complex procedures and allow for better control of bleeding 2 factors that contribute to the limited popularity of laparoscopic approaches in major surgeries and overcomes some of the technical limitations of conventional LH while significantly enhancing the flexibility and precision of liver resection surgery.[1–3] It is a surgical field and 3-dimensional view that facilitates in vivo suturing and delicate tissue dissection. However, RALH is associated with high costs and a significant machine failure rate.

The authors have no funding and conflicts of interest of disclose.

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

The research did not involve in any human or animal research, therefore there was no ethical approval from any ethics committee.

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[a] Department of Hepatobiliary Surgery, The First Hospital of Yulin City, Yulin City, Shaanxi Province, China.

* Correspondence: Furong Li, Department of Hepatobiliary Surgery, The First Hospital of Yulin City, 93 Yuxi Avenue, High-Tech Zone, Yulin City, Shaanxi Province, China (e-mail: lfr202406@163.com).

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Although previous meta-analyses have compared RALH with LH for the treatment of liver tumors, they only included studies published before 2018, and the findings remain controversial. For instance, Guan et al.[4] reported higher intraoperative bleeding in RALH compared to LH, while Qiu et al.[5] found a significant difference between the 2 groups.

Interestingly, we identified 10 newly published studies comparing RALH and LH outcomes in the treatment of liver tumors, which were not included in the previous meta-analyses. Therefore, it remains unclear whether liver resection using robotic methods offers superior outcomes compared with conventional laparoscopic techniques. To address this, we aim to perform an up-to-date meta-analysis to comprehensively evaluate and compare the clinical efficacy and safety of RALH versus LH.

2. Data and methods

2.1. Literature search

We conducted a comprehensive search of PubMed, Embase, Web of Science, and the Cochrane Library for controlled studies comparing RALH and LH in patients with liver tumors, covering the period from January 2000 to June 2024. The meta-analysis was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and Assessing the Methodological Quality of Systematic Reviews (AMSTAR) guidelines.[6,7] The PRISMA registration ID is CRD42024567325. The search terms used included robotics, computer-assisted surgery, laparoscopy, hepatectomy, liver resection, liver surgery, and liver neoplasms. We retrieved both MeSH terms and free-text terms from the MeSH Database and combined them into a search strategy. The detailed search strategy is provided in Supplementary Material 1 (Supplemental Digital Content, http://links.lww.com/MD/O228).

2.2. Inclusion and exclusion criteria

The inclusion criteria were as follows: studies comparing RALH with LH; studies including at least 1 outcome measure suitable for combination; preference given to the latest study in case of multiple studies in the same population; and no language restrictions.

The exclusion criteria were as follows: studies related to liver donor transplantation; case reports, conference abstracts, and animal experiments; and studies lacking full-text availability.

2.3. Data Extraction

The authors independently extracted and summarized the following data from each study: first author, year, country, study design, sample size, and outcome measures; intraoperative outcomes, including operation time (min), intraoperative blood loss (mL), intraoperative blood transfusion rate (%), intraoperative conversion rate (%), and hepatic hilar blockade rate (%);postoperative outcomes: postoperative complications (%), postoperative hospital stay (days), mortality (%), and total cost ($); and pathological outcome measures: $R0$ resection rate, $R1$ resection rate, malignancy rate, and tumor diameter (cm). Additionally, if the extracted information from the original article was inaccurate or missing, efforts were made to contact the corresponding authors to ensure data accuracy.

2.4. Quality evaluation

Two authors independently assessed the methodological quality of the included articles. The Newcastle-Ottawa Scale (NOS),[8] a risk assessment tool recommended by Cochrane, was used for nonrandomized controlled studies. The evaluation included 3 factors: selection of the study subjects, comparability of the study groups, and outcome assessment. Studies with scores >5 were considered to have high methodological quality.

2.5. Statistical methods

Statistical analysis was performed using Stata 16.0. The combined values and 95% confidence intervals (95% CI) were calculated as the mean difference (MD) for continuous outcomes and relative risk (RR) for dichotomous outcomes. Heterogeneity was assessed using the chi-squared (χ^2) test and I^2 statistic. If $I^2 > 50\%$, this indicated significant heterogeneity between studies. In such cases, the sources of heterogeneity were analyzed. If no obvious clinical heterogeneity was identified, a random-effects model was applied; otherwise, a fixed-effects model was used. Sensitivity analyses were conducted to evaluate the robustness of the results by excluding individual studies individually and repeating the meta-analysis. Finally, publication bias for the selected outcome indicators was assessed using funnel plots to evaluate potential biases.

3. Results

3.1. Search results, characteristics of included studies and quality evaluation

A total of 1388 articles were retrieved, of which 42[9–50] retrospective cohort studies were included, involving 29,969 patients (5673 in the RALH group and 24,296 in the LH group). The literature screening process is illustrated in Figure 1. The basic characteristics of the included studies are presented in Table 1, and the quality evaluation results are shown in Table 2. All studies had a Newcastle-Ottawa Scale (NOS) score > 5, indicating high methodological quality.

3.2. Meta-analytic results

3.2.1. Operative time.
A total of 36 studies[10,11,14,16–24,26–32,34–50] reported the operative time, including 27,239 patients. Due to significant heterogeneity across studies ($P < .001$, $I^2 = 97.8\%$), a random-effects model was applied. The results indicated that the operative time in the RALH group was significantly longer than that in the LH group (MD = 55.33; 95% CI: 34.84–75.83; $P < .001$) (Fig. 2A).

3.2.2. Intraoperative bleeding.
A total of 28 studies[10,11,16,17,19,20,23–25,28–32,34–36,38–42,44–47,49,50] reported on intraoperative bleeding, including 18,923 patients. Significant heterogeneity was observed ($P < .001$, $I^2 = 89.3\%$). The results indicated that intraoperative bleeding in the RALH group was significantly higher than in the LH group (MD = −28.35; 95% CI: −50.35 to −6.39; $P < .001$) (Fig. 2B).

3.2.3. Intraoperative transfusion rate.
A total of 21 studies[9,15,17–20,22–24,26,27,29,30,32,33,36,38–40,47,49] reported intraoperative blood transfusion rates, including 8630 patients. As there was no significant heterogeneity across studies ($P = .018$, $I^2 = 43.6\%$), a fixed-effects model was applied. The results indicated that there was no significant difference in the intraoperative transfusion rate between the RALH group and the LH group (RR = 0.99; 95% CI: 0.98–1.00; $P = .141$) (Fig. 2C).

3.2.4. Transfer abdomen opening rate.
A total of 31 studies[9–12,15,17–19,21–25,27,28,30–32,34,37–40,42–45,47–50] reported on conversion rates, including 27,872 patients. In the RALH

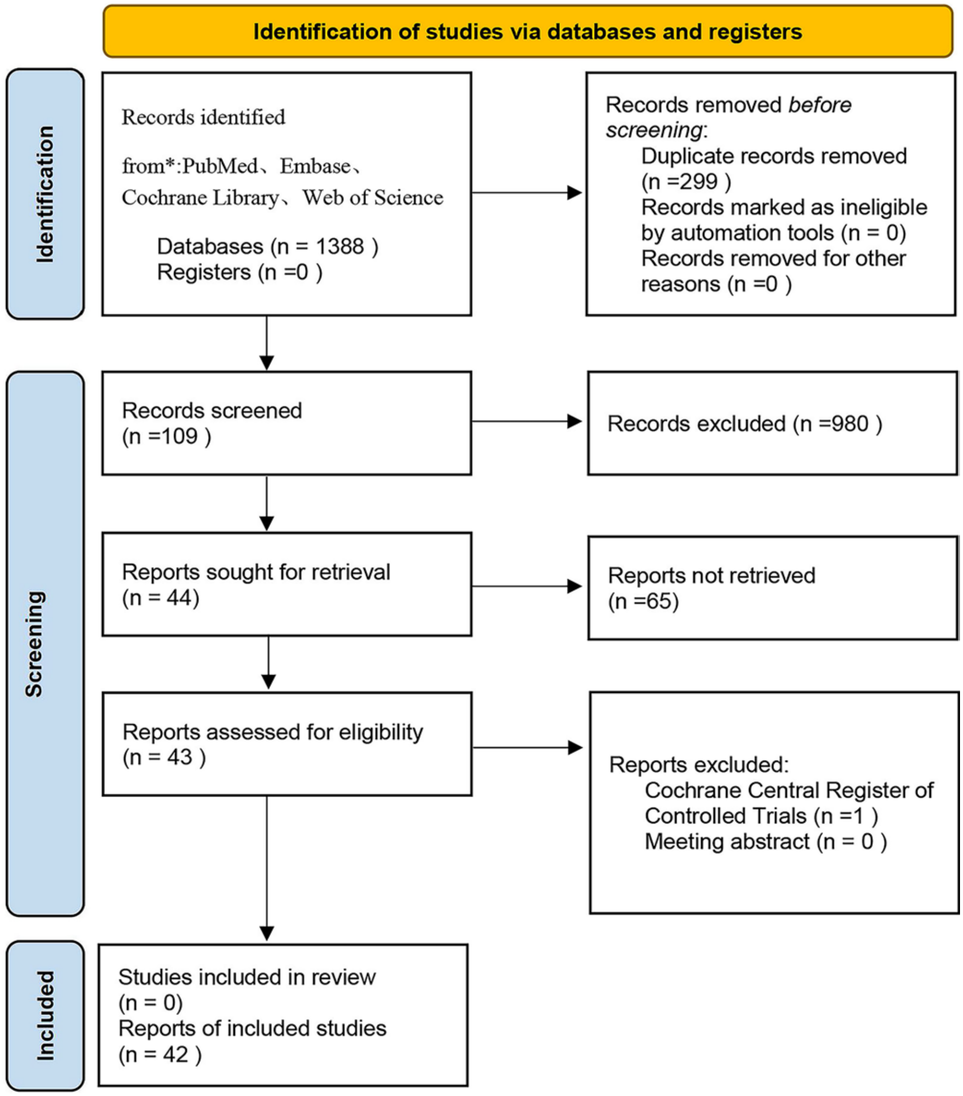

Figure 1. Flow chart of literature screening.

group, conversions were made to laparoscopic or open surgery, while in the LH group, conversions were only to open surgery. A fixed-effects model was used, as no significant heterogeneity was observed across studies ($P = .275$, $I^2 = 12.3\%$). The results indicated that the conversion rate in the RALH group was lower than that in the LH group (RR = 1.04; 95% CI: 1.03–1.05; $P < .001$) (Fig. 2D).

3.2.5. Hepatic hilar blocking rates. A total of 6 studies[18,21,23,25,30,41] reported hepatic hilar blocking rates, involving 433 patients. Significant heterogeneity was observed ($P = .003$, $I^2 = 72.3\%$); therefore, a random-effects model was applied. The results showed no significant difference in hepatic hilar blocking rates between the RALH and LH groups (RR = 1.92; 95% CI: 0.52–7.17; $P = .330$) (Fig. 2E).

3.2.6. Postoperative complications. A total of 38 studies[9–12,14,16,17,19–47,49,50] reported postoperative complications involving 29,000 patients. As there was no significant heterogeneity across the studies ($P = .004$, $I^2 = 41.9\%$), a fixed-effects model was used. The results indicated no significant difference in postoperative complications between the RALH and LH groups (RR = 1.01; 95% CI: 0.99–1.02; $P = .375$) (Fig. 3A).

3.2.7. Postoperative hospital stay. 30 studies[11,13,16,17,19–21,23–32,34,35,38,39,41,42,44–50] reported the length of the postoperative hospital stay, including 19,899 patients. Due to significant heterogeneity across studies ($P < .001$, $I^2 = 89.5\%$), a random-effects model was used. The results showed that there was no significant difference between the RALH and LH groups (MD = −0.18; 95% CI: −0.48–0.11; $P = .217$) (Fig. 3B).

3.2.8. Mortality rate. A total of 16 studies[9,13,19,27–29,34,38–40,42,43,47–50] reported on mortality rates, involving 12,565 patients. As there was moderate heterogeneity across the studies ($P = .015$, $I^2 = 53.4\%$), a random-effects model was applied. The results indicated no significant difference in mortality between the RALH and LH groups (RR = 1.00; 95% CI: 1.00–1.01; $P = .312$) (Fig. 3C).

3.2.9. Total cost. A total of 5 studies[17,32,46–48] reported on total costs, including 601 patients. Due to significant heterogeneity across the studies ($P < .001$, $I^2 = 98.5\%$), a random-effects model was applied. The results indicated that the total cost in the RALH group was significantly higher than in the LH group (MD = 0.43; 95% CI: 0.14 to 0.73; $P = .004$) (Fig. 3D).

3.2.10. R0 resection rate. A total of 11 studies[11,12,22,23,29–32,36,42,50] reported on R0 resection rates, involving 12,145 patients.

Table 1

Basic characteristics of the included literature.

Author	Year	Country	Design	Sample size (N)			Outcome indicators
				Total	RALH	LH	
Al-Temimi[9]	2019	USA	RCS	246	123	123	③④⑥⑧
Berber[10]	2010	USA	RCS	32	9	23	①②④⑥⑫⑬
Chong[11]	2019	Hongkong	RCS	183	91	92	①②④⑥⑦⑩⑬
Cipriani[12]	2022	Italy	RCS	1152	288	864	④⑥⑩⑬
Cortolillo[13]	2018	USA	RCS	724	204	520	⑦⑧
Croner[14]	2016	Germany	RCS	29	10	19	①⑥⑦⑧⑫⑬
Efanov[15]	2017	Russia	RCS	131	40	91	③④⑬
Elshaer[48]	2024	UK	RCS	81	60	21	①④⑦⑧⑨
Fruscione[16]	2018	USA	RCS	173	57	116	①②⑥⑦⑫
Hu[17]	2019	China	RCS	112	58	54	①②③④⑦⑨⑫⑬
Ji[18]	2011	China	RCS	33	13	20	①③④⑤⑥
Kadam[19]	2022	Singapore	RCS	2226	358	1868	①②③④⑥⑦⑧⑫⑬
Kim[20]	2016	Korea	RCS	43	12	31	①②③⑥⑦⑨⑫⑬
Krenzien[50]	2024	Singapore	RCS	3510	461	3049	①②③④⑥⑦⑧
Lai[21]	2016	Hongkong	RCS	135	100	35	①②③④⑥⑦⑩⑫
Lai[22]	2011	Hongkong	RCS	19	9	10	①④⑤⑥⑦⑫
Lai[23]	2012	Hongkong	RCS	49	32	17	①③④⑤⑥⑩⑪⑫⑬
Lee[24]	2015	Hongkong	RCS	136	70	66	①②③④⑥⑦⑪⑫⑬
Lee[25]	2019	Korea	RCS	23	13	10	②④⑤⑥⑦⑫⑬
Lim[26]	2019	France	RCS	172	61	111	①③⑥⑦⑪⑫⑬
Lim[27]	2020	Italy, France	RCS	388	277	111	①③④⑥⑦⑧⑫⑬
Liu[28]	2021	China	RCS	131	44	87	①②④⑥⑦⑧
Lorenz[29]	2021	Germany	RCS	155	44	111	①②③⑥⑦⑧⑫⑬
Magistri[30]	2016	Italy	RCS	46	22	24	①②③④⑤⑥⑦⑩⑪⑫
Marino[31]	2018	Poland	RCS	34	14	20	①②④⑥⑦⑩⑫
Mejia[32]	2019	USA	RCS	120	35	85	①②③④⑥⑦⑨⑩⑫⑬
Miller[33]	2021	USA	RCS	454	227	227	③⑥⑨
Montalti[34]	2015	Italy	RCS	108	36	72	①②④⑥⑦⑧⑪⑫
Packiam[35]	2012	USA	RCS	29	11	18	①②⑥⑦⑫⑬
Rahimli[36]	2020	Germany	RCS	25	12	13	①②③⑥⑦⑩⑪⑫⑬
Salloum[37]	2016	France	RCS	96	16	80	①④⑥⑫
Sijberden[51]	2024	Italy	RCS	10,075	1507	8568	①②④⑥⑦⑧⑩⑪
Spampinato[38]	2014	Italy	RCS	50	25	25	①②③④⑥⑦⑧⑪
Sucandy[39]	2022	Singapore	RCS	580	190	390	①②③④⑥⑦⑧⑫⑬
Tranchart[40]	2014	France	RCS	56	28	28	①②③④⑥⑧⑫⑬
Troisi[41]	2013	Belgium	RCS	263	40	223	①②④⑤⑥⑦⑪⑫⑬
Tsung[42]	2014	USA	RCS	171	57	114	①②④⑥⑦⑧⑩⑫⑬
Vining[43]	2023	USA	RCS	7767	933	6834	①④⑥⑧⑬
Wang[44]	2019	China	RCS	140	92	48	①②④⑥⑦⑫⑬
Wu[45]	2014	Taiwan	RCS	79	38	41	①②④⑥⑦⑫
Yu[46]	2014	Korea	RCS	30	13	17	①②⑥⑦⑨⑫⑬
Zhu[47]	2022	China	RCS	258	176	82	①②③④⑥⑦⑧⑨⑪⑫⑬

① = operative time, ② = intraoperative bleeding, ③ = intraoperative transfusion rate, ④ = transfer abdomen opening rate, ⑤ = hepatic hilar blocking rates, ⑥ = postoperative complications, ⑦ = postoperative hospital stay, ⑧ = mortality rate, ⑨ = total cost, ⑩ = *R*0 resection rate, ⑪ = *R*1 resection rate, ⑫ = tumor diameter, ⑬ = malignant tumor rate, RCS = retrospective cohort study.

As there was no significant heterogeneity across the studies ($P = .971$, $I^2 = 0\%$), a fixed-effects model was used. The results indicated no significant difference in R0 resection rates between the RALH and LH groups (RR = 1.01; 95% CI: 0.98 to 1.04; $P = .532$) (Fig. 4A).

3.2.11. R1 resection rate. A total of 10 studies[22,24,26,30,34,36,38,41,47,50] reported R1 resection rates, involving 11,182 patients. As there was no significant heterogeneity across the studies ($P = .050$, $I^2 = 48.4\%$), a fixed-effects model was used. The results indicated that the R1 resection rate in the RALH group was higher than in the LH group (RR = 1.04; 95% CI: 1.03 to 1.06; $P < .001$) (Fig. 4B).

3.2.12. Tumor diameter. A total of 27 studies[10,14,17,20–27,29–32,34–37,39–41,44–47] reported on tumor diameter, including 5088 patients. As there was no significant heterogeneity across studies ($P = .132$, $I^2 = 23.8\%$), a fixed-effects model was used. The results indicated that the tumor diameter in the RALH group was larger than that in the LH group (MD = 0.37; 95% CI: 0.24–0.49; $P < .001$) (Fig. 4C).

3.2.13. Malignant tumor rate. A total of 23 studies[10–12,14,15,17,20,22,24,25,27,29,32,35,36,39,40,42–44,46,47] reported on malignancy rates, including 1719 patients. Due to no significant heterogeneity across the studies ($P = .820$, $I^2 = 0\%$), a random-effects model was used. The results indicated no significant difference in the malignant tumor rate between the RALH and LH groups (RR = 1.00; 95% CI: 0.95–1.05; $P = .924$) (Fig. 4D).

3.2.14. Sensitivity analysis and publication bias. A sensitivity analysis was conducted for all outcome measures, and the results are presented in Supplementary Material 2 (Supplemental Digital Content, http://links.lww.com/MD/O228). A sensitivity analysis of the significantly heterogeneous outcome indicators (operative time, intraoperative blood loss, hilar blocking rate, postoperative hospital stay, and malignant tumor rate) was performed by excluding studies with the least weight, heaviest weight, or large standard deviation changes to test the stability of the results. The analysis showed that the heterogeneity in each group did not change significantly upon exclusion; no source

Table 2

The NOS scale quality score of the included studies.

		Object selection				Group comparability	The outcome evaluation			
Author	Year	1	2	3	4	5	6	7	8	Score
Al-Temimi[9]	2019	★	★	★	★	★		★		6
Berber[10]	2010	★	★	★	★	★	★	★	★	8
Chong[11]	2019	★	★	★	★	★★	★	★		8
Cipriani[12]	2022	★	★	★	★	★	★	★	★	9
Cortolillo[13]	2018	★	★	★	★	★		★		6
Croner[14]	2016	★	★	★	★	★★	★	★		8
Efanov[15]	2017	★	★	★	★	★		★		6
Elshaer[48]	2024	★	★	★	★	★	★	★	★	8
Fruscione[16]	2018	★	★	★	★	★	★	★		7
Hu[17]	2019	★	★	★	★	★		★	★	7
Ji[18]	2011	★	★	★	★	★	★	★		7
Kadam[19]	2022	★	★	★	★	★	★	★	★	8
Kim[20]	2016	★	★	★	★	★	★	★	★	8
Krenzien[49]	2024	★	★	★	★	★★	★	★	★	9
Lai[21]	2016	★	★	★	★	★	★		★	7
Lai[22]	2011	★	★	★	★	★	★	★		7
Lai[23]	2012	★	★	★	★	★	★	★	★	8
Lee[24]	2015	★	★	★	★	★★	★	★		8
Lee[25]	2019	★	★	★	★	★		★	★	7
Lim[26]	2019	★	★	★	★	★	★	★	★	8
Lim[27]	2020	★	★	★	★	★★	★	★	★	9
Liu[28]	2021	★	★	★	★	★	★	★	★	8
Lorenz[29]	2021	★	★	★	★	★	★	★		7
Magistri[30]	2016	★	★	★	★	★★	★	★		8
Marino[31]	2018	★	★	★	★	★	★	★		7
Mejia[32]	2019	★	★	★	★	★	★	★	★	8
Miller[33]	2021	★	★	★	★	★★		★		7
Montalti[34]	2015	★	★	★	★	★	★	★		7
Packiam[35]	2012	★	★	★	★	★★	★	★		8
Rahimli[36]	2020	★	★	★	★		★	★		
Salloum[37]	2016	★	★	★	★	★	★	★		7
Sijberden[50]	2024	★	★	★	★	★	★	★	★	8
Spampinato[38]	2014	★	★	★	★	★	★	★		7
Sucandy[39]	2022	★	★	★	★	★		★	★	7
Tranchart[40]	2014	★	★	★	★	★	★	★		7
Troisi[41]	2013	★	★	★	★	★	★	★		7
Tsung[42]	2014	★	★	★	★	★★		★	★	8
Vining[43]	2023	★	★	★	★	★★	★	★		8
Wang[44]	2019	★	★	★	★	★	★	★		7
Wu[45]	2014	★	★	★	★	★		★	★	7
Yu[46]	2014	★	★	★	★	★	★	★		7
Zhu[47]	2022	★	★	★	★	★	★	★		7

Notes: ★represents 1 point; 1, representativeness of the exposed cohort; 2, selection of nonexposed cohort; 3, confirmation of exposure; 4, no study subjects before study initiation; 5, comparability of the cohort; 6, assessment of outcome events; 7, occurrence of outcomes; 8, completeness of follow-up.

of heterogeneity was detected, and the exclusion process did not alter the overall results of the original analysis. Publication bias was assessed using the funnel plot for intraoperative bleeding, and the plot appeared to be symmetrical, indicating no significant publication bias (Fig. 5).

4. Discussion

Although LH is nearly 30 years old, a review of the literature found that it is still hindered by inherent limitations, such as limited range of motion, physiological tremor amplification, poor visualization, difficulty in suturing at certain sites, and a steep learning curve.[51] In the early 21st century, RALH was introduced to address these limitations by offering improved 3-dimensional visualization, tremor suppression, and greater precision in complex surgical tasks. However, despite these advancements, the clinical outcomes of RALH, as shown in our meta-analysis, do not demonstrate a clear superiority over LH in most outcome measures, indicating that both methods can achieve similar safety and efficacy profiles.[52]

A notable finding of our study was a significantly longer operative time in the RALH group compared to LH group (MD = 55.33; 95% CI: 34.84–75.83; $P < .001$). This may reflect the additional complexity of assembling and operating robotic systems, particularly in large liver resections, which are commonly performed using RALH.[53] As robotic technology evolves, operative times may decrease, particularly with advancements in the system setup and surgeon experience.[54] Studies by Boggi and Abond[55,56] support this trend, showing that RALH can be safely used in major hepatectomies. Furthermore, Tsun[42] highlighted that with experience, surgeons can reduce the operative times for RALH, suggesting that the learning curve remains an important factor. This learning curve should be acknowledged in clinical settings, where surgeon expertise can mitigate longer operative durations.

Our meta-analysis found higher intraoperative blood loss in the RALH group compared to LH group (MD=−28.35; 95% CI: −50.35–−6.39; $P < .001$). This is unexpected, given that robotic systems provide greater precision and maneuverability through EndoWrist, which has 7 degrees of freedom,

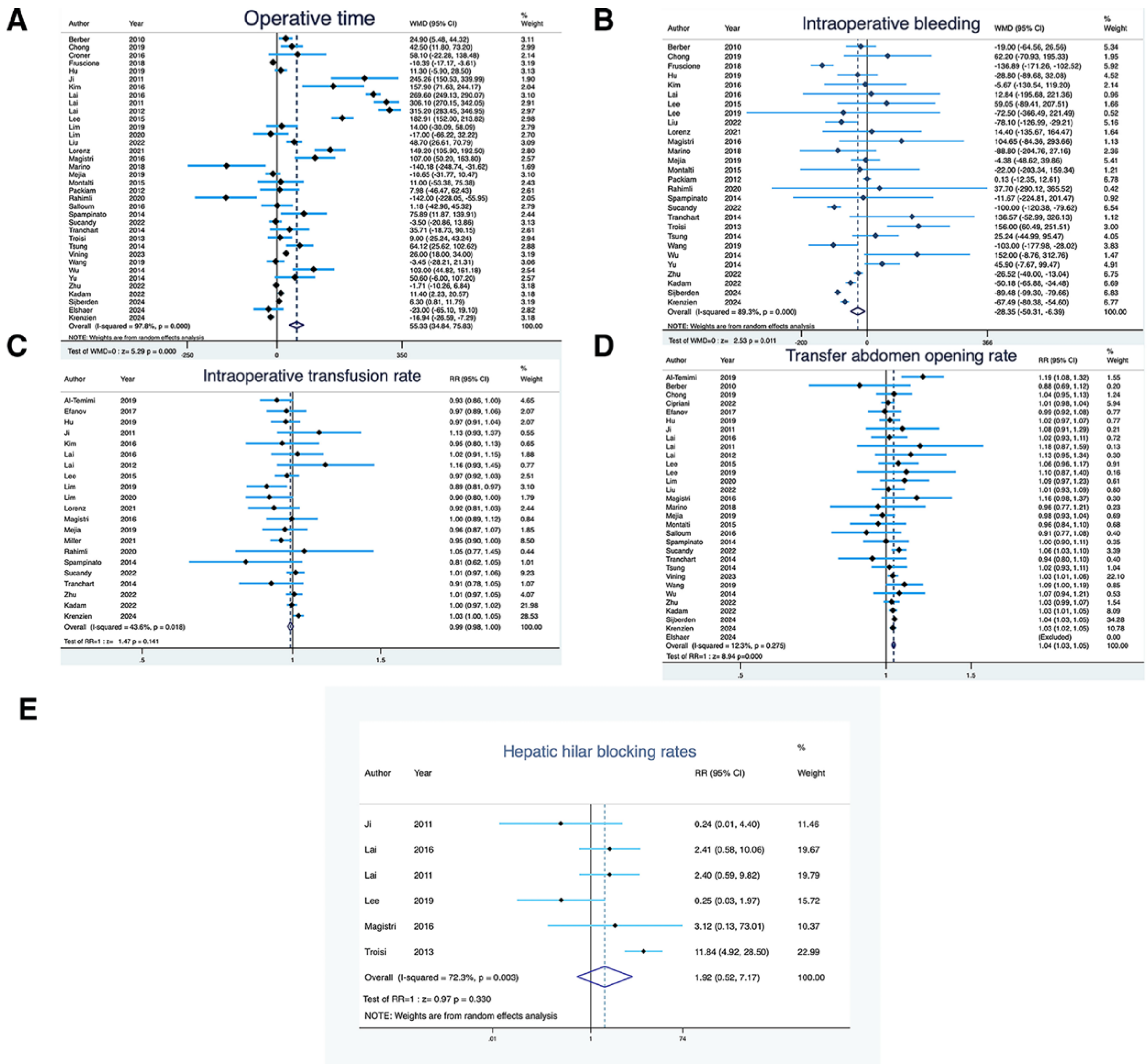

Figure 2. A meta-analysis of operation time (A) intraoperative bleeding volume (B) intraoperative transfusion rates (C) transfer abdomen opening rate (D) hepatic hilar blocking rates (E) comparing the 2 groups. CI = confidence interval (no units), RR = risk ratio (no units), WMD = weighted mean difference (no units).

offering better control over bleeding. This discrepancy may be attributed to differences in surgical protocols or transfusion thresholds across different regions, as no uniform transfusion policies were reported in the studies we analyzed. Interestingly, although robotic platforms should theoretically reduce intraoperative blood loss, this was not observed in our analysis. Additionally, it is worth noting that higher blood transfusion rates, although not significantly different between RALH and LH in our study, are linked to increased complication rates and worse disease-free survival in cancer patients.[57,58] This underscores the need for further research to optimize intraoperative management protocols for robotic surgery.

No significant differences were found between the RALH and LH groups in terms of postoperative complications, hospital stay, or mortality, suggesting that both approaches are equally safe for patients undergoing liver resection. This is clinically relevant, as it demonstrates that RALH offers no additional risk compared with LH, despite its technological advantages. Moreover, the R0 and R1 resection rates were similar between the groups, further supporting the oncological efficacy of both methods in achieving complete tumor resection. This is particularly important for long-term survival in liver cancer patients, where achieving negative margins (R0 resection) is a critical outcome determinant.

One of the most significant challenges with RALH is its higher total cost (MD = 0.43; 95% CI: 0.14–0.73; $P = .004$). The high upfront costs of robotic systems coupled with their annual maintenance fees limit the widespread adoption of RALH, particularly in healthcare settings with limited resources.[57] The lack of insurance coverage for robotic procedures further restricts access to RALH in many patients. However, as robotic technology advances and competition in the marketplace increases, costs may decline, making RALH more accessible.[58] Until these financial barriers are addressed, LH remains a more cost-effective alternative for most patients despite the potential technical advantages of robotic systems.

The findings of this meta-analysis provide clinically relevant insights into the comparison between RALH and LH. Although RALH offers certain technical advantages, such as enhanced precision and improved visualization, its higher cost and longer operative times raise questions about its practicality as a routine option for liver resection. Clinically, the choice between RALH and LH should be based on individual patient factors, including tumor complexity, patient comorbidities, and the availability of robotic technology. For more complex cases that require

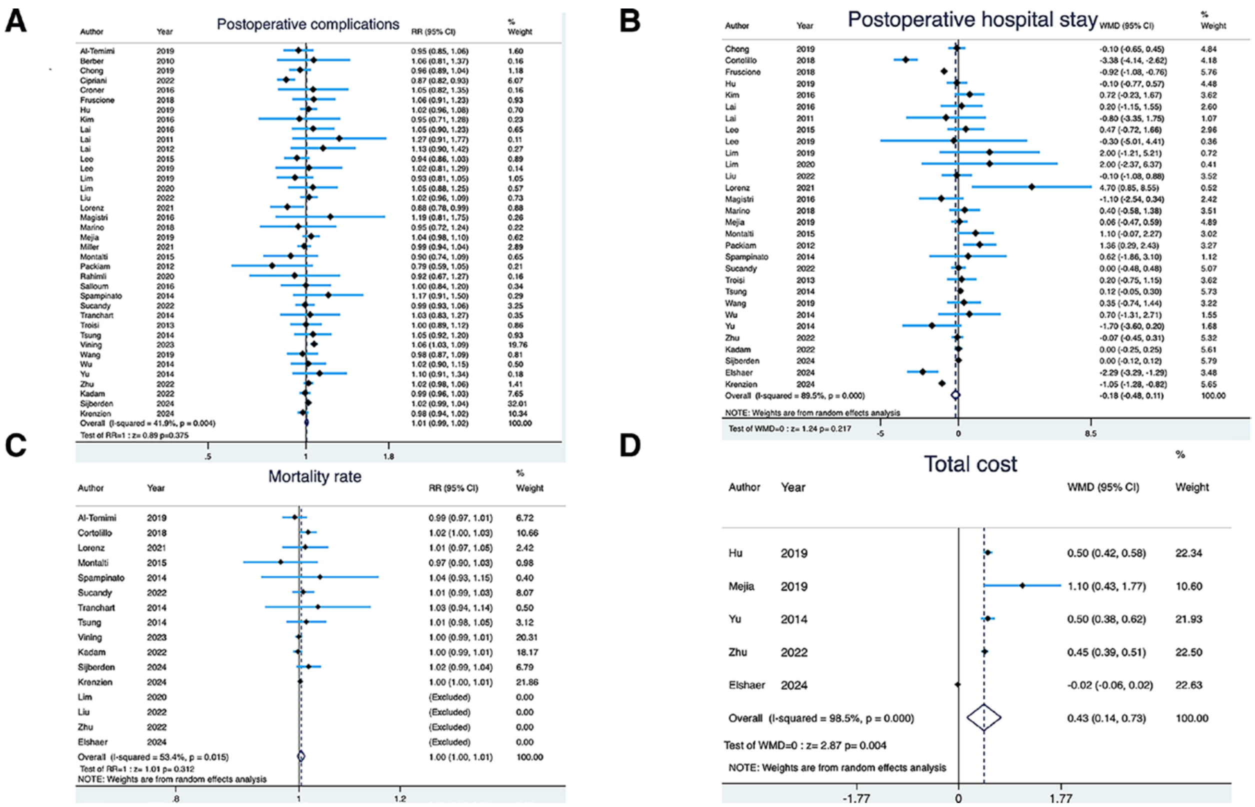

Figure 3. A meta-analysis of comparing postoperative complications (A) postoperative hospital stay (B) mortality comparisons (C) total costs (D) between 2 groups. CI = confidence interval (no units), RR = risk ratio (no units), WMD = weighted mean difference (no units).

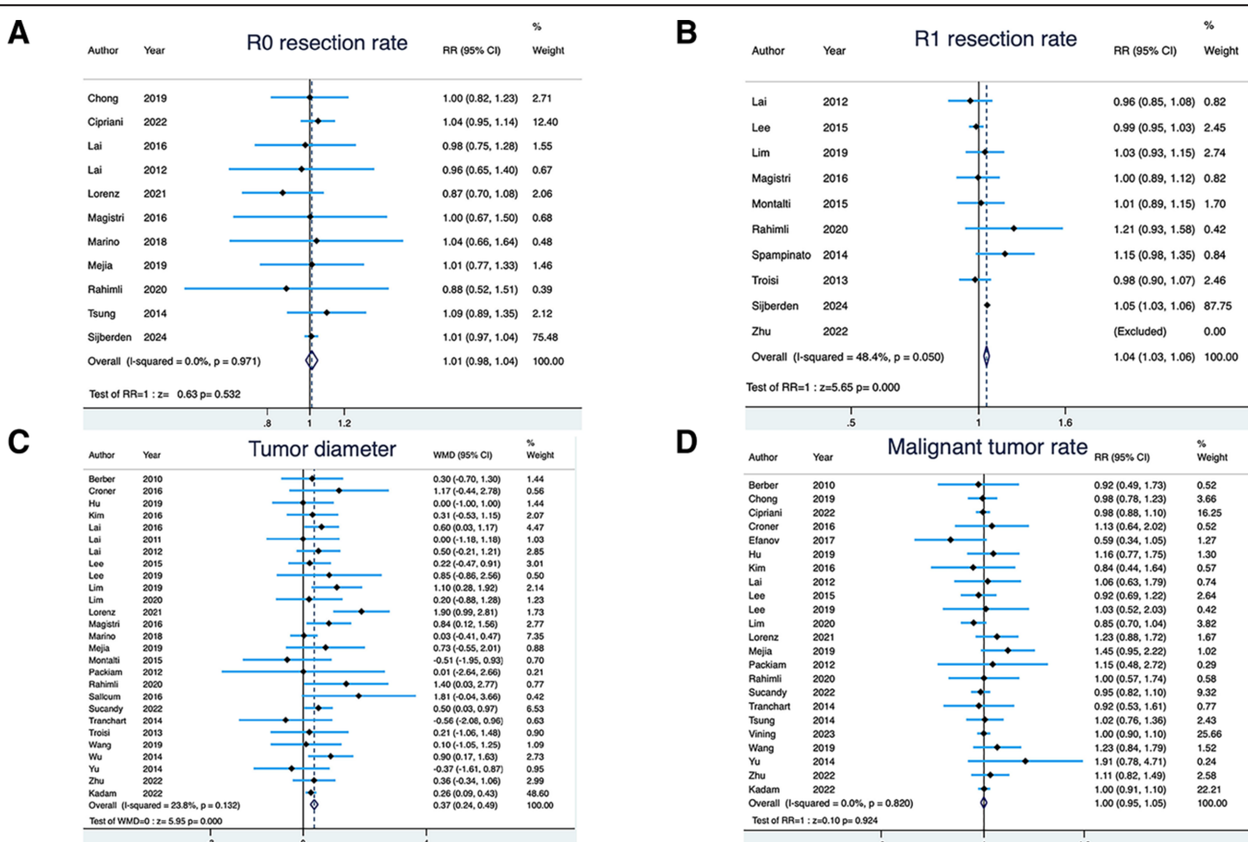

Figure 4. A meta-analysis of comparing *R*0 resection rates (A) *R*1 resection rates (B) tumor diameter (C) malignancy tumor rates (D) between the 2 groups. CI = confidence interval (no units), RR = risk ratio (no units), WMD = weighted mean difference (no units).

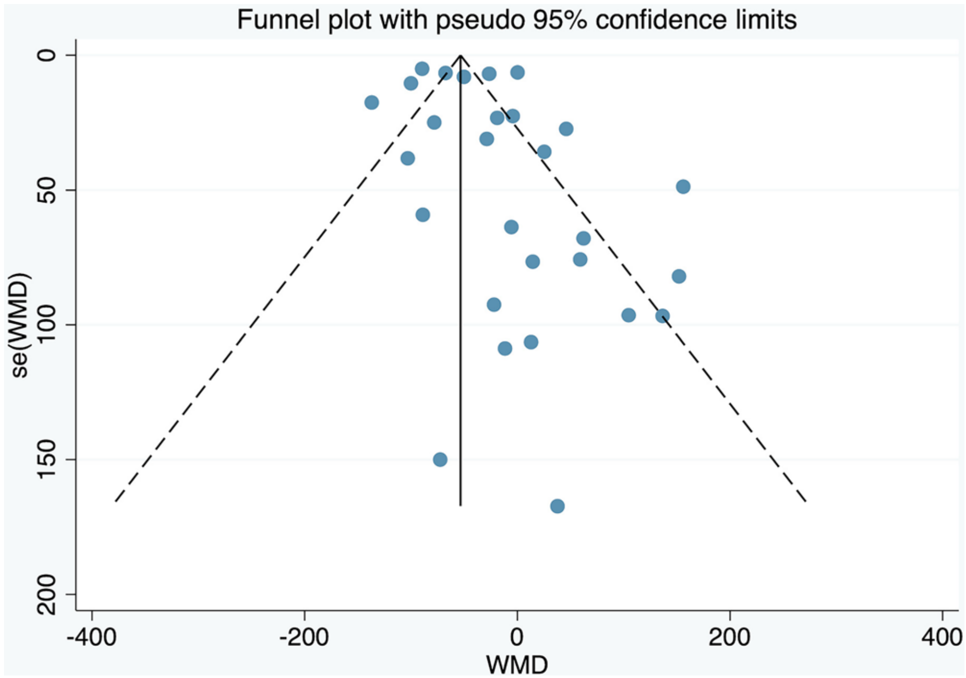

Figure 5. Intraoperative bleeding funnel plot. WMD = weighted mean difference (no units).

fine dissection or access to difficult anatomical regions, RALH may offer significant benefits. However, LH remains a faster and more cost-effective option for simpler resections. As robotic systems continue to evolve, further research is needed to explore the long-term benefits of RALH, including its impact on recurrence rates and overall survival.

This meta-analysis had several limitations. First, the analysis was based on retrospective cohort studies that were subject to selection bias. The lack of prospective randomized controlled trials makes it difficult to draw definitive conclusions about the superiority of 1 approach over another. Second, the included studies did not provide sufficient data to assess long-term prognostic outcomes such as recurrence rates and overall survival. Third, the significant heterogeneity observed in some key outcomes, such as operative time and intraoperative blood loss, reflects variations in surgical techniques, tumor characteristics, and institutional practices. While sensitivity analyses were conducted to assess the robustness of the results, future studies should focus on standardizing the surgical protocols to reduce heterogeneity.

In conclusion, our meta-analysis indicated that RALH and LH have similar efficacy and safety in the treatment of liver tumors. However, RALH is associated with higher costs and longer operative times and thus cannot replace LH as the standard of care. Further randomized controlled trials and long-term follow-up studies are needed to better understand the role of RALH in liver surgery and to identify which patients may benefit the most from this advanced technology.

Author contributions

Conceptualization: Fuyong Niu, Yefei Wang, Zhiqiang He, Hailin Wang.
Data curation: Fuyong Niu, Yefei Wang, Zhiyuan Bai, Zhiqiang He, Hailin Wang.
Formal analysis: Fuyong Niu, Zhiqiang He, Hailin Wang.
Funding acquisition: Furong Li.
Investigation: Yefei Wang, Zhiyuan Bai.
Methodology: Yefei Wang, Zhiyuan Bai, Zhiqiang He, Hailin Wang.
Project administration: Furong Li.
Resources: Furong Li.
Software: Fuyong Niu, Hailin Wang.
Supervision: Hailin Wang, Furong Li.
Visualization: Fuyong Niu.
Writing – original draft: Fuyong Niu, Zhiyuan Bai, Zhiqiang He, Hailin Wang.
Writing – review & editing: Fuyong Niu, Zhiyuan Bai, Zhiqiang He, Hailin Wang, Furong Li.

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