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Review Article

Feasibility and safety of robotic radical resection for hilar cholangiocarcinoma in highly selected patients: A systematic review and meta-analysis with meta-regression

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To examine the feasibility and safety of robotic radical resection (RRR) for hilar cholangiocarcinoma (HCCA). A PRISMA-compliant meta-analysis with meta-regression was conducted, including studies reporting outcomes of RRR in patients with HCCA. Six studies comprising 295 patients were included. In highly selected patients (body mass index [BMI] < 25 kg/m" ; tumor size < 3 cm), RRR of HCCA proved safe and feasible (Clavien-Dindo ≥ III complications: 14.8% [95% confidence interval 8.7%–20.8%]; 30-day mortality: 1.9% [0%–4.2%]; conversion to open surgery: 1.9% [0%–4.2%]; intraoperative blood loss: 210 mL [119–301 mL]; operative time: 481 minutes [339–623 minutes]; R0 resection rate: 82.2% [75.0%–89.4%]; retrieved lymph nodes: 12 [9–16]). Younger age ($p = 0.008$), higher BMI ($p = 0.009$), larger tumors ($p = 0.048$), and performing liver resections ($p = 0.017$) increased blood loss. American Society of Anesthesiologists status ≥ III ($p < 0.001$) and Bismuth IV disease ($p < 0.001$) increased operative times. Preoperative biliary drainage ($p = 0.027$) enhanced R0 resection rates. RRR led to less bleeding (mean difference [MD]: –184 mL, $p = 0.0005$), longer operative times (MD: 162 minutes, $p = 0.001$), and improved R0 resection rates (odds ratio: 3.29, $p = 0.006$) compared with the open approach. Subject to selection bias and type 2 error, RRR for HCCA might be safe and feasible in highly selected patients (favorable BMI and tumor size). The findings should not be taken as definitive conclusions but may be used for hypothesis generation in subsequent trials.

Key Words: Robotics; Cholangiocarcinoma; Klatskin tumor

INTRODUCTION

Radical resection remains the only curative treatment for hilar cholangiocarcinoma [1]. Radical resection of hilar cholangiocarcinoma, technically challenging due to anatomical considerations (proximity to hepatic artery, portal vein, and caudate lobe) and procedural complexity (necessitating loco-regional lymphadenectomy, bilioenteric reconstruction, and possibly extensive liver resection including the caudate lobe), requires a steep learning curve [1]. However, recent advances in surgical techniques have expanded the indications for minimally invasive surgery in complex hepato-pancreato-biliary operations, thereby increasing the popularity of minimally-invasive approaches for radical resection of hilar cholangiocarcinoma [2,3].

Although the available evidence is limited, the safety and feasibility of laparoscopic radical resection of hilar cholangiocarcinoma in strictly selected patients have been demonstrated [2,3]; however, the laparoscopic resection of this carcinoma is still in an early developmental phase [3]. The effectiveness

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of the laparoscopic method has promoted the examination of robotic radical resection of hilar cholangiocarcinoma. Robotic surgical systems offer potential advantages such as three-dimensional visualization, extremely flexible robotic arms, enhanced dexterity, precise dissection in confined spaces, and superior handling of tissues and instruments [4,5]. Recent studies have focused on the outcomes of robotic radical resection of hilar cholangiocarcinoma, providing a basis for a systematic review and meta-analysis. We aim to conduct a systematic review and meta-analysis to assess the feasibility and safety of robotic radical resection for hilar cholangiocarcinoma.

METHODS

Methodological and reporting compliance

The study was undertaken and reported according to the Cochrane Handbook for Systematic Reviews (version 6.4) [6] and the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 guidelines [7].

Registration and protocol

The study adhered to a predefined protocol registered in PROSPERO, an open international database for prospectively registered systematic reviews.

Eligibility criteria

Study design

We included all retrospective and prospective studies (cohort studies, case-control studies, case series, and randomized controlled trials) that involved at least 10 patients. Systematic reviews, meta-analyses, scoping reviews, review articles, case reports, and correspondence were excluded.

Population

All adult patients aged 18 and older who underwent robotic radical resection for hilar cholangiocarcinoma were considered eligible. Radical resection was defined as resection aimed at achieving R0 resection, including bile duct resection with or without (extended) hepatectomy and with or without caudate lobe resection, depending on disease extent.

Intervention and comparison

The robotic approach was the primary intervention of interest. Comparisons, where possible, included open and laparoscopic approaches.

Outcomes

The primary outcomes of interest included complications (Clavien-Dindo ≥ III), 30-day mortality, conversion to open surgery, intraoperative blood loss, operative time, R0 resection, and the number of retrieved lymph nodes.

Information sources and search strategy

A comprehensive search strategy, including appropriate search keywords, limits, thesaurus headings, and operators, was developed, adopted, and implemented across several electronic sources: Scopus, MEDLINE, the Cochrane Central Register of Controlled Trials, the Cumulative Index to Nursing and Allied Health Literature, the International Standard Randomised Controlled Trial Number Registry, the International Clinical Trials Registry Platform, ClinicalTrials.gov, and the Grey Literature Network Service (Appendix 1). Two authors with expertise in evidence synthesis designed and conducted the search strategy on 3 November 2024 without language restrictions.

Study selection, data collection, and data items

Two authors independently screened the identified articles by examining titles and abstracts based on the eligibility criteria and retrieved the full texts of potentially eligible articles. Articles that satisfied the eligibility criteria were selected for inclusion. In cases of discrepancy in the findings of the first two authors, a third author provided an opinion on eligibility. The data items were established during the protocol development stage by authors with expertise in the field and subsequent to the selection of eligible studies by authors with expertise in evidence synthesis utilizing a pilot-testing technique on randomly selected studies. Data items were recorded on an electronic data collection sheet by two independent authors. These data included information about bibliometric parameters, study design, the studied population and their demographic characteristics, body mass index (BMI), American Society of Anesthesiologists (ASA) status, preoperative biliary drainage, Bismuth classification, tumor size, liver resection, caudate lobe resection, and the outcomes.

Study risk of bias assessment

The risk of bias in the included studies was assessed using the JBI (Joanna Briggs Institute) Critical Appraisal Tool [8] for case series by two independent authors. If any discrepancy arose in the assessments by the first two authors, a third author provided an opinion.

Effect measures and synthesis methods

OpenMeta[Analyst] software was utilized for proportion meta-analysis modeling, and RevMan 5.4 software (Nordic Cochrane Centre) was employed for comparative meta-analysis modeling. In the proportion meta-analysis model, numerical estimations of the overall effect (pooled risk for dichotomous variables and the pooled mean for continuous variables) were derived after integrating quantitative data from individual studies. In the comparative meta-analysis model, the odds ratio (OR) was computed as a summary effect measure for dichotomous variables and mean difference (MD) for continuous variables. Forest plots incorporating random-effects model-

Table 1. Baseline characteristics of the included studies

Authors	Year	Country	Journal	Design	Included population	Sample size (n)			JBI risk of bias
						Robotic	Open	Laparoscopic	
Liu et al. [10]	2024	China	Sci Rep	Retrospective series	Patients undergoing robotic radical resection of hilar cholangiocarcinoma	10	0	20	Low
Sucandy et al. [11]	2024	USA	Ann Surg Oncol	Prospective series	Patients undergoing robotic radical resection of perihilar cholangiocarcinoma	38	93	0	Low
Huang et al. [12]	2023	China	Gastroenterol Rep	Retrospective series	Patients undergoing robotic radical resection of perihilar cholangiocarcinoma	10	20	0	Moderate
Magistri et al. [13]	2023	Italy	Eur J Surg Oncol	Retrospective series	Patients undergoing robotic radical resection of perihilar cholangiocarcinoma	14	0	0	Low
Li et al. [14]	2020	China	Int J Med Robot	Retrospective series	Patients undergoing robotic radical resection of hilar cholangiocarcinoma	48	0	0	Moderate
Xu et al. [15]	2016	China	Surg Endosc	Retrospective series	Patients undergoing robotic radical resection of hilar cholangiocarcinoma	10	32	0	Moderate

JBI, Joanna Briggs Institute.

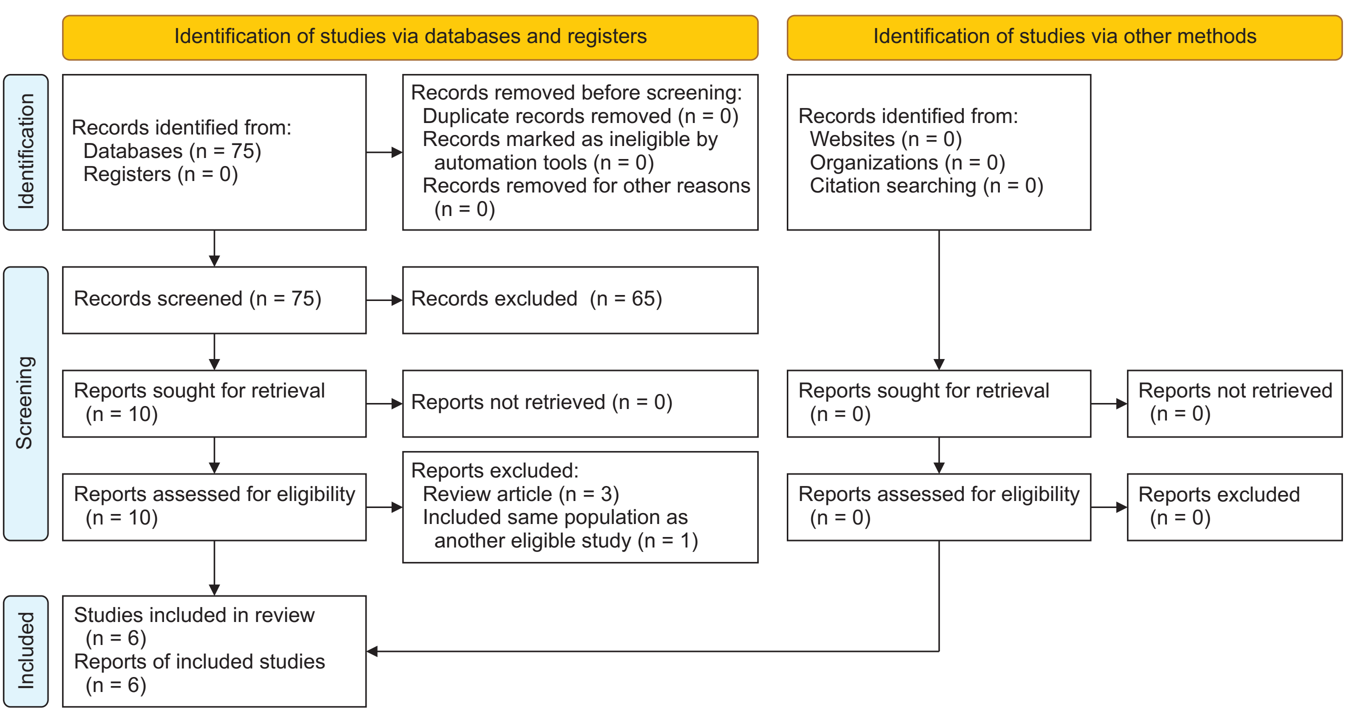

Fig. 1. Study PRISMA flow diagram.

ing and 95% confidence intervals (CIs) were constructed to illustrate the results. Meta-regression was conducted to assess the impact of variables such as age, male sex, BMI, ASA III or above, preoperative biliary drainage, Bismuth classification, tumor size, liver resection, and caudate lobe resection on the outcomes. Individual patients were considered as the unit of analysis. Statistical heterogeneity was quantified as I^2 using Cochran's Q test (χ^2), with heterogeneity classified as low when I^2 ranged from 0%–25%, moderate from 25%–75%, and high from 75%–100%. Sensitivity analyses, including leave-one-out analysis and separate analysis for studies with low overall risk of bias, were conducted if the outcome was assessed by at least four studies.

Assessment of reporting bias

The protocol intended to assess the risk of reporting bias by constructing a funnel plot if the outcome was reported by at least ten studies; however, given that the outcome was reported by fewer than ten studies, reporting bias could not be assessed.

Certainty assessment

The GRADE system was employed to determine the certainty of evidence concerning operative mortality [9].

Protocol compliance

The study adhered strictly to the registered protocol out any deviations.

RESULTS

Study selection and characteristics

A search of the information sources yielded 75 articles; 65 articles were directly excluded after screening their titles and abstracts. The full-text review of the remaining 10 articles resulted in the exclusion of four articles (three were review articles; one included the same population as another eligible study). Consequently, six case series [10-15] (five retrospective and one prospective) were included. A total of 130 patients underwent robotic radical resection for hilar cholangiocarcinoma and were included for proportion meta-analysis. The baseline characteristics of the included studies are documented in Table 1 and the PRISMA flow diagram is depicted in Fig. 1.

Table 2. Baseline characteristics of the included patients

	Value
No of patients	130
Age (yr)	64.1 (60.4–67.8)
Male sex	78 out of 130 (60.0)
BMI (kg/m^2)	23.5 (21.9–25.1)
ASA III or above	38 out of 130 (29.2)
Preoperative biliary drainage	85 out of 130 (65.4)
Bismuth I	33 out of 130 (25.4)
Bismuth II	16 out of 130 (12.3)
Bismuth III	66 out of 130 (50.8)
Bismuth IV	15 out of 130 (11.5)
Tumor size (cm)	2.35 (1.77–2.92)
Liver resection	91 out of 130 (70.0)

Values are presented as mean (95% confidence interval) or number (%).
BMI, body mass index; ASA, American Society of Anesthesiologists.

Baseline characteristics of included patients

Table 2 summarizes the baseline characteristics of the included patients. The average age of these patients was 64.1 years (95% CI, 60.4–67.8), with 60.0% (78 out of 130) being male. The mean BMI was reported as 23.5 kg/m^2 (95% CI, 21.9–25.1), and 29.2% (38 out of 130) were classified as having an ASA status of ≥ III. Preoperative biliary drainage was performed in 65.4% (85 out of 130) of the cases. Regarding the Bismuth classification

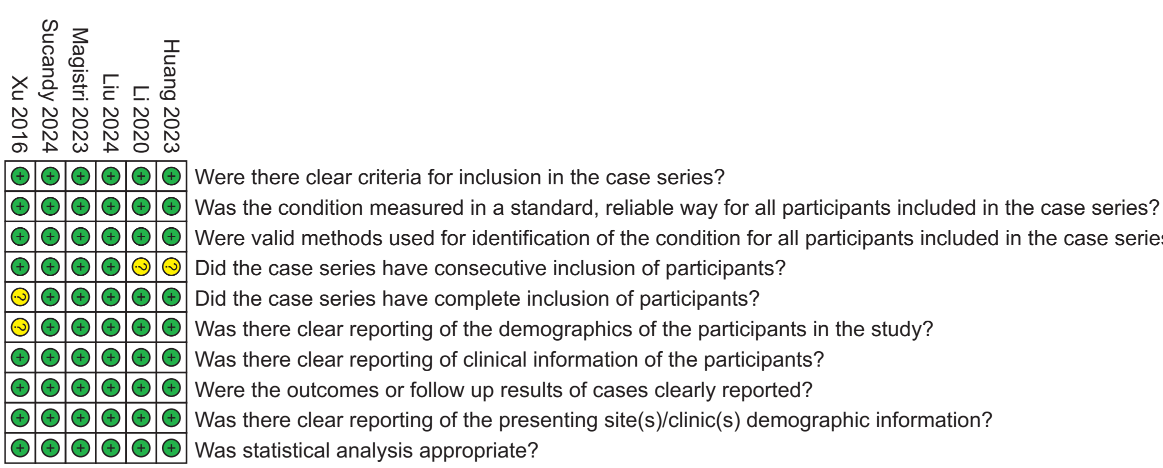

Fig. 2. Outcomes of the methodological quality assessment of the studies included in the proportion meta-analysis model, as evaluated using the Joanna Briggs Institute Critical Appraisal tool.

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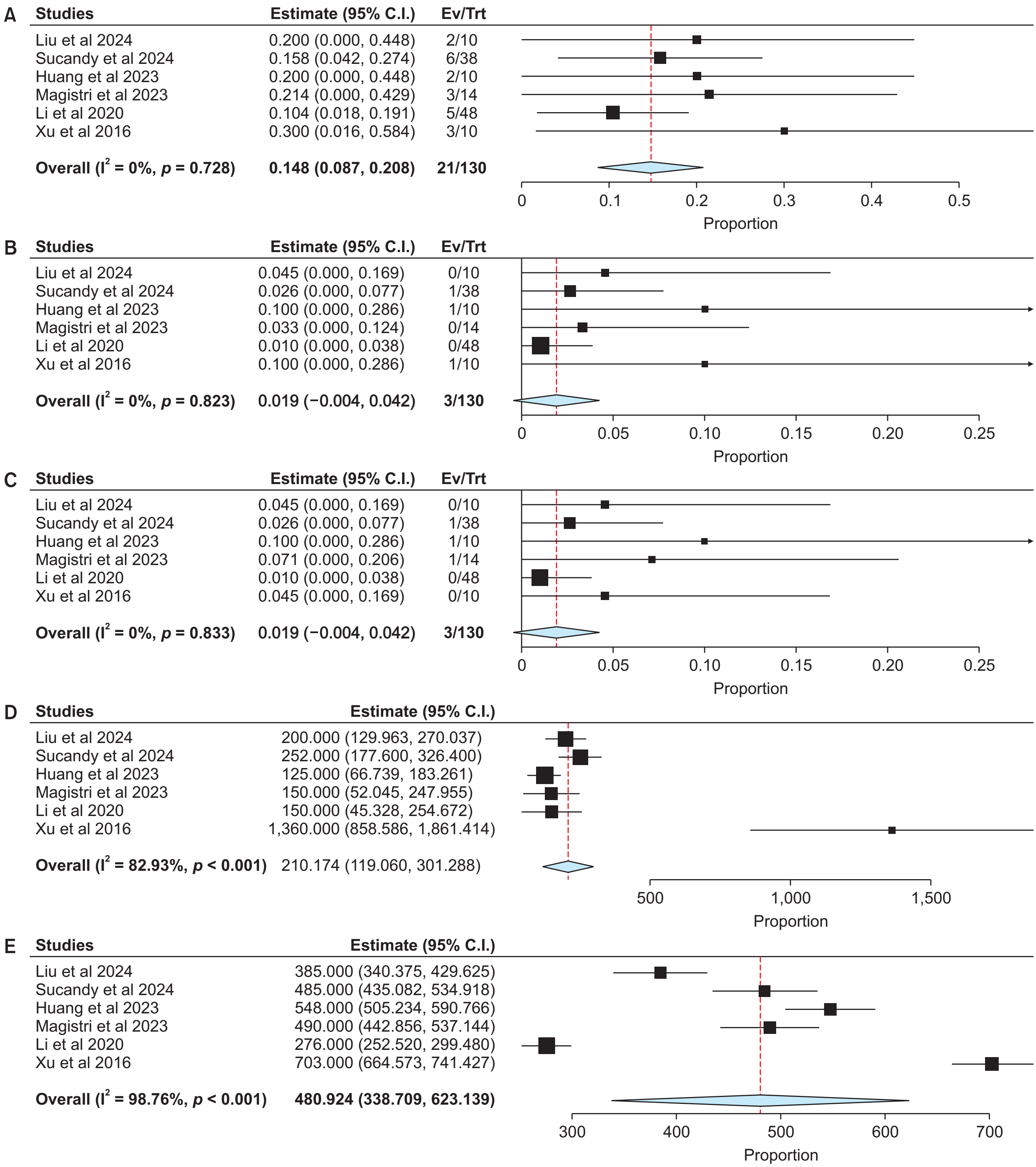

Fig. 3. Forest plots for the outcomes in the proportion meta-analysis model: (A) Complications (Clavien-Dindo ≥ III); (B) 30-day mortality; (C) conversion to open surgery; (D) intraoperative blood loss; (E) operative time; (F) R0 resection; (G) number of retrieved lymph nodes. Ev/Trt, events/total; CI, confidence interval.

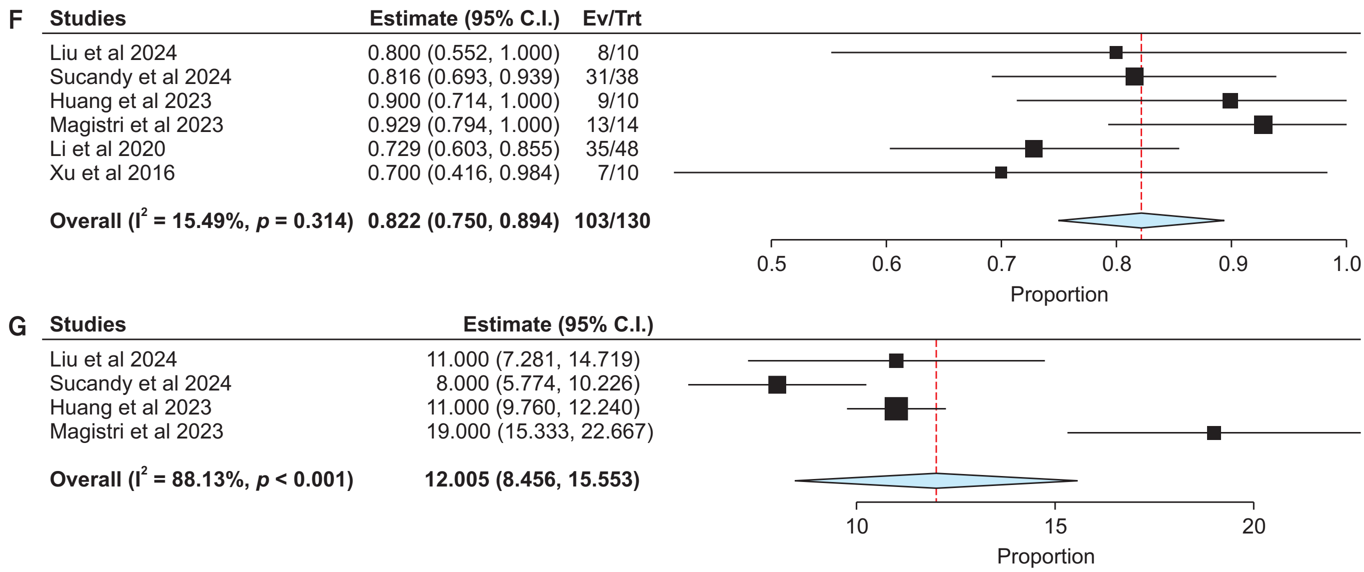

Fig. 3. Continued.

of hilar cholangiocarcinoma, 25.4% were Bismuth I (33 out of 130), 12.3% Bismuth II (16 out of 130), 50.8% Bismuth III (66 out of 130), and 11.5% Bismuth IV (15 out of 130). The average tumor size was 2.35 cm (95% CI, 1.77–2.92), and liver resection was required in 70.0% (91 out of 130) of the patients.

Risk of bias in studies

Fig. 2 illustrates the outcomes of methodological quality assessments of the studies included in the proportion meta-analysis model, utilizing the JBI Critical Appraisal tool.

Proportion meta-analysis outcome synthesis

Complications (Clavien-Dindo ≥ III)

The pooled risk of Clavien-Dindo ≥ III complications was 14.8% (95% CI, 8.7%–20.8%; 130 patients; six studies) (Fig. 3). The statistical heterogeneity was low (I^2 = 0%) and the GRADE system suggested moderate certainty.

30-day mortality

The pooled risk of 30-day mortality was 1.9% (95% CI, 0%–4.2%; 130 patients; six studies) (Fig. 3). The statistical heterogeneity was low (I^2 = 0%) and the GRADE system suggested high certainty.

Conversion to open

The pooled risk of conversion to open surgery was 1.9% (95% CI, 0%–4.2%; 130 patients; six studies) (Fig. 3). The statistical heterogeneity was low (I^2 = 0%) and the GRADE system suggested high certainty.

Intraoperative blood loss

The pooled mean intraoperative blood loss was 210 mL (95% CI, 119–301; 130 patients; six studies) (Fig. 3). The statistical heterogeneity was high (I^2 = 83%) and the GRADE system suggested moderate certainty.

Operative time

The pooled mean operative time was 481 minutes (95% CI, 339–623; 130 patients; six studies) (Fig. 3). The statistical heterogeneity was high (I^2 = 99%) and the GRADE system suggested moderate certainty.

R0 resection

The pooled likelihood of achieving R0 resection was 82.2% (95% CI, 75.0%–89.4%; 130 patients; six studies) (Fig. 3). The statistical heterogeneity was low (I^2 = 16%) and the GRADE system suggested high certainty.

Number of retrieved lymph nodes

The pooled mean number of retrieved lymph nodes was 12 (95% CI, 9–16; 72 patients; four studies) (Fig. 3). The statistical heterogeneity was high (I^2 = 88%) and the GRADE system suggested moderate certainty.

Meta-regression

Table 3 presents the results of meta-regression analyses for the outcomes. Significant associations were identified.

a) Younger age (coefficient: –53.357, p = 0.008), higher BMI (coefficient: 27.890, p = 0.009), larger tumors (coefficient: 100.711, p = 0.048), and performance of liver resection (coefficient: 1.901, p = 0.017) were predictors of increased intraoperative blood loss.

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Table 3. Results of meta-regression analyses

Independent variable	Dependent variables													
	Complication (CD≥ III)		30-day mortality		Conversion to open		Intraoperative blood loss		Operative time		R0 resection		Number of retrieved lymph node	
	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value	Coefficient	*p*-value
Age	0.0001	0.964	0.001	0.726	0.0010	0.673	–53.357	0.008*	–10.426	0.308	0.012	0.181	20.493	0.045*
Male	0.0010	0.842	0.0001	0.775	0.0001	0.959	9.487	0.132	3.549	0.258	–0.003	0.149	0.361	0.844
BMI	0.0001	0.985	0.0010	0.946	0.0001	0.974	27.890	0.009*	–14.023	0.641	–0.017	0.488	–12.555	0.474
ASA III or above	0.0010	0.400	0.0010	0.396	0.0010	0.388	–0.509	0.600	3.944	< 0.001*	0.002	0.291	2.529	0.001*
Preoperative biliary drainage	0.0020	0.264	0.0010	0.365	0.0010	0.281	–3.879	0.505	2.999	0.261	0.004	0.027*	4.188	< 0.001*
Bismuth I	–0.0030	0.144	–0.0010	0.301	–0.0010	0.309	–10.812	0.226	–6.371	0.031	–0.003	0.256	6.758	< 0.001*
Bismuth II	–0.0020	0.799	0.0001	0.974	–0.0001	0.966	–8.960	0.830	–4.747	0.784	–0.007	0.403	2.207	0.714
Bismuth III	0.0050	0.386	0.0020	0.443	0.0020	0.439	–7.242	0.688	–2.300	0.759	0.002	0.737	–5.456	< 0.001*
Bismuth IV	0.0040	0.108	0.0010	0.281	0.0010	0.279	17.775	0.058	9.350	< 0.001*	0.004	0.156	0.919	0.831
Tumor size	0.0430	0.553	0.0150	0.615	0.0150	0.615	100.711	0.048*	134.454	0.239	0.051	0.548	38.221	0.688
Liver resection	0.0020	0.183	0.0010	0.34	0.0010	0.338	1.901	0.017*	2.670	0.230	0.001	0.427	–2.858	< 0.001*
Caudate lobe resection	0.0001	0.798	0.0001	0.734	–0.0001	0.865	5.476	0.155	0.565	0.669	–0.002	0.122	–1.195	0.079

BMI, body mass index; ASA, American Society of Anesthesiologists; CD, Clavien-Dindo.
*Statistically significant (p <0.05).

b) ASA status ≥ III (coefficient: 3.944, $p < 0.001$) and Bismuth IV (coefficient: 9.350, $p < 0.001$) were associated with longer operative times.

c) Preoperative biliary drainage (coefficient: 0.004, $p = 0.027$) was associated with increased R0 resection rates.

d) Older age (coefficient: 20.493, $p = 0.045$), ASA status ≥ III (coefficient: 2.529, $p = 0.001$), preoperative biliary drainage (coefficient: 4.188, $p < 0.001$), and Bismuth I disease (coefficient: 6.758, $p < 0.001$) increased the number of retrieved lymph nodes, whereas Bismuth III disease (coefficient:

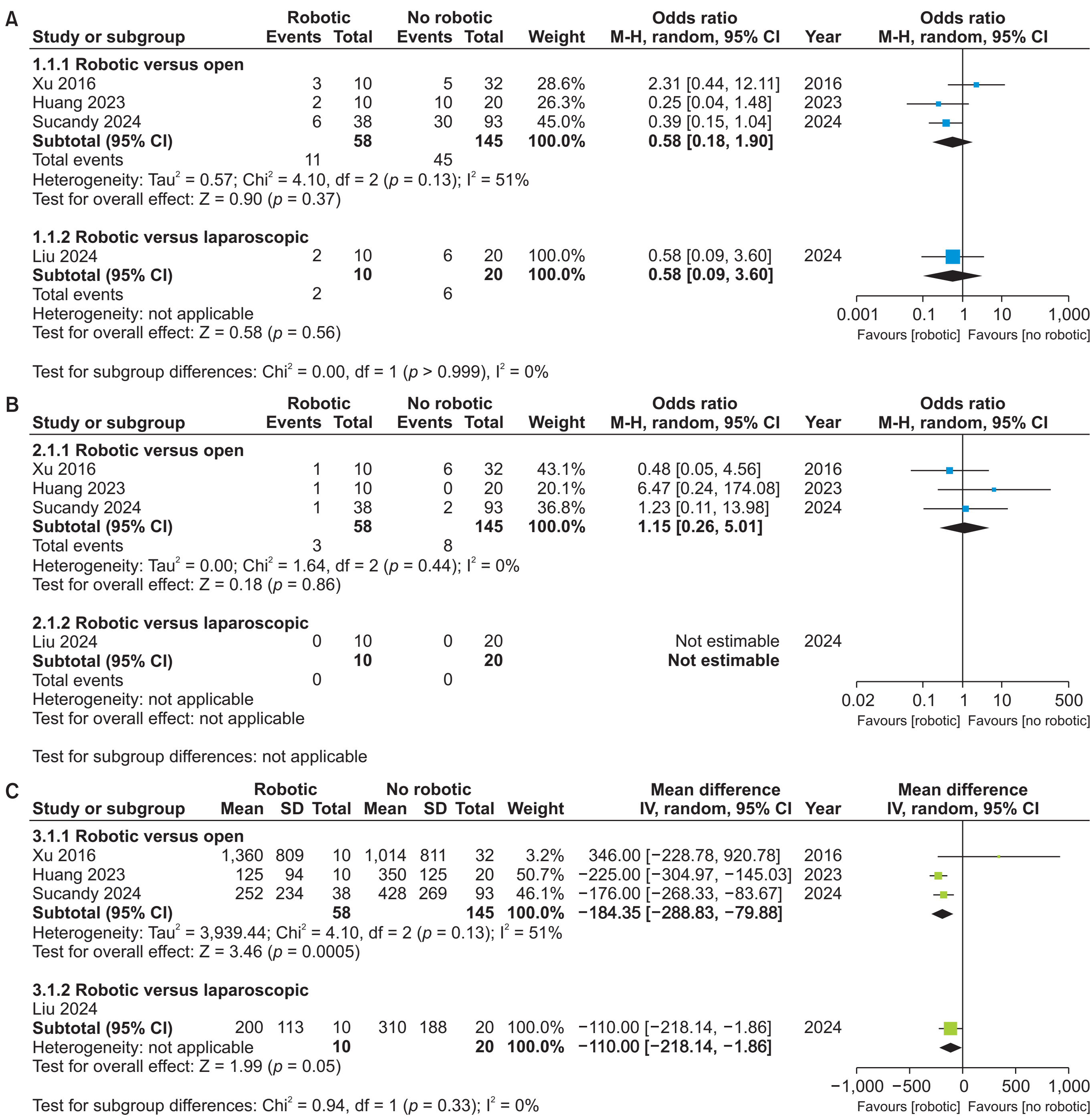

Fig. 4. Forest plots for the following outcomes in a comparison meta-analysis model: (A) Complications (Clavien-Dindo ≥ III); (B) 30-day mortality; (C) intraoperative blood loss; (D) operative time; (E) R0 resection; (F) number of retrieved lymph nodes. M-H, Mantel–Haenszel; CI, confidence interval, SD, standard deviation.

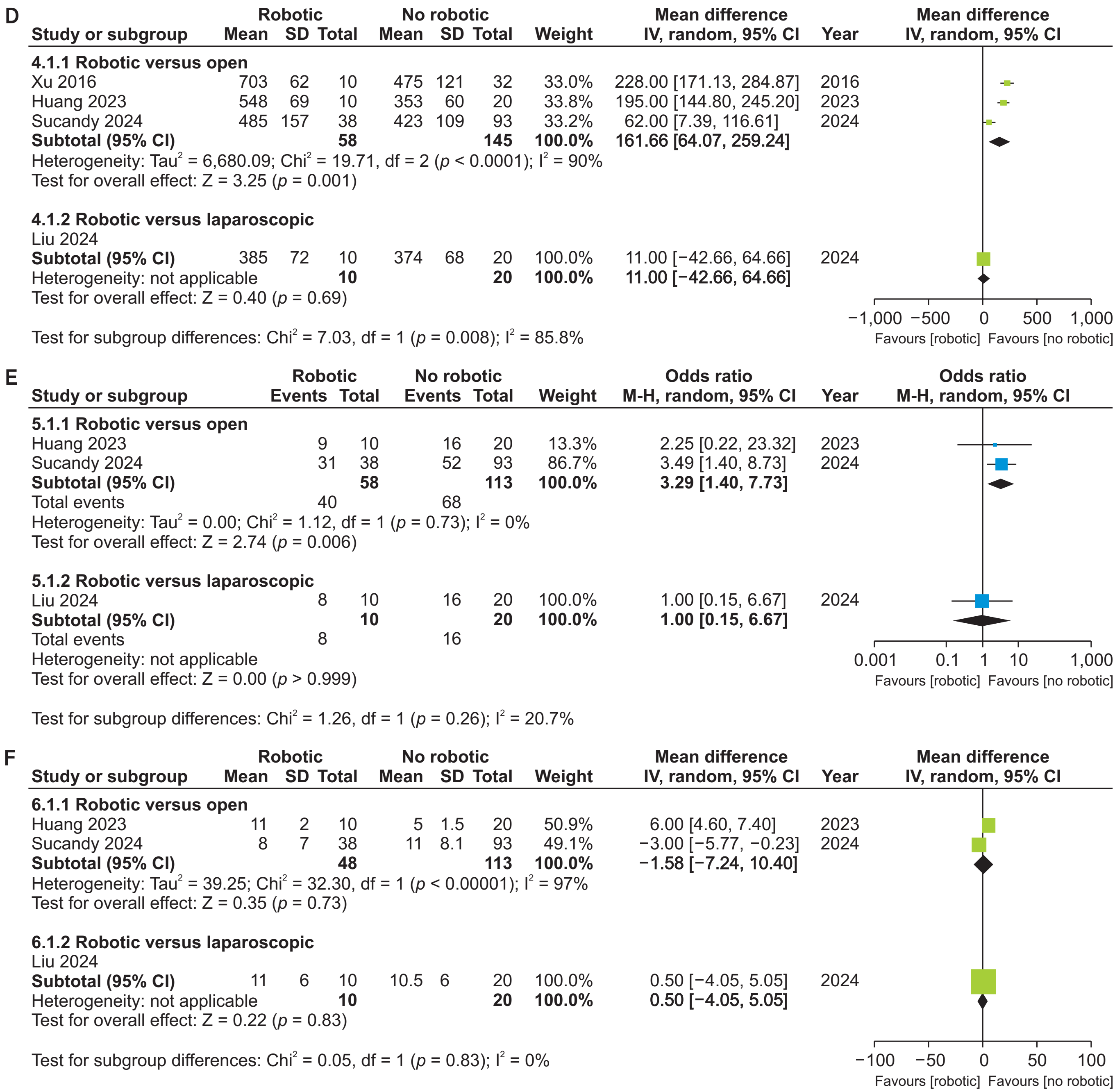

Fig. 4. Continued.

–5.456, $p < 0.001$) and liver resection (coefficient: –2.858, $p < 0.001$) decreased it.

Robotic versus open approach

Complications (Clavien-Dindo ≥ III)

No significant difference was observed in the risk of Clavien-Dindo ≥ III complications between the robotic and open approaches (OR: 0.58, 95% CI: 0.18–1.90, $p = 0.37$; 203 patients; three studies) (Fig. 4). The statistical heterogeneity was moderate ($I^2 = 51\%$) and the GRADE system suggested moderate certainty.

30-day mortality

There was no significant difference in the risk of 30-day mortality between the robotic and open approaches (OR: 1.15, 95% CI: 0.26–5.01, $p = 0.86$; 203 patients; three studies) (Fig. 4).

The statistical heterogeneity was low ($I^2 = 0\%$) and the GRADE system suggested moderate certainty.

Intraoperative blood loss

The robotic approach was associated with significantly less intraoperative blood loss compared to the open approach (MD: –184 mL, 95% CI: –289, –80, $p = 0.0005$; 203 patients; three studies) (Fig. 4). The statistical heterogeneity was moderate ($I^2 = 51\%$) and the GRADE system suggested moderate certainty.

Operative time

The robotic approach was associated with a significantly longer operative time compared to the open approach (MD: 162 minutes, 95% CI: 64–259, $p = 0.001$; 203 patients; three studies) (Fig. 4). The statistical heterogeneity was high ($I^2 = 90\%$) and the GRADE system suggested moderate certainty.

R0 resection

Robotic approach was associated with a higher rate of achieving R0 resection compared with the open approach (OR: 3.29, 95% CI: 1.40–7.73, $p = 0.006$; 203 patients; three studies) (Fig. 4). The statistical heterogeneity was low ($I^2 = 0\%$) and the GRADE certainty was moderate.

Number of retrieved lymph nodes

There was no significant difference in the number of retrieved lymph nodes between the robotic and open approaches (MD: –1.58, 95% CI: –7.24–10.40, $p = 0.73$; 161 patients; two studies) (Fig. 4). The statistical heterogeneity was high ($I^2 = 97\%$) and the GRADE system suggested low certainty.

Robotic versus laparoscopic approach

Complications (Clavien-Dindo ≥ III)

There was no significant difference in the frequency of Clavien-Dindo ≥ III complications between the robotic and laparoscopic approaches (OR: 0.58, 95% CI: 0.09–3.60, $p = 0.560$; 30 patients; one study) (Fig. 4). The GRADE framework suggested a low certainty of evidence.

30-day mortality

No difference was observed in the risk of 30-day mortality between the robotic and laparoscopic approaches (OR: not estimable; risk difference: 0.00, 95% CI: −0.14, 0.14, $p > 0.999$; 30 patients; one study) (Fig. 4). The GRADE framework suggested a low certainty of evidence.

Intraoperative blood loss

Robotic approach was associated with reduced intraoperative blood loss compared to the laparoscopic approach (MD: –110 mL, 95% CI: –218, –2, $p = 0.050$; 30 patients; one study) (Fig. 4). The GRADE framework suggested a low certainty of evidence.

Operative time

There was no significant difference in operative time between the robotic and laparoscopic approaches (MD: 11 minutes, 95% CI: −43, 65, $p = 0.690$; 30 patients; one study) (Fig. 4). The GRADE framework suggested a low certainty of evidence.

R0 resection

No significant difference was observed in the risk of achieving R0 resection between the robotic and laparoscopic approaches (OR: 1.00, 95% CI: 0.15–6.67, $p > 0.999$; 30 patients; one study) (Fig. 4). The GRADE framework suggested a low certainty of evidence.

Number of retrieved lymph nodes

No significant difference was noted in the number of retrieved lymph nodes between the robotic and laparoscopic approaches (MD: 0.50, 95% CI: −4.05, 5.05, $p = 0.83$; 30 patients; one study) (Fig. 4). The GRADE framework suggested a low certainty of evidence.

Sensitivity analyses

Leave-one-out analysis and separate analysis for studies with a low overall risk of bias did not affect the direction of effect size.

DISCUSSION

We conducted a systematic review and meta-analysis, supplemented with meta-regression, to assess the feasibility and safety of robotic radical resection for hilar cholangiocarcinoma. Our analysis of 130 patients from six studies revealed that robotic radical resection is safe and feasible in highly selected patients (favorable BMI and tumor size) (moderate certainty): (Clavien-Dindo ≥ III complications: 14.8% [8.7%–20.8%]; 30-day mortality: 1.9% [0%–4.2%]; conversion to open surgery: 1.9% [0%–4.2%]; intraoperative blood loss: 210 mL [119–301]; operative duration: 481 minutes [339–623]; R0 resection rate: 82.2% [75.0%–89.4%]; number of retrieved lymph nodes: 12 [9–16]). Factors such as younger age, higher BMI, larger tumors, and inclusion of liver resection were associated with increased intraoperative blood loss. ASA status ≥ III and Bismuth IV disease were linked to prolonged operative times. Preoperative biliary drainage was found to enhance the R0 resection rate. The robotic approach resulted in reduced intraoperative blood loss, extended operative time, and improved rates of R0 resection compared to the open approach (moderate certainty); however, it was comparable to the laparoscopic approach (very low certainty).

While this study is the first meta-analysis to quantify the outcomes of robotic radical resection for hilar cholangiocarcinoma using a proportion meta-analysis model and evaluates predictors of these outcomes through a comprehensive meta-regression model, recent meta-analyses have already assessed the outcomes of robotic radical resection of hilar cholangiocarcinoma using significantly different approaches. Hu et al. [16] conducted a meta-analysis of four studies involving 102 patients who underwent robotic resection of hilar cholangiocarcinoma and 165 patients who underwent open surgery, concluding that the robotic approach was comparable to the open approach in terms of safety and feasibility. A primary concern regarding the study by Hu et al. [16] is the lack of adequate information on methodology and design in three of the four included studies, and the references within the article do not correspond with the studies analyzed; hence, the methodology of the included studies and the accuracy of the data could not be confidently assessed. Furthermore, the meta-analysis by Hu et al. [16] omitted recently published articles included in the current review and did not evaluate the predictors of outcomes through meta-regression. In another systematic review of case reports and case series, Brolese et al. [17] concluded that robotic resection of hilar cholangiocarcinoma was feasible and safe; however, the study by Brolese et al. [17] neither included the recently published articles nor conducted a meta-analysis. Cipriani et al. [2] carried out a systematic review without a meta-analysis on minimally invasive approaches in the management of hilar cholangiocarcinoma and concluded that these approaches are safe and feasible. While the results of these studies are consistent with the findings of the current study and support its external validity, the inclusion of the most recently published studies, the performance of proportion and comparison meta-analyses, and comprehensive meta-regression of potential predictors would make the design and findings of the current study novel, potentially leading to more robust conclusions.

The safety and feasibility of the robotic approach may be elucidated by the advantages of robotic surgical systems, which include three-dimensional visualization, highly flexible robotic arms, enhanced dexterity, precise dissection in narrow spaces, and better handling of tissue and instruments. These features collectively facilitate R0 resection with reduced intraoperative blood loss, as demonstrated in the current study [11,12]. The extended operative time relative to the open approach can be attributed to the steep learning curve [2,3]. Despite these benefits, the use of the robotic approach for resection of hilar cholangiocarcinoma remains in the initial development phase, with limited but evolving evidence. The findings of the current study provide the most reliable evidence on safety and feasibility outcomes and their potential predictors; thus, these results should be utilized for hypothesis generation in future trials.

The cases included in the eligible studies of this meta-analysis presented favorable baseline characteristics conducive to robotic resection. Individuals were relatively young (mean age: 64 years) with 71% classified as ASA I or II; they exhibited a favorable BMI (mean BMI 23.5 kg/m^2); tumor size was notably small (mean tumor size: 2.35 cm); 37% had Bismuth I-II disease and merely 12% had Bismuth IV disease. Consequently, it can be contended that these characteristics may not reflect those of the majority of patients with hilar cholangiocarcinoma undergoing curative resection. Moreover, this may indicate that patients were chosen for robotic resection due to their favorable traits, leading to potential selection bias; therefore, the outcomes of robotic radical resection in patients with less favorable baseline characteristics warrant further investigation.

Given that hilar cholangiocarcinoma spreads radially and longitudinally, achieving negative margins at both the proximal and distal bile ducts, along with negative radial margins at the liver transection plane and the dissection plane in the hepatoduodenal ligament, is crucial for successful R0 resection and improved outcomes [18]. Moreover, caudate lobe resection is necessary to secure R0 resection in patients with Bismuth II-IV disease. However, achieving a negative radial resection margin and performing caudate lobe resection present significant challenges via the robotic approach. While the analysis indicated that R0 resection was accomplished in 82% of the robotic cases, details on the radial resection margins in cases where R0 resection was not achieved were not provided in the included studies. Hence, the impact of the robotic approach on achieving negative resection margins remains unresolved and should be explored in subsequent studies.

Although the safety of laparoscopic and robotic caudate lobe resection has been demonstrated by limited evidence [19,20], the data concerning the safety and feasibility of robotic caudate lobe resection in patients with hilar cholangiocarcinoma are even more scarce and continue to develop. In the present study, 57% of patients underwent caudate lobe resection, suggesting feasibility; however, the results are prone to confounding by indication and significant selection bias, precluding definitive conclusions.

Meta-regression analyses indicated that preoperative biliary drainage was associated with increased R0 resection and a higher count of retrieved lymph nodes. These relationships have not previously been reported. Two hypotheses may be proposed to elucidate these findings. Firstly, preoperative biliary drainage might provide detailed mapping of the carcinoma's extent relative to the complex biliary tract, including intrahepatic and segmental bile ducts, thereby enabling a more targeted dissection, enhancing lymph node retrieval and R0 resection. Alternatively, the observed associations could stem from statistical errors arising from the small sample sizes of the included studies. Therefore, definitive conclusions cannot yet be drawn, and future research may determine which hypothesis is more valid.

The current study possesses several limitations. The evidence provided is mainly derived from a limited number of retrospective case series, potentially introducing selection bias. The studies included had small sample sizes, which increases the likelihood of a type 2 error. Additionally, there was considerable heterogeneity in operative times. In the study by Li et al. [14], 54% of patients were classified as having Bismuth I or II, none exhibited Bismuth IV disease, and only 46% underwent liver resection. The absence of liver resection in 54% of cases may have contributed to shorter operative times and fewer severe complications. Consequently, the study by Li et al. [14] likely contributed to the heterogeneity in operative times. Nevertheless, we have downgraded the evidence accordingly, and the leave-one-out analyses indicate that the overall results are robust against the influence of individual studies. The inability to formally assess publication bias, owing to a lack of more than 10 eligible studies, further limits the comparative evidence; thus, whether the robotic approach offers clinically significant benefits over the laparoscopic or open approaches remains unclear. Finally, this study did not assess the long-term outcomes of the robotic approach in hilar cholangiocarcinoma resection, which should be addressed in future research. Considering these limitations, due to the potential for type 2 error, selection bias in the included studies, and inability to rule out publication bias, the outcomes of this study should not be the basis for definitive conclusions but can certainly contribute to hypothesis generation in future trials.

In highly selected patients (favourable BMI and tumor size), robotic radical resection of hilar cholangiocarcinoma may be safe and feasible. Given the possible type 2 error associated with small sample sizes, the risk of selection bias in the included studies, and the inability to eliminate publication bias, the findings from this study should not serve as conclusive evidence but may facilitate hypothesis generation in future research. The current study contributes information about potential outcome predictors for hypothesis generation in future trials.

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CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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Appendix 1. Literature search strategy

Search number	Search description	Action
Number 1	Robotic	Titles, abstracts, keywords
Number 2	MeSH term: [robotics]	Explode all trees
Number 3	Number 1 OR Number 2	Combined with OR
Number 4	hilar cholangiocarcinoma	Titles, abstracts, keywords
Number 5	perihilar cholangiocarcinoma	Titles, abstracts, keywords
Number 6	peri-hilar cholangiocarcinoma	Titles, abstracts, keywords
Number 7	MeSH term: [klatskin tumour]	Explode all trees
Number 8	Number 4 OR Number 5 OR Number 6 OR Number 7	Combined with OR
Number 9	Number 3 AND Number 8	Combined with AND

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