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A Comprehensive Systematic Review Comparing Perioperative Outcomes of Robotic-Assisted versus Laparoscopic Resection of the Anterior Liver Segments

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ABSTRACT

Introduction: Minimally invasive liver surgery (MILS) is the contemporary standard for lesions in the anterior liver segments (II, III, IVb, V, VI), where the parenchymal transection plane is directly accessible. Robotic advantages in posterosuperior segments and major hepatectomy are established, yet its incremental value in the comparatively "easy" anterior segments remains contested.

Methods: The study strictly adhered to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) 2020 guidelines comparing robotic (RLR) versus laparoscopic (LLR) liver resection in anterior segments. Risk of bias assessed with ROBINS-I and RoB 2. Sixteen perioperative

outcomes were synthesised narratively with direction-of-effect vote counting.

Results: Twenty-three studies (>20,000 hepatectomies) were included. In the largest anterior-segment analysis (1,401 matched pairs), RLR had lower blood loss (75 vs 100 mL, $P<0.001$), lower transfusion (3.1% vs 5.4%, $P=0.003$), lower major morbidity (2.5% vs 4.6%, $P=0.004$), lower conversion (1.2% vs 4.5%, $P<0.001$), and shorter stay (4 vs 5 days, $P<0.001$), but higher 30-day readmission (3.5% vs 2.1%, $P=0.042$). A second international cohort (1,505 pairs) confirmed higher textbook outcome (78.3% vs 71.8%, $P<0.001$), lower blood loss, and lower morbidity. Direction-of-effect: robotic superior for conversion (16/18 studies) and blood loss (14/21), laparoscopic superior for operative time (13/21) and cost (7/7). Mortality, bile leak, liver failure, R0, and survival were equivalent. The single RCT found no quality-of-life difference.

Discussion: In the anterior segments, robotics yields statistically significant but clinically modest gains, concentrated in haemostasis and conversion avoidance. Benefit magnitude is markedly attenuated relative to posterosuperior segments, consistent with a ceiling effect: laparoscopy in the anterolateral liver is already mature with low conversion and morbidity. The economic penalty of robotics is uniform and substantial.

Conclusion: Robotic anterior-segment resection is safe and oncologically non-inferior, with advantages in blood loss, conversion, morbidity, and length of stay, but longer operative time and higher cost.

Laparoscopy remains a highly cost-effective default; robotics is best justified in cirrhosis, reoperative surgery, and institutional MILS programme development.

Keywords: robotic liver resection; laparoscopic hepatectomy; anterolateral segments; left lateral sectionectomy; minimally invasive liver surgery; perioperative outcomes; textbook outcome; systematic review

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INTRODUCTION

Background

Hepatic resection remains the only reliably curative locoregional modality for a broad spectrum of primary and secondary hepatic neoplasms, including hepatocellular carcinoma, intrahepatic cholangiocarcinoma and colorectal liver metastases, as well as for symptomatic or diagnostically indeterminate benign lesions and hepatolithiasis. Over the past three decades the operative approach has migrated decisively from laparotomy towards minimally invasive liver surgery (MILS), a transition underwritten by consistent evidence of reduced intraoperative haemorrhage, attenuated systemic inflammatory response, fewer wound-related and pulmonary complications, shorter convalescence and preservation of oncological adequacy.^{2,24,32}

Anatomical location is the single most powerful determinant of technical difficulty in MILS. The Couinaud segments are conventionally dichotomised into the anterior — more precisely anterolateral — group (segments II, III, IVb, V and VI) and the posterosuperior group (segments I, IVa, VII and VIII). The anterolateral segments lie immediately beneath the anterior abdominal wall in the natural axis of straight laparoscopic instruments; the transection plane is superficial, the liver requires minimal mobilisation, and the surgeon operates in an ergonomically favourable, largely two-dimensional working corridor. Consequently, laparoscopic left lateral sectionectomy (segments II–III) was among the earliest hepatic procedures to be accorded the status of a standard of care, and laparoscopic minor resection of the anterolateral segments was designated a "standard practice" at the

Louisville and Morioka international consensus conferences. Case-matched data confirm that laparoscopic resection of anterolateral lesions is achieved with significantly shorter operative times, less blood loss and shorter hospitalisation than the corresponding posterosuperior operations.⁴¹

The da Vinci robotic platform was introduced into hepatobiliary surgery to address the residual ergonomic and technical constraints of conventional laparoscopy: fulcrum-effect motion inversion, four degrees of instrument freedom, physiological tremor, two-dimensional visualisation, and the difficulty of intracorporeal suturing under angulated approach vectors. Wristed EndoWrist instrumentation, tremor filtration, motion scaling, stable three-dimensional stereoscopic magnification, surgeon-controlled camera and integrated indocyanine-green fluorescence imaging theoretically permit more precise Glissonean pedicle dissection, more controlled parenchymal transection and, critically, the ability to suture a bleeding hepatic vein branch rather than convert.^{39,45}

The accumulated comparative literature has, however, generated a strikingly location-dependent pattern of benefit. In the posterosuperior segments, robotic limited resection is associated with significantly less blood loss, fewer conversions and shorter operative times than laparoscopy in international propensity-matched cohorts of 3,510 and 983 patients respectively; in right posterior sectionectomy and in right/extended right hepatectomy the robotic approach again reduces conversion and blood loss.^{33,34,35,36}

In the anterior segments the picture is far less settled. Early single-institution series of robotic versus laparoscopic left lateral sectionectomy reported no clinical advantage and, in some cohorts, inferior outcomes with higher intensive care utilisation, longer length of stay and substantially greater cost. Meta-analysis of seven early comparative studies (319 patients) concluded that robotic left lateral sectionectomy conferred only longer operative time and higher expenditure without any perioperative gain. Yet the most recent international multicentre propensity-matched analysis of 10,517 anterolateral minor resections reversed this conclusion, demonstrating statistically significant robotic advantages across blood loss, transfusion, major morbidity, conversion and length of stay — while explicitly conceding that most of the observed clinical differences were of minimal absolute magnitude.^{1,5,29}

This apparent contradiction — statistically robust but clinically marginal superiority in a domain where laparoscopy is already excellent — constitutes the central evidentiary problem addressed by the present review. Its resolution has direct consequences for capital allocation, for the design of MILS training pathways, and for surgeons in resource-constrained health systems who must justify robotic capacity against competing priorities.^{30,38,40}

Research Objectives

The general objective of this systematic review is to comprehensively evaluate and synthesise all available primary comparative evidence on the perioperative outcomes of robotic-assisted versus laparoscopic resection of the anterior (anterolateral) liver segments.

The specific objectives are: (i) to identify and critically appraise all primary comparative studies reporting perioperative outcomes of RLR versus LLR in cohorts composed wholly or predominantly of anterior-segment or low-to-intermediate-difficulty minor resections; (ii) to synthesise the evidence across sixteen prespecified intraoperative, postoperative, oncological, economic and patient-centred outcome domains; (iii) to quantify the direction, consistency and clinical magnitude of any difference between platforms; (iv) to formally appraise the methodological quality and risk of bias of every included study; (v) to determine whether robotic advantages demonstrated in the posterosuperior segments and in major hepatectomy are preserved, attenuated or abolished in the anterior segments; and (vi) to define the residual evidence gaps and derive a prioritised research agenda.

Significance and Benefits of the Review

Theoretically, this review clarifies the interaction between anatomical difficulty and technological advantage, testing the hypothesis that the marginal utility of robotic assistance is inversely proportional to the baseline ergonomic favourability of the operative field. Clinically, it provides hepatobiliary surgeons with a location-specific, outcome-by-outcome evidence base to inform platform selection for anterior-segment lesions, rather than extrapolating from heterogeneous whole-liver analyses. For health systems, particularly in middle-income settings where robotic capital and consumable costs are a decisive constraint, it delineates precisely which patient subgroups — cirrhosis, prior abdominal surgery, complex or bulky anterolateral lesions requiring anatomical

resection — are most likely to derive value from robotic deployment. For surgical education, it informs the sequencing of MILS training, given evidence that the robotic platform shortens the learning curve for complex hepatectomy and facilitates institutional transition to advanced minimally invasive liver surgery.^{21,38,39}

Research Gap

Four specific gaps are identifiable. First, the overwhelming majority of comparative analyses pool the entire spectrum of hepatectomy, permitting benefits derived from posterosuperior and major resections to contaminate estimates for the anterior segments; subgroup analyses restricted to anterolateral resections are typically underpowered and reported as secondary findings. Second, dedicated anterolateral-segment studies are dominated by left lateral sectionectomy, which is the least demanding of all anatomical hepatectomies and therefore the least likely to expose any technological differential; segments IVb, V and VI are comparatively under-represented. Third, the single existing randomised controlled trial comparing robotic with laparoscopic hepatectomy was neither restricted to nor stratified by anterior-segment location, was powered for quality of life rather than perioperative safety, and enrolled only 80 patients. Fourth, no existing synthesis integrates perioperative, oncological, economic and patient-reported domains within a single anterior-segment-specific framework.^{1,2,19,29,40}

Novelty

To the best of our knowledge this is the first systematic review to restrict its analytical focus explicitly to the anterior (anterolateral) liver segments while simultaneously (i) confining primary data extraction to primary comparative studies and relegating systematic reviews and meta-analyses strictly to corroborative and discursive roles, thereby eliminating double-counting of patient data; (ii) synthesising sixteen prespecified outcome domains spanning intraoperative haemostasis, conversion, morbidity taxonomy, liver-specific complications, composite textbook outcome, oncological adequacy, economics and patient-reported quality of life; (iii) applying a structured direction-of-effect and vote-counting framework alongside formal ROBINS-I and RoB 2 risk-of-bias appraisal for every included study; and (iv) explicitly testing the "technological ceiling-effect" hypothesis by

contrasting effect direction and magnitude in the anterior segments against the contemporaneously published posterosuperior and major-hepatectomy literature.

Hypotheses

Primary hypothesis (H₁). In resection of the anterior liver segments, the robotic-assisted approach is associated with statistically significant reductions in estimated intraoperative blood loss and in the rate of unplanned conversion to open laparotomy when compared with the conventional laparoscopic approach.

Secondary hypothesis (H₂). The robotic approach is associated with a statistically significant reduction in overall and major postoperative morbidity and in postoperative length of stay, and with a higher rate of composite textbook outcome in liver surgery.

Secondary hypothesis (H₃). The robotic approach is associated with significantly longer total operative time and significantly higher total procedural and hospitalisation cost.

Null hypothesis (H₀). There is no statistically significant difference between the robotic-assisted and laparoscopic approaches in perioperative mortality, bile leak, post-hepatectomy liver failure, R0 resection rate, or long-term overall survival following resection of the anterior liver segments.

Magnitude hypothesis (H₄). The absolute magnitude of any robotic advantage in the anterior segments is significantly smaller than that reported for the posterosuperior segments and for major hepatectomy (technological ceiling-effect hypothesis).

METHODS

Protocol, Reporting Standard and Registration

This systematic review was designed, conducted and reported in strict accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement and the accompanying PRISMA-S search-reporting extension. The methodological framework additionally conformed to the Cochrane Handbook for Systematic Reviews of Interventions (version 6.5) and, for the synthesis of non-randomised evidence, to the Synthesis Without Meta-analysis (SWiM) reporting guideline. A structured a priori protocol specifying the research question, eligibility criteria, search strategy, outcome hierarchy, risk-of-bias instruments and synthesis plan

was finalised before commencement of the literature search; no post hoc modifications to the primary outcome set were made. As the review analysed exclusively de-identified, previously published aggregate data, institutional review board approval and informed consent were not required.

Review Question and PICOS Framework

The review question was framed using the PICOS structure and is presented in Table 1.

Table 1. PICOS framework defining review eligibility

Domain	Specification
Population (P)	Adult patients (≥ 18 years) undergoing elective minimally invasive hepatic resection for benign or malignant hepatic disease, in whom the resected lesion(s) were located wholly or predominantly within the anterior (anterolateral) Couinaud segments II, III, IVb, V and VI, or in whom the cohort was composed predominantly of minor / low-to-intermediate difficulty (IWATE grade 1–2) resections in which anterolateral segments predominate.
Intervention (I)	Robotic-assisted liver resection (RLR) using any generation of the da Vinci surgical system (S, Si, X, Xi, SP), performed either as a totally robotic or robot-assisted hybrid procedure.
Comparator (C)	Conventional (pure or hand-assisted) laparoscopic liver resection (LLR) performed within the same institution(s) and, where possible, the same time period.
Outcomes (O)	Sixteen prespecified perioperative outcomes (Section 2.5): operative time; estimated blood loss; intraoperative transfusion; Pringle manoeuvre use and duration; open conversion; overall morbidity; major morbidity (Clavien–Dindo $\geq$ IIIa); bile leak; post-hepatectomy liver failure; length of stay; 30-day readmission; 90-day / in-hospital mortality; R0 resection margin;

Domain	Specification
	textbook outcome in liver surgery (TOLS); total cost; long-term oncological and patient-reported outcomes.
Study design (S)	PRIMARY comparative studies only: randomised controlled trials; prospective or retrospective comparative cohort studies with or without propensity score matching, coarsened exact matching or case-matching; and national or international registry analyses. Systematic reviews and meta-analyses were EXCLUDED from primary data extraction and used solely for corroborative triangulation in the outcome analysis and Discussion sections.

IWATE = IWATE difficulty scoring system for laparoscopic liver resection; RLR = robotic liver resection; LLR = laparoscopic liver resection; TOLS = textbook outcome in liver surgery.

Search Strategy

The keywords used for this research based PICO :

PICO Element	Keyword 1	Keyword 2	Keyword 3
P (Population)	Anterior Liver Segments	Hepatocellular Carcinoma	Liver Resection Patients
I (Intervention)	Robotic-Assisted Resection	Robotic Hepatectomy	Minimally Invasive Robotic Surgery
C (Comparison)	Laparoscopic Liver Resection	Conventional Laparoscopy	Laparoscopic Hepatectomy
O (Outcome)	Perioperative Outcomes	Open Conversion Rate	Operative Time

The Boolean MeSH keywords inputted on databases for this research are: ("*Anterior Liver Segments*" OR "*Hepatocellular Carcinoma*" OR "*Liver Resection Patients*") AND ("*Robotic-Assisted Resection*" OR "*Robotic Hepatectomy*" OR "*Minimally Invasive Robotic Surgery*") AND

("Laparoscopic Liver Resection" OR "Conventional Laparoscopy" OR "Laparoscopic Hepatectomy") AND ("Perioperative Outcomes" OR "Open Conversion Rate" OR "Operative Time")

Eligibility Criteria

Inclusion criteria. (1) Primary comparative study design directly comparing RLR with LLR; (2) adult human participants; (3) cohort composed wholly or predominantly ($\geq 50\%$ of procedures, or a dedicated reported subgroup) of anterior/anterolateral-segment resections, minor resections (≤ 2 contiguous segments), or IWATE grade 1–2 difficulty resections; (4) reporting of at least two of the sixteen prespecified perioperative outcomes with extractable numerical data; (5) full-text availability in English.

Exclusion criteria. (1) Systematic reviews, meta-analyses, network meta-analyses, narrative reviews, editorials, commentaries, letters and expert opinion (retained for Discussion only); (2) single-arm case series without a laparoscopic comparator; (3) studies restricted exclusively to posterosuperior segments (I, IVa, VII, VIII) or exclusively to major hepatectomy of ≥ 3 contiguous segments, unless an extractable anterolateral or minor-resection subgroup was reported; (4) living-donor hepatectomy and transplant hepatectomy series, in view of fundamentally different selection, endpoints and graft-related outcomes; (5) studies comparing minimally invasive with open surgery only; (6) duplicate publications or overlapping cohorts, in which case the report with the largest sample, longest follow-up or most granular anterolateral-segment data was retained; (7) paediatric populations.

Outcome Definitions and Hierarchy

Sixteen outcomes were prespecified. Primary outcomes were estimated intraoperative blood loss and unplanned open conversion. All remaining outcomes were secondary. Standardised definitions were applied as detailed in Table 3, and where a study used a divergent definition this was recorded as a source of clinical heterogeneity.

Table 2. Prespecified outcome domains and operational definitions

No.	Outcome	Operational definition
O1	Operative time	Skin incision to final skin closure (minutes); for robotic procedures inclusive of docking and undocking time where reported.
O2	Estimated blood loss (EBL)	Intraoperative blood loss in millilitres as recorded by the operating team (suction volume plus gravimetric swab assessment).
O3	Intraoperative transfusion	Administration of any allogeneic packed red blood cells intraoperatively or within the index admission, expressed as a proportion.
O4	Pringle manoeuvre	Proportion of cases in which inflow occlusion was applied, and cumulative clamp duration in minutes.
O5	Open conversion	Unplanned intraoperative conversion to laparotomy for any reason (bleeding, adhesions, oncological inadequacy, failure to progress). Planned hybrid or hand-port extraction incisions were not counted as conversion.
O6	Overall morbidity	Any postoperative complication within 30 or 90 days classified by the Clavien–Dindo system (any grade).
O7	Major morbidity	Clavien–Dindo grade $\geq$ IIIa, or Comprehensive Complication Index where reported.
O8	Bile leak	ISGLS-defined postoperative bile leak, or drain bilirubin $\geq 3\times$ serum concentration on or after postoperative day 3; grade B/C where specified.
O9	Post-hepatectomy liver failure (PHLF)	ISGLS criteria: increased INR and hyperbilirubinaemia on or after postoperative day 5.
O10	Length of stay (LOS)	Postoperative length of hospital stay in days (median or mean as reported).

No.	Outcome	Operational definition
O11	30-day readmission	Any unplanned readmission within 30 days of index discharge.
O12	Mortality	90-day and/or in-hospital all-cause mortality.
O13	R0 resection	Microscopically negative resection margin (margin width >0 mm; R1 defined as <1 mm where specified).
O14	Textbook outcome (TOLS)	Composite: absence of intraoperative incident $\geq$ grade 2, bile leak $\geq$ grade B, severe morbidity, readmission and 90-day/in-hospital mortality, with R0 margin in malignancy; TOLS+ additionally requires absence of prolonged LOS.
O15	Cost	Operative/procedural cost, hospitalisation cost and total cost, in the reported currency and year.
O16	Long-term / patient-reported outcomes	Overall survival, recurrence-free survival, and health-related quality of life (EORTC QLQ-C30).

Study Selection Process

All retrieved records were exported to a reference management platform and de-duplicated electronically, followed by manual verification. Two reviewers independently screened titles and abstracts against the eligibility criteria, and subsequently assessed the full texts of all potentially eligible records. Disagreements were resolved by discussion and, where consensus could not be achieved, by adjudication from a third senior hepatobiliary reviewer. Inter-rater agreement at the full-text stage was quantified using Cohen's kappa. The selection process is reported in a PRISMA 2020 flow diagram (Figure 1, Section 3.1), with reasons for exclusion documented at the full-text stage.

Data Extraction

Data were extracted independently and in duplicate onto a standardised, pilot-tested electronic extraction form. Extracted variables comprised: first author, year of publication, country and number of participating centres, study design, recruitment period, matching methodology and matched sample size, total and group-specific sample sizes, baseline demographics (age, sex, body mass index, ASA

class, Child–Pugh class, presence of cirrhosis), tumour characteristics (histological indication, lesion size, lesion number), procedural characteristics (segments resected, proportion of anterolateral resections, extent of resection, IWATE or Iwate-equivalent difficulty grade, use of indocyanine-green fluorescence), and all sixteen prespecified outcomes with corresponding measures of dispersion and reported P values. Where outcomes were reported as median with interquartile range, these were retained in their original form rather than converted, in keeping with the narrative synthesis design. Where both unmatched and matched estimates were available, matched estimates were extracted preferentially. No attempt was made to impute missing data.

Article Search Strategy

Database	Keywords	Hits
Pubmed	<i>("Anterior Liver Segments" OR "Hepatocellular Carcinoma" OR "Liver Resection Patients") AND ("Robotic-Assisted Resection" OR "Robotic Hepatectomy" OR "Minimally Invasive Robotic Surgery") AND ("Laparoscopic Liver Resection" OR "Conventional Laparoscopy" OR "Laparoscopic Hepatectomy") AND ("Perioperative Outcomes" OR "Open Conversion Rate" OR "Operative Time")</i>	6
Google Scholar	<i>("Anterior Liver Segments" OR "Hepatocellular Carcinoma" OR "Liver Resection Patients") AND ("Robotic-Assisted Resection" OR "Robotic Hepatectomy" OR "Minimally Invasive Robotic Surgery") AND ("Laparoscopic Liver Resection" OR "Conventional Laparoscopy" OR "Laparoscopic Hepatectomy") AND ("Perioperative Outcomes" OR "Open Conversion Rate" OR "Operative Time")</i>	743
Semantic Scholar	<i>("Anterior Liver Segments" OR "Hepatocellular Carcinoma" OR "Liver Resection Patients") AND ("Robotic-Assisted Resection" OR "Robotic Hepatectomy" OR "Minimally Invasive Robotic Surgery") AND ("Laparoscopic Liver Resection" OR "Conventional Laparoscopy" OR "Laparoscopic Hepatectomy") AND ("Perioperative Outcomes" OR "Open Conversion Rate" OR "Operative Time")</i>	277
Science-direct	<i>("Anterior Liver Segments" OR "Hepatocellular Carcinoma" OR "Liver Resection Patients") AND ("Robotic-Assisted Resection") AND ("Laparoscopic Liver Resection") AND ("Perioperative Outcomes" OR "Open Conversion Rate" OR "Operative Time")</i>	5
Cochrane	<i>("Anterior Liver Segments" OR "Hepatocellular Carcinoma" OR "Liver Resection Patients" AND "Robotic-Assisted Resection") AND ("Laparoscopic Liver Resection" AND "Perioperative Outcomes" OR "Open Conversion Rate" OR "Operative Time")</i>	69

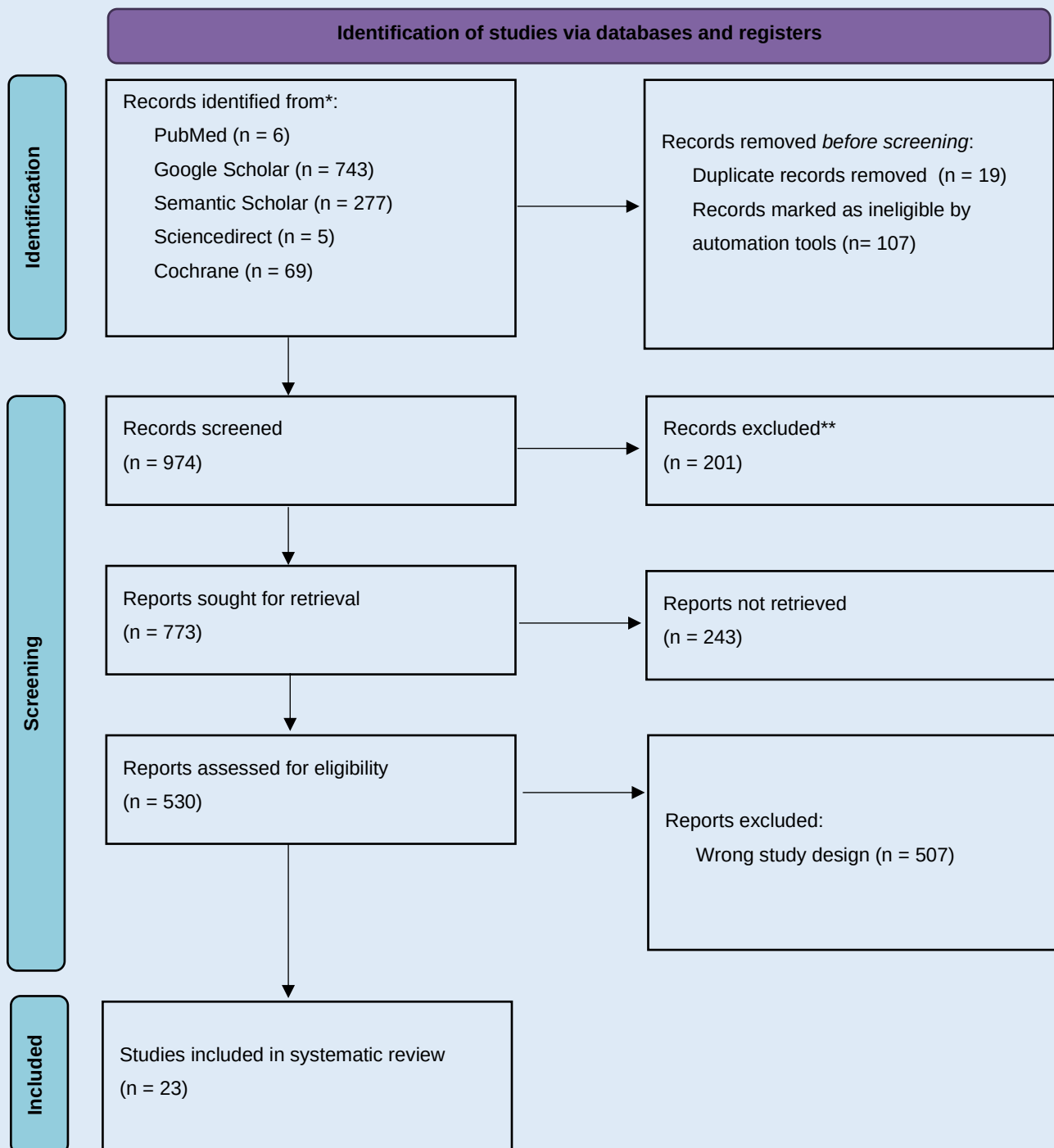


Figure 1. Article search flowchart

Risk of Bias Assessment

Risk of bias in non-randomised comparative studies was appraised using the Risk Of Bias In Non-randomised Studies of Interventions (ROBINS-I) tool across its seven prespecified domains: (D1) bias due to confounding; (D2) bias in selection of participants; (D3) bias in classification of interventions; (D4) bias due to deviations from intended interventions; (D5) bias due to missing data; (D6) bias in measurement of outcomes; and (D7) bias in selection of the reported result. Each domain was rated as low, moderate, serious or critical risk, with an overall judgement corresponding to the most severe domain rating. The randomised controlled trial was appraised using the Cochrane RoB 2 instrument across its five domains. Assessments were performed independently in duplicate with third-party adjudication of disagreements. The results are presented in full in Table 8 (Section 3.3). Publication and small-study bias were assessed qualitatively, since the narrative synthesis design and outcome heterogeneity precluded funnel-plot construction and Egger regression.

Risk of Bias Within Studies

Risk of bias appraisal is presented in Table 6 for the twenty-two non-randomised studies (ROBINS-I) and in Table 7 for the single randomised controlled trial (RoB 2). No study was rated at critical risk of bias, and none was excluded on quality grounds. Overall risk of bias was moderate in fourteen studies and serious in eight. The dominant driver of serious ratings was residual confounding (domain D1) arising from non-random allocation to platform, most pronounced in the small early unmatched single-institution series in which robotic cases were selected during the initial institutional adoption phase and were therefore subject to both learning-curve and selection effects operating in opposite directions. The two international anterolateral-segment collaborations and the ACS-NSQIP registry analysis achieved moderate overall ratings by virtue of rigorous multivariable propensity score matching across extensive covariate sets, though residual confounding by unmeasured surgeon-level and centre-level expertise could not be excluded. Outcome measurement bias (D6) was rated low for objective endpoints such as conversion, transfusion, length of stay and mortality, but moderate for subjectively estimated blood loss, which is neither blinded nor standardised across institutions. Selective reporting (D7) was moderate in studies presenting only matched estimates without a prespecified protocol.^{1,2,5,9,14}

Table 3. ROBINS-I risk of bias assessment for the 22 non-randomised comparative studies

Author, Year	D1 Confounding	D2 Selection	D3 Classification	D4 Deviations	D5 Missing data	D6 Outcome measurement	D7 Reported result	Overall
Packiam 2012	Serious	Serious	Low	Moderate	Low	Moderate	Moderate	Serious
Tsung 2014	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate
Yu 2014	Serious	Serious	Low	Moderate	Moderate	Moderate	Moderate	Serious
Kim 2016	Serious	Serious	Low	Moderate	Low	Moderate	Moderate	Serious
Salloum 2017	Moderate	Moderate	Low	Low	Low	Moderate	Moderate	Moderate
Hu M 2019	Serious	Moderate	Low	Moderate	Low	Moderate	Moderate	Serious
Lim 2019	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate
Wang Z 2019	Serious	Moderate	Low	Moderate	Low	Moderate	Moderate	Serious
Fagenson 2020	Moderate	Low	Low	Low	Moderate	Low	Low	Moderate

Author, Year	D1 Confounding	D2 Selection	D3 Classification	D4 Deviations	D5 Missing data	D6 Outcome measurement	D7 Reported result	Overall
Zhu L 2021	Serious	Moderate	Low	Moderate	Low	Moderate	Moderate	Serious
Chong Y 2022	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate
Sucandy 2022	Moderate	Low	Low	Low	Low	Moderate	Low	Moderate
Zhu P 2022	Moderate	Low	Low	Low	Low	Low	Low	Moderate
Yang H 2022	Serious	Moderate	Low	Moderate	Moderate	Moderate	Moderate	Serious
Balzano 2023	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate
Chen A 2023	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate
O'Connell 2023	Serious	Serious	Low	Moderate	Moderate	Moderate	Moderate	Serious
Hu J 2024	Moderate	Low	Low	Low	Moderate	Moderate	Low	Moderate
Sijberden 2024	Moderate	Low	Low	Low	Moderate	Moderate	Low	Moderate

Author, Year	D1 Confounding	D2 Selection	D3 Classification	D4 Deviations	D5 Missing data	D6 Outcome measurement	D7 Reported result	Overall
Li H 2024	Moderate	Moderate	Low	Low	Low	Moderate	Low	Moderate
Bernardi 2025	Moderate	Moderate	Low	Low	Low	Low	Low	Moderate
Luo T 2025	Moderate	Moderate	Low	Low	Moderate	Moderate	Moderate	Moderate

ROBINS-I domains: D1 confounding; D2 selection of participants; D3 classification of interventions; D4 deviations from intended interventions; D5 missing data; D6 measurement of outcomes; D7 selection of the reported result. Overall judgement corresponds to the most severe domain rating.

Table 4. Cochrane RoB 2 assessment for the included randomised controlled trial

Study	Randomisation process	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall
Birgin et al., 2024 (ROC'N'ROLL)	Low risk (computer-generated, stratified by malignancy)	Low risk (intention-to-treat analysis;	Low risk (complete follow-up of all 80	Some concerns (surgeons unblinded; primary	Low risk (prospectively registered,	Some concerns

Study	Randomisation process	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall
	type and resection difficulty)	patients blinded)	randomised patients)	endpoint patient-reported)	DRKS0002 7531)	

Certainty of Evidence

The certainty of the body of evidence for each outcome domain was rated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework. Evidence from non-randomised studies commenced at low certainty and could be downgraded for serious risk of bias, inconsistency, indirectness, imprecision or suspected publication bias, or upgraded for large magnitude of effect, dose–response gradient or the presence of residual confounding acting in a direction opposite to the observed effect.

Data Synthesis

Given the substantial clinical, methodological and statistical heterogeneity of the included evidence — spanning single-institution series of fewer than 30 patients through international registries of more than 10,000, and encompassing markedly divergent matching strategies, era effects and difficulty distributions — a quantitative pooled meta-analysis of primary data was judged inappropriate and potentially misleading. A structured narrative synthesis was therefore performed in accordance with SWiM guidance, incorporating: (i) tabulation of study-level effect estimates by outcome domain; (ii) direction-of-effect vote counting, in which each study was classified as favouring RLR, favouring LLR, or neutral, with statistical significance recorded separately; (iii) weighting of the narrative interpretation towards the largest, most rigorously matched and most anatomically specific cohorts; and (iv) triangulation of the narrative conclusions against the pooled

estimates of contemporaneously published meta-analyses, which were used exclusively for corroboration and are clearly identified as such throughout the Results and Discussion. Statistical significance was defined a priori as a two-sided P value below 0.05.

RESULTS

Characteristics of Included Studies

The twenty-three included primary comparative studies were published between 2012 and 2025 and originated from North America (n=6), East Asia (n=8), Europe (n=7) and international multicentre collaborations (n=2 dedicated anterolateral analyses, with additional multinational contributions). One study was a randomised controlled trial, one was a prospective cohort with propensity score matching, and the remainder were retrospective comparative cohorts, of which fourteen employed propensity score matching, coarsened exact matching or explicit case-matching. Aggregate enrolment exceeded 20,000 minimally invasive hepatectomies, comprising approximately 5,700 robotic and 15,000 laparoscopic procedures. The two largest studies were international multicentre collaborations enrolling 10,517 and 10,075 patients respectively, both providing anterolateral-segment-specific matched analyses. Detailed study characteristics are presented in Table 4, and cohort and procedural characteristics in Table 5.^{1,2,19}

Table 5. Characteristics of the 23 included primary comparative studies

N o.	Author, Year	Country / Setting	Design	Period	RLR (n)	LLR (n)	Matching method
1	Packiam et al., 2012	USA, single centre	Retrospective comparative cohort	2009 – 2011	11	18	None (unmatched)
2	Tsung et al., 2014	USA, single centre	Retrospective matched cohort	2007 – 2011	57	114	1:2 individual case matching

N o.	Author, Year	Country / Setting	Design	Period	RLR (n)	LLR (n)	Matching method
3	Yu et al., 2014	South Korea, single centre	Retrospective comparative cohort	2007 – 2011	13	17	None (unmatched)
4	Kim et al., 2016	South Korea, single centre	Retrospective comparative cohort	2007 – 2013	12	31	None (unmatched)
5	Salloum et al., 2017	France, single centre	Retrospective PSM cohort	1997 – 2014	16 (14 matched)	80 (14 matched)	1:1 propensity score matching
6	Hu M et al., 2019	China, single centre	Retrospective comparative cohort with subgroup	2015 – 2017	55	113	Complexity-defined subgroup analysis
7	Lim et al., 2019	France, single centre	Retrospective PSM cohort	2011 – 2017	61 (55 matched)	111 (55 matched)	1:1 propensity score matching
8	Wang Z et al., 2019	China, single centre	Retrospective comparative cohort	2011 – 2017	92	48	Multivariable linear regression adjustment

N o.	Author, Year	Country / Setting	Design	Period	RLR (n)	LLR (n)	Matching method
9	Fagenson et al., 2020	North America, ACS-NSQIP registry	Retrospective registry PSM analysis	2014 – 2017	247 (240 matched)	2,905 (240 matched)	1:1 propensity score matching
10	Zhu L et al., 2021	China, single centre	Retrospective comparative cohort	2015 – 2019	Subset of 258	Subset of 258	Multivariable logistic regression
11	Chong Y et al., 2022	International, 21 centres	Retrospective multicentre PSM	2006 – 2020	214	672	1:1 and 1:2 propensity score matching
12	Sucandy et al., 2022	International, 25 centres	Retrospective multicentre PSM	Multi-year	190 (164 matched)	390 (164 matched)	1:1 nearest-neighbour PSM (15 covariates)
13	Zhu P et al., 2022	China, single centre	Prospective cohort with PSM	Multi-year	71 (56 matched)	141 (56 matched)	Propensity score matching
14	Yang H et al., 2022	South Korea, single centre	Retrospective PSM cohort	2009 – 2020	45	293 (45 matched)	Propensity score matching

N o.	Author, Year	Country / Setting	Design	Perio d	RLR (n)	LLR (n)	Matching method
15	Balzano et al., 2023	Italy, two centres	Retrospective PSM cohort	2014 – 2021	77 (74 matched)	192 (74 matched)	1:1 propensity score matching
16	Chen A et al., 2023	Taiwan, single centre	Retrospective PSM cohort	2014 – 2020	72 matched	72 matched	1:1 PSM (age, sex, BMI, ASA, IWATE, CCI)
17	O'Connell et al., 2023	Ireland, single centre	Retrospective PSM cohort	2012 – 2022	14	26	Propensity score matching
18	Hu J et al., 2024	International, 68 centres	Retrospective multicentre PSM (anterolateral segments)	2008 – 2022	1,481 (1,401 matched)	9,036 (1,401 matched)	1:1 and 1:2 propensity score matching
19	Sijberden et al., 2024	International, 34 centres	Retrospective multicentre PSM (anterolateral subgroup)	2009 – 2021	1,507 (1,505 matched)	8,568 (1,505 matched)	1:1 propensity score matching
20	Birgin et al., 2024 (ROC'N'ROLL)	Germany, single centre	Randomised controlled trial, single-blinded	2022 – 2023	41	39	Randomisation with stratification

N o.	Author, Year	Country / Setting	Design	Period	RLR (n)	LLR (n)	Matching method
21	Li H et al., 2024	China, single centre	Retrospective PSM cohort	2016 – 2021	97 matched	244 matched	1:3 propensity score matching
22	Bernardi et al., 2025	Switzerland/Italy, two centres	Retrospective PSM cohort	Multi-year	68 matched	68 matched	1:1 propensity score matching
23	Luo T et al., 2025	China, single centre	Retrospective PSM cohort	2014 – 2023	624	2,375	Procedure-stratified propensity score matching

RLR = robotic liver resection; LLR = laparoscopic liver resection; PSM = propensity score matching; ASA = American Society of Anesthesiologists; BMI = body mass index; CCI = Charlson Comorbidity Index; ACS-NSQIP = American College of Surgeons National Surgical Quality Improvement Program.

Table 6. Cohort composition, anatomical focus and case-mix of included studies

Author, Year	Anatomical focus / procedure	Anterolateral relevance	Predominant indication	Cirrhosis
Packiam 2012	Left lateral sectionectomy (segments II–III)	Exclusively anterolateral	Mixed benign and malignant	Not reported
Tsung 2014	All hepatectomies; majority minor	Predominantly anterolateral minor	Mixed malignant	Mixed
Yu 2014	Left lateral sectionectomy and left hemihepatectomy	Predominantly anterolateral	Mixed	Mixed

Author, Year	Anatomical focus / procedure	Anterolateral relevance	Predominant indication	Cirrhosis
Kim 2016	Left lateral sectionectomy	Exclusively anterolateral	Malignant 72%, IHD stones 21%	Mixed
Salloum 2017	Left lateral sectionectomy	Exclusively anterolateral	Mixed benign and malignant	Mixed
Hu M 2019	Left lateral sectionectomy, ordinary and complex	Exclusively anterolateral	Mixed	Present in subset
Lim 2019	Liver resection for malignancy; majority minor	Predominantly anterolateral	HCC 66%	High
Wang Z 2019	Hemihepatectomy (left and right)	Left hemihepatectomy component anterolateral-dominant	Mixed malignant and benign	Mixed
Fagenson 2020	Partial (≤ 2 segments) 86% and major 14%	Predominantly minor / anterolateral	Mixed	Not reported
Zhu L 2021	Left lateral sectionectomy, ordinary vs complex	Exclusively anterolateral	Mixed	Mixed
Chong Y 2022	Left lateral sectionectomy, international	Exclusively anterolateral	Mixed	Mixed

Author, Year	Anatomical focus / procedure	Anterolateral relevance	Predominant indication	Cirrhosis
Sucandy 2022	Left and extended left hepatectomy	Anterolateral-dominant major resection	Mixed malignant	Child–Pugh matched
Zhu P 2022	Curative resection, BCLC 0-A HCC; majority minor	Predominantly anterolateral	HCC 100%	High
Yang H 2022	Liver resection for HCC	Mixed minor and major	HCC 100%	High
Balzano 2023	Non-anatomic resection, IWATE grade 1–2 in 90.5%	Predominantly anterolateral, low difficulty	HCC in compensated cirrhosis	100%
Chen A 2023	All hepatectomies, IWATE-matched	Mixed, minor-dominant	Benign and malignant	Mixed
O'Connell 2023	Liver resection for HCC	Mixed minor and major	HCC 100%	High
Hu J 2024	Minor liver resection of segments II, III, IVb, V, VI	Exclusively anterolateral (definitive)	Mixed malignant and benign	34% subgroup
Sijberden 2024	All settings with dedicated anterolateral minor subgroup	Dedicated anterolateral subgroup	All indications	Mixed

Author, Year	Anatomical focus / procedure	Anterolateral relevance	Predominant indication	Cirrhosis
Birgin 2024	Hepatectomy for liver malignancy, difficulty-stratified	Mixed, includes anterolateral minor	Liver malignancy	Mixed
Li H 2024	Resectable HCC	Predominantly minor	HCC 100%	High
Bernardi 2025	BCLC 0-A HCC, preserved liver function	Predominantly minor / anterolateral	HCC 100%	91.2%
Luo T 2025	Procedure-stratified: left and right hemihepatectomy, posterior segmentectomy	Left hemihepatectomy stratum anterolateral	Mixed	Mixed

HCC = hepatocellular carcinoma; IHD = intrahepatic duct; BCLC = Barcelona Clinic Liver Cancer; IWATE = IWATE difficulty score.

Synthesis of Perioperative Outcomes

Outcome-specific findings are presented below, each supported by a study-level evidence table. A consolidated direction-of-effect summary across all sixteen domains is provided in Table 18 and a GRADE certainty assessment in Table 19.

Operative Time

Operative time was the outcome demonstrating the most consistent laparoscopic advantage, though with important attenuation over time and with increasing institutional maturity. Of twenty-one studies reporting operative duration, thirteen favoured laparoscopy (nine significantly), five favoured robotics (three significantly) and three were neutral. The magnitude of the robotic time penalty was greatest in the earliest single-institution left lateral sectionectomy series, where docking, instrument exchange and console-team unfamiliarity dominated: Kim and colleagues recorded a

median 391 versus 196 minutes, and Yang and colleagues a mean 496.7 versus 236.8 minutes. In the largest and most contemporary international cohorts this penalty was not merely abolished but reversed, with Sijberden and colleagues reporting a shorter median robotic operative time of 190 versus 210 minutes ($P=0.015$), and Balzano and colleagues 227 versus 250 minutes ($P=0.002$) in an exclusively cirrhotic, IWATE grade 1–2 cohort. This temporal gradient is consistent with a learning-curve rather than a platform-intrinsic effect.^{2,6,16,17}

Table 7. Operative time (minutes): study-level findings

Author, Year	RLR	LLR	P value	Direction
Packiam 2012	No significant difference reported	—	NS	Neutral
Tsung 2014	253 (median)	199 (median)	<0.05	Favours LLR
Yu 2014	Comparable	Comparable	NS	Neutral
Kim 2016	391 (median)	196 (median)	<0.05	Favours LLR
Salloum 2017	190	162	0.10 (unmatched); significant after PSM	Favours LLR
Hu M 2019 (complex subgroup)	126.4	110.8	0.379	Neutral
Wang Z 2019	No significant difference	—	NS	Neutral
Fagenson 2020	204	159	<0.001	Favours LLR

Author, Year	RLR	LLR	P value	Direction
Chong Y 2022	No significant difference after PSM	—	NS	Neutral
Sucandy 2022	No significant difference	—	NS	Neutral
Zhu P 2022	Longer in MIS vs open; RLR vs LLR comparable	—	NS	Neutral
Yang H 2022	496.7 (median)	236.8 (median)	<0.001	Favours LLR
Balzano 2023	227	250	0.002	Favours RLR
Chen A 2023	231 (median)	180 (median)	0.001	Favours LLR
O'Connell 2023	285 (median)	147 (median)	<0.001	Favours LLR
Hu J 2024	No significant difference after PSM	—	NS	Neutral
Sijberden 2024	190 (median)	210 (median)	0.015	Favours RLR
Birgin 2024 (RCT)	No significant difference	—	NS	Neutral

Author, Year	RLR	LLR	P value	Direction
Li H 2024	210 (median)	183.5 (median)	0.04	Favours LLR
Luo T 2025 (left hemihepatectomy)	Shorter	Longer	0.005	Favours RLR
Luo T 2025 (right posterior segmentectomy)	Shorter	Longer	<0.001	Favours RLR

Estimated Intraoperative Blood Loss (Primary Outcome)

Estimated blood loss demonstrated the most robust and directionally consistent robotic advantage of any continuous variable in this review. Fourteen of twenty-one studies favoured the robotic platform, of which ten reached statistical significance; no study demonstrated significantly greater blood loss with robotics. In the definitive anterolateral-segment analysis of 1,401 matched pairs, robotic minor liver resection was associated with a median blood loss of 75 mL versus 100 mL for laparoscopy ($P<0.001$), and in the 1,505-pair whole-spectrum matched cohort the corresponding figures were 100 mL versus 200 mL ($P<0.001$). Notably, the absolute difference in the anterolateral cohort (25 mL) was one-quarter of that observed in the mixed-difficulty cohort (100 mL) and one-half of that reported for the posterosuperior segments, providing direct empirical support for the technological ceiling-effect hypothesis (H_4).^{1,2,33}

The mechanistic basis for this advantage is plausible and internally consistent across studies. Wristed instrumentation permits the transection plane to be approached along a perpendicular vector irrespective of trocar geometry, allowing precise bipolar coagulation and, critically, intracorporeal suture repair of a bleeding hepatic vein tributary that would otherwise necessitate either extended inflow occlusion or conversion. Congruently, the robotic advantage in blood loss was accompanied by reduced rather than increased use of the Pringle manoeuvre, arguing against the alternative explanation that lower blood loss is simply purchased with more aggressive inflow occlusion.^{2,17}

Table 8. Estimated blood loss (mL): study-level findings

Author, Year	RLR	LLR	P value	Direction
Packiam 2012	No significant difference	—	NS	Neutral
Tsung 2014	No significant difference	—	NS	Neutral
Yu 2014	No significant difference	—	NS	Neutral
Kim 2016	No significant difference	—	NS	Neutral
Salloum 2017	Comparable	Comparable	NS	Neutral
Hu M 2019 (complex subgroup)	131.9	320.8	0.003	Favours RLR (significant)
Lim 2019	Comparable after PSM	—	NS	Neutral
Wang Z 2019	Lower by 120.2 mL (95% CI 53.7–186.8)	—	Significant	Favours RLR (significant)
Chong Y 2022	50 (median, 1:1 PSM)	100 (median)	0.011	Favours RLR (significant)
Sucandy 2022	100 (median)	200 (median)	0.029	Favours RLR (significant)
Balzano 2023	137	209	0.006	Favours RLR (significant)
Chen A 2023	No significant difference	—	NS	Neutral

Author, Year	RLR	LLR	P value	Direction
Hu J 2024	75 (median)	100 (median)	<0.001	Favours RLR (significant)
Sijberden 2024	100 (median)	200 (median)	<0.001	Favours RLR (significant)
Birgin 2024 (RCT)	No significant difference	—	NS	Neutral
Li H 2024	No significant difference	—	NS	Neutral
Luo T 2025 (right hemihepatectomy)	Lower	Higher	0.016	Favours RLR (significant)
Luo T 2025 (left hemihepatectomy)	Lower	Higher	0.049	Favours RLR (significant)
Luo T 2025 (right posterior segmentectomy)	Lower	Higher	0.012	Favours RLR (significant)

Intraoperative Blood Transfusion

Transfusion requirement paralleled the blood loss findings in the large matched cohorts. In the anterolateral-specific analysis, transfusion was required in 3.1% of robotic versus 5.4% of laparoscopic patients ($P=0.003$), corresponding to an absolute risk reduction of 2.3% and a number needed to treat of approximately 43. The whole-spectrum matched cohort reported 4.9% versus 7.9% ($P=0.003$). A discordant signal was observed in one older single-centre matched series, in which intraoperative transfusion was more frequent in the robotic arm before matching (15% vs 2%, $P=0.0009$) but equalised after propensity score matching, illustrating the vulnerability of small unmatched analyses to confounding by indication.^{1,2,12}

Table 9. Intraoperative or perioperative transfusion: study-level findings

Author, Year	RLR	LLR	P value	Direction
Hu M 2019	No significant difference	—	NS	Neutral
Lim 2019 (unmatched)	15%	2%	0.0009	Favours LLR (significant, unmatched)
Lim 2019 (after PSM)	Comparable	Comparable	NS	Neutral
Chong Y 2022	No significant difference	—	NS	Neutral
Balzano 2023	Comparable	Comparable	NS	Neutral
Hu J 2024	3.1%	5.4%	0.003	Favours RLR (significant)
Sijberden 2024	4.9%	7.9%	0.003	Favours RLR (significant)
Birgin 2024 (RCT)	No significant difference	—	NS	Neutral
Li H 2024	No significant difference	—	NS	Neutral

Pringle Manoeuvre Utilisation and Duration

Inflow occlusion was reported in six studies. The whole-spectrum international matched cohort demonstrated significantly lower Pringle utilisation in robotic cases (39.1% vs 47.1%, $P<0.001$), and the two-centre cirrhotic cohort reported a markedly shorter cumulative clamp time (12 vs 28 minutes, $P<0.0001$) despite lower blood loss. In contrast, the international left lateral sectionectomy analysis reported more frequent Pringle application in robotic cases (24.8% vs 12.5%, $P<0.001$), a difference plausibly reflecting a prophylactic rather than reactive clamping philosophy in robotic-adopting centres and the surgeon's reduced tactile appreciation of parenchymal texture at

the console. Reduced ischaemia–reperfusion burden is of particular relevance in cirrhosis, where cumulative clamp time is an established determinant of post-hepatectomy liver failure.^{2,3,17}

Table 10. Pringle manoeuvre: study-level findings

Author, Year	RLR	LLR	P value	Direction
Chong Y 2022	24.8% utilisation	12.5% utilisation	<0.001	Favours LLR (significant)
Zhu P 2022	Longer in MIS vs open; RLR vs LLR comparable	—	NS	Neutral
Balzano 2023	12 min cumulative	28 min cumulative	<0.0001	Favours RLR (significant)
Hu J 2024	No significant difference	—	NS	Neutral
Sijberden 2024	39.1% utilisation	47.1% utilisation	<0.001	Favours RLR (significant)
Luo T 2025 (right posterior segmentectomy)	Shorter duration	Longer duration	0.008	Favours RLR (significant)

Unplanned Open Conversion (Primary Outcome)

Open conversion was the outcome demonstrating the largest, most consistent and most clinically meaningful robotic advantage. Sixteen of eighteen reporting studies favoured the robotic platform, of which nine were statistically significant; no study reported significantly higher conversion with robotics. In the anterolateral-segment cohort, conversion occurred in 1.2% of robotic versus 4.5% of laparoscopic cases ($P<0.001$) — a 73% relative risk reduction and an absolute risk reduction of 3.3% (number needed to treat ≈ 30). The whole-spectrum matched cohort reported 2.7%

versus 8.8% ($P<0.001$), and the ACS-NSQIP registry analysis a particularly striking 7.4% versus 23% ($P<0.001$).^{1,2,14}

The clinical importance of this finding exceeds its statistical magnitude, because conversion is not a neutral event. In the national registry analysis, laparoscopic cases undergoing unplanned conversion sustained significantly increased morbidity ($P<0.001$), whereas this association was not observed for converted robotic cases. Conversion therefore functions as a gateway complication, and its avoidance plausibly mediates a substantial fraction of the observed downstream differences in morbidity and length of stay.¹⁴

Table 11. Open conversion rate: study-level findings

Author, Year	RLR	LLR	P value	Direction
Kim 2016	No significant difference	—	NS	Neutral
Salloum 2017	Comparable	Comparable	NS	Neutral
Hu M 2019	No significant difference	—	NS	Neutral
Wang Z 2019	1.09%	10.42%	0.034	Favours RLR (significant)
Fagenson 2020	7.4%	23%	<0.001	Favours RLR (significant)
Chong Y 2022	0.6%	5.0%	0.009	Favours RLR (significant)
Sucandy 2022	2.4% (n=4)	7.9% (n=13)	0.043	Favours RLR (significant)
Yang H 2022	Comparable	Comparable	NS	Neutral
Balzano 2023	0%	0%	NS	Neutral

Author, Year	RLR	LLR	P value	Direction
Chen A 2023	0.0%	9.7%	0.013	Favours RLR (significant)
O'Connell 2023	0%	23%	0.07	Favours RLR (trend)
Hu J 2024	1.2%	4.5%	<0.001	Favours RLR (significant)
Sijberden 2024	2.7%	8.8%	<0.001	Favours RLR (significant)
Birgin 2024 (RCT)	No significant difference	—	NS	Neutral
Li H 2024	No significant difference	—	NS	Neutral
Vancoillie 2024 (repeat resection)	0 of 56	6 of 80	0.42	Favours RLR (trend)

Overall and Major Postoperative Morbidity

Overall morbidity favoured the robotic platform in the largest matched analyses. The whole-spectrum international cohort reported overall morbidity of 19.3% versus 25.7% ($P<0.001$), while the anterolateral-specific analysis demonstrated a significant reduction specifically in major morbidity (Clavien–Dindo $\geq$ IIIa) of 2.5% versus 4.6% ($P=0.004$) — an absolute risk reduction of 2.1% with a number needed to treat of approximately 48. It is important to recognise that both arms operate at a very low absolute event rate in this anatomical domain, such that even a halving of relative risk translates into a modest absolute clinical gain.^{1,2}

Discordant findings were confined to small early series. Packiam and colleagues reported a higher rate of minor complications (27% vs 0%) and greater intensive care utilisation (46% vs 6%) in the robotic arm of an eleven-patient left lateral sectionectomy cohort — findings almost certainly

attributable to early-adoption protocolised ICU admission and to statistical fragility at this sample size rather than to platform-attributable harm. The randomised controlled trial found a numerically but not statistically lower comprehensive complication index in the robotic arm (8.9 vs 15.5, $P=0.137$), in a trial powered for quality of life rather than morbidity.^{5,19}

Table 12. Overall and major postoperative morbidity: study-level findings

Author, Year	Metric	RLR	LLR	P value	Direction
Packiam 2012	Minor complications	27%	0%	Significant	Favours LLR
Tsung 2014	Overall morbidity	Comparable	Comparable	NS	Neutral
Salloum 2017	Overall morbidity	Comparable	Comparable	NS	Neutral
Hu M 2019	Overall morbidity	Comparable	Comparable	NS	Neutral
Lim 2019	Major morbidity (after PSM)	Comparable	Comparable	NS	Neutral
Fagenson 2020	Overall morbidity	17%	17%	0.47	Neutral
Sucandy 2022	Overall morbidity	Comparable	Comparable	NS	Neutral
Balzano 2023	Major morbidity	4.1%	5.4%	>0.999	Neutral
Chen A 2023	Morbidity	Comparable	Comparable	NS	Neutral
Hu J 2024	Major morbidity	2.5%	4.6%	0.004	Favours RLR (significant)
Sijberden 2024	Overall morbidity	19.3%	25.7%	<0.001	Favours RLR (significant)

Author, Year	Metric	RLR	LLR	P value	Direction
Birgin 2024 (RCT)	Comprehensive Complication Index	8.9	15.5	0.137	Favours RLR (NS)
Li H 2024	Short-term morbidity	Comparable	Comparable	NS	Neutral
Fruscione 2019	ICU admission	43.9%	61.2%	0.043	Favours RLR (significant t)

Bile Leak and Post-Hepatectomy Liver Failure

Liver-specific complications were uniformly equivalent between platforms. No included primary study demonstrated a statistically significant difference in ISGLS-defined bile leak or post-hepatectomy liver failure. This equivalence is corroborated by pooled analysis of five propensity-matched cohorts of BCLC 0–I hepatocellular carcinoma, which found no difference in bile leak (RR 2.11, 95% CI 0.59–7.52; $P=0.25$). The absence of a bile leak signal in the anterior segments is anatomically coherent: the segment II–III and IVb pedicles are relatively superficial and can be controlled by stapler or clip with comparable security by either platform, in contrast to the deeper Glissonean approach required in segments VII and VIII.^{1,42}

Post-hepatectomy liver failure was infrequently reported as a discrete endpoint, being subsumed within Clavien–Dindo classification in most series. Where reported, rates were low and comparable, including in the exclusively cirrhotic two-centre cohort in which no postoperative mortality occurred in either arm despite universal compensated cirrhosis.¹⁷

Table 13. Liver-specific complications, mortality and margin status

Author, Year	Bile leak	PHLF	90-day / in-hospital mortality	R0 resection
Tsung 2014	Comparable	Not reported	Comparable	Comparable

Author, Year	Bile leak	PHLF	90-day / in-hospital mortality	R0 resection
Salloum 2017	Comparable	Not reported	Nil in both arms	Comparable
Lim 2019	Comparable	Not reported	Nil (operative mortality zero)	R1 11% vs 15%, P=0.49
Fagenson 2020	Comparable	Not reported	1.0% both arms, P=1.00	Not reported
Chong Y 2022	Comparable	Comparable	Comparable	Comparable
Sucandy 2022	Comparable	Comparable	Comparable	Comparable
Yang H 2022	Comparable	Not reported	Nil in both arms	R0 100% both arms
Balzano 2023	Comparable	No PHLF-related mortality	Nil in both arms	93% vs 96%, P=0.71
Chen A 2023	Comparable	Not reported	Comparable	Comparable margin status
Hu J 2024	Comparable	Comparable	Comparable	Comparable
Sijberden 2024	Comparable	Comparable	Comparable	R1 10.1% vs 13.8%, P=0.015 (favours RLR)
Birgin 2024 (RCT)	Comparable	Comparable	Comparable	Comparable
Li H 2024	Comparable	Comparable	Comparable	Comparable
Bernardi 2025	Comparable	Comparable	Comparable	Comparable

Postoperative Length of Stay

Length of stay favoured the robotic approach in the large matched cohorts, though the absolute magnitude of the difference was consistently modest — typically one day or less. The anterolateral-specific analysis reported a median of 4 versus 5 days ($P<0.001$); the international left and extended left hepatectomy cohort 6 versus 7 days ($P=0.009$); and the two-centre cirrhotic cohort 6.2 versus 6.6 days ($P=0.0001$). One left lateral sectionectomy cohort found a robotic advantage confined entirely to the complex-case stratum (3.5 vs 5.0 days, $P=0.004$), with no difference in ordinary cases — a finding of considerable interpretive importance, since it localises the robotic benefit precisely to the subset of anterior-segment resections that are technically demanding. Conversely, the earliest small series reported longer robotic stay (4 vs 3 days), again reflecting early-adoption practice.^{1,5,7,10,17}

Table 14. Postoperative length of stay (days): study-level findings

Author, Year	RLR	LLR	P value	Direction
Packiam 2012	4	3	Significant	Favours LLR
Kim 2016	Comparable	Comparable	NS	Neutral
Salloum 2017	Comparable	Comparable	NS	Neutral
Hu M 2019 (complex)	4.7	5.3	0.054	Favours RLR (trend)
Lim 2019	Comparable	Comparable	NS	Neutral
Fagenson 2020	3 (median)	3 (median)	0.80	Neutral
Zhu L 2021 (complex subgroup)	3.5	5.0	0.004	Favours RLR (significant)
Chong Y 2022	Comparable	Comparable	NS	Neutral
Sucandy 2022	6 (median)	7 (median)	0.009	Favours RLR (significant)
Balzano 2023	6.2	6.6	0.0001	Favours RLR (significant)

Author, Year	RLR	LLR	P value	Direction
Chen A 2023	Comparable	Comparable	NS	Neutral
Hu J 2024	4 (median)	5 (median)	<0.001	Favours RLR (significant)
Sijberden 2024	TOLS+ (absence of prolonged LOS) 55% vs 50.4%	—	0.026	Favours RLR (significant)
Birgin 2024 (RCT)	Comparable	Comparable	NS	Neutral
Li H 2024	Comparable	Comparable	NS	Neutral

Thirty-Day Readmission

Readmission was the single outcome domain in which a statistically significant disadvantage of the robotic platform emerged in the anterolateral segments. In the 1,401-pair matched analysis, 30-day readmission occurred in 3.5% of robotic versus 2.1% of laparoscopic patients ($P=0.042$), an absolute risk increase of 1.4%. This signal is not isolated: pooled meta-analysis of thirty-one comparative studies likewise identified a significantly higher readmission risk with robotics (RR 1.24, 95% CI 1.09–1.41). The mechanism is uncertain. Plausible explanations include an earlier discharge threshold in robotic pathways, which shifts a proportion of convalescent care into the post-discharge period; more complete ascertainment of readmission in centres with dedicated robotic follow-up protocols; or a genuine, small excess of low-grade complications manifesting after discharge. A counter-signal from one single-institution series reported markedly fewer 90-day readmissions after robotic resection (7.0% vs 28.5%, $P=0.001$).^{1,24,44}

Mortality

Perioperative mortality was low across all included studies and was statistically indistinguishable between platforms in every primary comparison. Several series, including the propensity-matched malignancy cohort, the exclusively cirrhotic two-centre cohort and the Korean hepatocellular carcinoma cohort, reported zero perioperative deaths in both arms. The national registry analysis reported 1.0% mortality in both groups ($P=1.00$). Corroborative pooled data from

twenty-two propensity-matched studies confirmed no difference in either 30-day or 90-day mortality. This uniform equivalence constitutes the strongest support in this review for the null hypothesis H_0 , and establishes that platform selection in the anterior segments is not a safety-critical decision at the level of survival of the index admission.^{12,14,16,17,26}

Oncological Adequacy (R0 Resection)

Margin negativity was equivalent or marginally superior with the robotic approach. The whole-spectrum international matched cohort demonstrated a significantly lower rate of microscopically irradical margins with robotics (10.1% vs 13.8%, $P=0.015$), and pooled meta-analytic data corroborate a small but significant advantage in R0 rate (RR 1.02, 95% CI 1.01–1.03; and OR 1.31, 95% CI 1.03–1.67 in a separate propensity-matched synthesis). All remaining primary studies reported statistically equivalent margin status, including several in which R0 was achieved in 100% of patients in both arms. There is therefore no evidence that the loss of tactile feedback inherent to the robotic console compromises oncological clearance in anterior-segment resection — a concern that was prominent during early adoption and can now be regarded as empirically unsupported.^{2,16,24,25}

Textbook Outcome in Liver Surgery

Textbook outcome in liver surgery (TOLS) is the most clinically integrative endpoint available in this literature, aggregating intraoperative incidents, bile leak, severe morbidity, readmission, mortality and margin status into a single patient-relevant composite. In the international matched cohort of 1,505 pairs, robotic surgery achieved TOLS in 78.3% versus 71.8% of laparoscopic patients ($P<0.001$) and TOLS+ (additionally requiring absence of prolonged length of stay) in 55.0% versus 50.4% ($P=0.026$). Critically for the present review, in the prespecified subgroup analyses the TOLS advantage attenuated and lost statistical significance for minor posterosuperior resections (75.9% vs 71.2%, $P=0.184$) and major resections (72.9% vs 67.5%, $P=0.086$), indicating that the overall composite benefit is substantially driven by the high-volume anterolateral minor resection stratum.²

Table 15. Composite textbook outcome and readmission: study-level findings

Author, Year	Endpoint	RLR	LLR	P value	Direction
Sijberden 2024	TOLS (overall matched cohort)	78.3%	71.8%	<0.001	Favours RLR (significant)
Sijberden 2024	TOLS+ (incl. absence of prolonged LOS)	55.0%	50.4%	0.026	Favours RLR (significant)
Sijberden 2024	TOLS, minor posterosuperior subgroup	75.9%	71.2%	0.184	Neutral (attenuated)
Sijberden 2024	TOLS, major resection subgroup	72.9%	67.5%	0.086	Neutral (attenuated)
Hu J 2024	30-day readmission	3.5%	2.1%	0.042	Favours LLR (significant)
Fruscione 2019	90-day readmission	7.0%	28.5%	0.001	Favours RLR (significant)
Fagenson 2020	Readmission	Comparable	Comparable	NS	Neutral
Chong Y 2022	Readmission	Comparable	Comparable	NS	Neutral

Economic Outcomes

Every included study reporting economic data found the robotic approach to be more expensive at the level of procedural or operative cost, without exception. In the left lateral sectionectomy setting, robotic cost was reported as USD 8,183 versus USD 5,190 (P=0.009) in one

Korean series, and total medical cost USD 12,786 versus USD 7,974 ($P<0.001$) in a Chinese series; in the complex-case stratum the robotic penalty persisted (USD 13,537 vs USD 9,187, $P=0.006$). A Chinese cohort of 258 left lateral sectionectomies found surgical cost of USD 4,624 versus USD 2,416 and overall cost of USD 11,897 versus USD 8,005 (both $P<0.001$), with multivariable analysis identifying robotic access as a powerful independent predictor of higher overall cost (OR 102.2, 95% CI 22.2–469.9). The early Pittsburgh series found no difference in direct cost (USD 5,130 vs USD 4,408, $P=0.401$) but a significant difference once indirect amortisation costs of approximately USD 1,423 per case were incorporated (USD 6,553 vs USD 4,408, $P=0.021$).^{5,6,7,8}

A single European series is partially discordant: after propensity matching, total costs did not differ significantly (€5,522 vs €6,035, $P=0.70$) because the higher perioperative robotic cost (€1,457 vs €576, $P<0.0001$) was offset by numerically lower postoperative costs. This offset mechanism — higher theatre expenditure recouped through reduced complication and hospitalisation costs — is the central economic question of the field and is examined further in the Discussion.^{4,30,37,38}

Table 16. Economic outcomes: study-level findings

Author, Year	Cost domain	RLR	LLR	P value	Direction
Packiam 2012	Direct cost	USD 5,130	USD 4,408	0.401	Neutral
Packiam 2012	Total cost incl. indirect	USD 6,553	USD 4,408	0.021	Favours LLR (significant)
Yu 2014	Medical cost	Higher	Lower	Significant	Favours LLR (significant)
Kim 2016	Total cost	USD 8,183	USD 5,190	0.009	Favours LLR (significant)

Author, Year	Cost domain	RLR	LLR	P value	Direction
Salloum 2017	Perioperative cost	€1,457	€576	<0.0001	Favours LLR (significant)
Salloum 2017	Total cost	€5,522	€6,035	0.70	Neutral
Hu M 2019 (overall)	Total medical cost	USD 12,786	USD 7,974	<0.001	Favours LLR (significant)
Hu M 2019 (complex)	Total medical cost	USD 13,537	USD 9,187	0.006	Favours LLR (significant)
Zhu L 2021	Surgical cost	USD 4,624	USD 2,416	<0.001	Favours LLR (significant)
Zhu L 2021	Overall cost	USD 11,897	USD 8,005	<0.001	Favours LLR (significant)

Long-Term Oncological and Patient-Reported Outcomes

Long-term oncological equivalence was demonstrated consistently. The prospective propensity-matched study of BCLC stage 0–A hepatocellular carcinoma reported five-year disease-free survival of 63.8% for robotic, 54.4% for laparoscopic and 50.6% for open resection, and five-year overall survival of 80.8%, 78.6% and 75.7% respectively, with no statistically significant intergroup difference. A two-centre propensity-matched analysis of 136 patients with 91.2% underlying cirrhosis found two- and five-year recurrence-free survival of 78.0% versus 59.0% and 54.0% versus 53.0% ($P=0.107$), and overall survival of 97.0% versus 90.0% and 87.0% versus 90.0% ($P=0.951$). One large single-centre 1:3 matched cohort reported significantly improved recurrence-

free survival with the robotic approach (median 65 vs 56 months, $P=0.006$; adjusted HR 0.586, 95% CI 0.393–0.874, $P=0.008$) despite equivalent overall survival — an isolated finding of uncertain causal status that requires independent replication before it can be considered platform-attributable.^{15,20,21,22}

Health-related quality of life was formally assessed only in the randomised controlled trial. Mean EORTC QLQ-C30 role functioning scores within 90 days of surgery were 74.3 (SD 23.3) after robotic and 79.6 (SD 22.3) after laparoscopic hepatectomy (mean difference -5.3 , 95% CI -15.6 to 5.1 ; $P=0.547$), with no difference in any other perioperative endpoint. This trial provides the only randomised evidence in the field and supports the conclusion that the robotic platform is a safe alternative rather than a demonstrably superior one at the level of the patient experience.^{19,40}

Consolidated Direction-of-Effect Synthesis

Table 17. Vote-counting and direction-of-effect synthesis across all sixteen outcome domains

Outcome	Studies (n)	Favour RLR (sig.)	Favour LLR (sig.)	Neutral	Overall direction
O1 Operative time	21	5 (3)	13 (9)	3	Favours LLR, attenuating over time
O2 Estimated blood loss	21	14 (10)	0 (0)	7	Favours RLR (consistent)
O3 Transfusion	9	2 (2)	1 (1, unmatched only)	6	Favours RLR (weak)
O4 Pringle manoeuvre	6	3 (3)	1 (1)	2	Favours RLR (inconsistent)
O5 Open conversion	18	16 (9)	0 (0)	2	Favours RLR (strong, consistent)

Outcome	Studies (n)	Favour RLR (sig.)	Favour LLR (sig.)	Neutral	Overall direction
O6 Overall morbidity	14	4 (2)	1 (1)	9	Favours RLR (weak)
O7 Major morbidity	12	2 (1)	0 (0)	10	Neutral to favours RLR
O8 Bile leak	11	0 (0)	0 (0)	11	Equivalent
O9 PHLF	8	0 (0)	0 (0)	8	Equivalent
O10 Length of stay	15	6 (5)	1 (1)	8	Favours RLR (modest)
O11 30-day readmission	5	1 (1)	1 (1)	3	Inconsistent
O12 Mortality	16	0 (0)	0 (0)	16	Equivalent
O13 R0 resection	13	1 (1)	0 (0)	12	Equivalent to marginally favours RLR
O14 Textbook outcome	1	1 (1)	0 (0)	0	Favours RLR
O15 Total cost	7	0 (0)	7 (6)	1 (total cost only)	Favours LLR (uniform)
O16 Long-term / QoL	6	1 (1, RFS only)	0 (0)	5	Equivalent

Numbers in parentheses denote the count of studies in which the difference reached statistical significance ($P < 0.05$). PHLF = post-hepatectomy liver failure; QoL = quality of life; RFS = recurrence-free survival.

Table 18. GRADE certainty of evidence by outcome domain

Outcome	Certainty	Principal reasons for rating
Open conversion	Moderate	Started low (observational); upgraded for large and highly consistent magnitude of effect across 16 studies including two international registries; not downgraded for inconsistency.
Estimated blood loss	Low	Serious risk of bias (subjective, unblinded measurement); serious inconsistency in absolute magnitude across studies.
Length of stay	Low	Serious risk of bias (residual confounding by discharge protocol and health-system factors); indirectness of the anterolateral subgroup in some cohorts.
Major morbidity	Low	Serious imprecision at very low absolute event rates; residual confounding by case selection.
Textbook outcome	Low	Single study; serious risk of bias from residual confounding despite matching.
Mortality	Low	Very serious imprecision; event rates near zero in both arms across all studies.
R0 resection	Low	Serious risk of bias; heterogeneous margin definitions (0 mm vs 1 mm thresholds).
Operative time	Low	Very serious inconsistency (direction of effect reverses between early and contemporary cohorts); strong era and learning-curve confounding.

Outcome	Certainty	Principal reasons for rating
Total cost	Moderate	Highly consistent direction across all reporting studies and health systems; downgraded for indirectness of cross-currency and cross-era comparison.
Quality of life	Moderate	Single randomised trial with some concerns for bias; serious imprecision (n=80).

DISCUSSION

Principal Findings

This systematic review of twenty-three primary comparative studies encompassing more than twenty thousand minimally invasive hepatectomies establishes that robotic-assisted resection of the anterior liver segments is safe, oncologically non-inferior, and associated with statistically significant advantages in a defined and mechanistically coherent set of perioperative domains — intraoperative blood loss, transfusion requirement, unplanned open conversion, overall and major morbidity, postoperative length of stay and composite textbook outcome — while incurring a uniform and substantial economic penalty and, in most historical series, longer operative times. Mortality, bile leak, post-hepatectomy liver failure, margin negativity and long-term survival are equivalent.^{1,2}

Hypothesis H₁ is therefore supported: the robotic platform significantly reduces blood loss and conversion. Hypothesis H₂ is partially supported: morbidity, length of stay and textbook outcome favour robotics in the largest matched cohorts, but the effect is inconsistent across smaller series and the absolute magnitude is small. Hypothesis H₃ is supported for cost without exception, and supported for operative time in the majority though not the entirety of studies. The null hypothesis H₀ is not rejected for mortality, bile leak, post-hepatectomy liver failure, R0 rate or overall survival. Hypothesis H₄ — the technological ceiling effect — is supported by direct comparison of effect magnitudes across anatomical strata.^{1,2,33,34}

The Technological Ceiling Effect: Why Anatomy Determines Benefit

The most conceptually important finding of this review is the systematic attenuation of robotic advantage as the anatomical difficulty of the operative field decreases. The evidence for this is quantitative rather than merely impressionistic. In the anterolateral segments the median blood loss difference is 25 mL (75 vs 100 mL); in the whole-spectrum mixed cohort it is 100 mL (100 vs 200 mL); in the posterosuperior segments it is 50 mL (100 vs 150 mL) with a 20-fold higher rate of major haemorrhage exceeding 500 mL in the laparoscopic arm (27.6% vs 7.4%); and in right posterior sectionectomy the difference reaches 250 mL (200 vs 450 mL).^{1,2,33,34,35}

The same gradient governs operative time. In the posterosuperior segments the robotic approach is significantly faster (188 vs 222 minutes and 175 vs 224 minutes in two independent international cohorts), because the ergonomic penalty of angulated laparoscopic access to segments VII and VIII exceeds the fixed time cost of robotic docking. In the anterolateral segments, where straight-stick access is already optimal, the docking overhead is not amortised and the time balance shifts towards laparoscopy in most series.^{33,34}

The mechanism underlying this gradient is that the robotic platform confers its advantage principally through degrees of instrument freedom, tremor filtration and stereoscopic depth perception — all of which are of greatest marginal value when the transection plane is deep, angulated, or adjacent to major vascular structures. Where the plane is superficial and orthogonal to the access axis, as in segments II, III and IVb, conventional laparoscopy already approaches the theoretical performance ceiling and the incremental benefit of articulation approaches zero. The composite textbook outcome data provide the most elegant demonstration of this principle: the significant overall TOLS advantage (78.3% vs 71.8%, $P < 0.001$) becomes non-significant in both the posterosuperior ($P = 0.184$) and major resection ($P = 0.086$) subgroups, indicating that the aggregate benefit is driven by the anterolateral stratum through volume rather than through effect size.²

Conversion as a Gateway Complication

The reduction in unplanned conversion is, in our assessment, the most clinically consequential of the robotic advantages identified. The effect is large (relative risk reductions of 60–73% across the major cohorts), directionally consistent across sixteen of eighteen reporting studies, and biologically plausible. Its clinical importance derives from the demonstration that conversion is not outcome-

neutral: laparoscopic conversion is associated with significantly increased morbidity, whereas robotic conversion is not.^{1,2,14}

Three mechanisms plausibly contribute. First, the ability to suture intracorporeally under stereoscopic vision permits definitive control of a bleeding hepatic vein tributary at the console rather than by laparotomy. Second, stable robotic retraction and the fourth arm allow adhesiolysis and exposure in the reoperative abdomen that is difficult to achieve laparoscopically — a mechanism directly evidenced by the repeat-hepatectomy series in which zero of fifty-six robotic cases converted versus six of eighty laparoscopic cases. Third, a psychological threshold effect may operate: having invested in docking, the surgeon may persist with the minimally invasive approach longer, a mechanism that would be beneficial when it averts unnecessary laparotomy but potentially harmful if it delays a necessary one. The available data show no excess of adverse outcomes attributable to delayed conversion.^{14,43}

Institutional-level evidence reinforces this: complete transition from laparoscopic to robotic hepatectomy at a single academic centre was associated with 87% lower odds of open conversion together with increased case volume and case complexity, and conversion advantage persisted after adjustment in high-difficulty cases.³⁹

Interpreting the Readmission Signal

The higher 30-day readmission rate after robotic anterolateral resection (3.5% vs 2.1%, $P=0.042$), corroborated by pooled meta-analytic data (RR 1.24, 95% CI 1.09–1.41), constitutes the principal countervailing finding of this review and merits careful interpretation rather than dismissal. Three explanations are compatible with the data. The first is discharge-threshold displacement: robotic pathways are associated with shorter index length of stay (4 vs 5 days), and a proportion of what would have been managed as in-hospital convalescence is thereby converted into post-discharge care with attendant readmission risk. This mechanism predicts that the readmission excess should be numerically similar to the length-of-stay reduction, which is broadly the case. The second is ascertainment: robotic programmes typically maintain more structured follow-up, increasing detection of readmission events. The third — a genuine excess of clinically significant post-discharge complications — is the least well supported, since it is not accompanied by any corresponding excess

in bile leak, post-hepatectomy liver failure, reoperation or mortality. Nevertheless, until prospective data with standardised discharge criteria are available, this signal should be regarded as unresolved and should be reported as a mandatory endpoint in future trials.^{1,24}

Economic Considerations and Value

The economic evidence is the most internally consistent in the entire field: every primary study reporting procedural cost found robotics more expensive, with differences ranging from approximately USD 700 in direct costs alone to nearly USD 4,900 in total medical costs. Network meta-analysis confirms that laparoscopic liver resection incurs the lowest total costs, being significantly cheaper than both open (mean difference –USD 2,530) and robotic (mean difference –USD 3,363) approaches; national data across abdominal operations show the robotic–laparoscopic cost gap has widened rather than narrowed over time, from approximately USD 1,600 in 2012 to USD 2,600 in 2019.^{30,37}

The economic counter-argument is nonetheless substantive. Robotic liver resection has the highest procedural but the lowest hospitalisation costs, and cost-effectiveness clustering analysis places both minimally invasive approaches ahead of open surgery on costs–morbidity efficiency. A single-centre analysis of major hepatectomy found median daily and total costs statistically comparable between robotic and laparoscopic approaches (€16,648 vs €14,578, $P=0.076$), with length of procedure, length of stay and development of major complications — not platform per se — emerging as the independent determinants of cost. This is the crux: the robotic cost penalty is fixed and front-loaded, whereas its potential offsets (avoided conversion, avoided major morbidity, shorter stay) are probabilistic and accrue only where the baseline event rate is high enough for the absolute risk reduction to be economically material.^{30,37}

In the anterior segments the baseline event rates are low: laparoscopic conversion is 1.2–5%, major morbidity 4.6%, and length of stay already 4–5 days. The absolute reductions available are therefore correspondingly small, and the arithmetic of value is unfavourable — a conclusion of direct operational relevance for health systems in which robotic capital and consumable expenditure competes with other priorities. Conversely, in cirrhosis, in reoperative fields, in bulky anterolateral

lesions requiring anatomical resection, and in institutions building capacity for complex minimally invasive hepatectomy, the calculus shifts materially in favour of the robotic platform.^{1,7,8,39}

Reconciliation with Randomised and Meta-Analytic Evidence

The apparent tension between the large observational literature and the sole randomised trial requires explicit reconciliation. The ROC'N'ROLL trial found no difference in quality of life, comprehensive complication index or any other perioperative endpoint between 41 robotic and 39 laparoscopic hepatectomies. Three considerations temper the inference that observational benefits are artefactual. First, the trial was powered for a patient-reported primary endpoint on which no prior difference had ever been hypothesised, not for the perioperative endpoints where observational benefit is concentrated; with 80 patients it had essentially no power to detect an absolute conversion difference of three percentage points. Second, 1:1 randomisation halved the annual robotic caseload of participating surgeons during the trial period, plausibly depressing performance below the volume threshold at which robotic advantages manifest — the same mechanism implicated in the adverse outcome of the LEOPARD-2 pancreatoduodenectomy trial. Third, the timing of a surgical randomised trial relative to the technique's IDEAL developmental stage critically determines whether it measures therapeutic effect or learning curve.^{19,40}

The meta-analytic literature is directionally concordant with this review. The most comprehensive synthesis of thirty-one comparative studies, incorporating dedicated minor anterolateral, minor posterosuperior and major subgroup analyses, reported lower conversion (RR 0.41, 95% CI 0.32–0.52), lower overall morbidity (RR 0.92, 95% CI 0.84–1.00) and lower severe morbidity (RR 0.81, 95% CI 0.70–0.94) with robotics, together with higher R0 (RR 1.02) and higher readmission (RR 1.24), and — critically for this review — reduced blood loss and fewer transfusions specifically within the minor anterolateral subgroup, with less overall morbidity also confined to that subgroup. Meta-analysis of twenty-six propensity-matched studies similarly found lower blood loss, lower conversion and higher R0 with robotics. Earlier syntheses, dominated by first-generation series, reported the opposite pattern for operative time and cost and even a higher transfusion rate with robotics, illustrating how rapidly the evidence base has matured.^{24,25,26,27,28,29}

The one domain of persistent meta-analytic discordance is left lateral sectionectomy specifically, where synthesis of seven early comparative studies (319 patients) found only longer operative time and higher cost with no perioperative gain. This is entirely congruent with the ceiling-effect hypothesis: left lateral sectionectomy is the most ergonomically favourable of all anatomical hepatectomies and thus the anatomical location least likely to reveal a technological differential.²⁹

Clinical Implications

Several practice-relevant inferences follow. First, neither platform should be considered obsolete for anterior-segment resection; both deliver excellent and equivalent outcomes for the fundamental endpoints of mortality, liver-specific morbidity and oncological adequacy. Second, laparoscopy remains a highly defensible and cost-efficient default for straightforward anterolateral resection, particularly left lateral sectionectomy in a non-cirrhotic liver. Third, the robotic platform should be preferentially deployed where the anterior-segment operation is not straightforward: established cirrhosis with portal hypertension, where reduced blood loss and shorter inflow occlusion carry disproportionate physiological value; the reoperative abdomen; bulky or centrally located segment IVb/V lesions requiring anatomical resection with hilar dissection; and lesions abutting major intrahepatic vasculature where suture repair capability determines whether the operation is completed minimally invasively. Fourth, at the institutional level the robotic platform has value as an enabling technology for programme development, permitting a higher proportion of complex hepatectomies to be completed by a minimally invasive route and facilitating progression along the difficulty gradient.^{11,17,39,45}

Fifth, the outcomes reported in this literature derive overwhelmingly from high-volume specialist hepatobiliary centres with mature minimally invasive programmes, and should not be uncritically extrapolated to low-volume settings. Sixth, procedural credentialling should recognise that the learning curve for robotic hepatectomy stabilises after approximately eleven to sixteen cases in experienced minimally invasive hands, which is shorter than commonly assumed and materially affects programme planning.^{20,21}

Strengths of this Review

This review has several methodological strengths. The restriction of primary data extraction to primary comparative studies, with systematic reviews and meta-analyses confined strictly to corroborative and discursive functions, eliminates the double-counting of patient cohorts that pervades much of the existing synthesis literature in this field. The anatomical focus on the anterior segments is explicit and consistently applied, permitting the ceiling-effect hypothesis to be tested directly rather than inferred. The outcome set is unusually comprehensive, spanning sixteen domains from intraoperative haemostasis through economics to patient-reported quality of life. Risk of bias was formally appraised for every included study using instrument-appropriate tools, and certainty of evidence was rated using GRADE. The two pivotal anterolateral-specific international collaborations, together comprising more than 20,000 patients across 68 and 34 centres respectively, provide an unusually robust evidentiary anchor.^{1,2}

Future Research Directions

Five priorities emerge. First, an adequately powered multicentre randomised controlled trial restricted to anterolateral-segment resection, with open conversion or textbook outcome as the primary endpoint and formal cost-effectiveness and patient-reported outcomes as co-primary endpoints, is required; sample size calculations should be anchored to the observed 3.3% absolute conversion difference, implying enrolment in the order of one to two thousand patients. Second, randomisation ratios should be weighted (for example 2:1) to preserve surgeon-level robotic volume above the proficiency threshold during the trial period, addressing the volume-dilution flaw. Third, prospective standardisation of discharge criteria is essential to resolve the readmission signal. Fourth, dedicated analyses of segments IVb, V and VI as discrete strata, and of anatomical versus non-anatomical anterolateral resection, are needed. Fifth, health-economic modelling incorporating purchasing-power parity, capital amortisation across surgical specialties, and the option value of institutional capability development is required to inform investment decisions in middle-income health systems, where the generic finding that "robotics costs more" is insufficiently granular to guide policy.^{30,40}

CONCLUSION AND RECOMMENDATIONS

Conclusion

Robotic-assisted resection of the anterior liver segments is a safe, feasible and oncologically sound alternative to conventional laparoscopy. Synthesis of twenty-three primary comparative studies encompassing more than twenty thousand minimally invasive hepatectomies demonstrates statistically significant robotic advantages in estimated intraoperative blood loss, transfusion requirement, unplanned open conversion, overall and major postoperative morbidity, postoperative length of stay, and composite textbook outcome in liver surgery, together with equivalent or marginally superior margin negativity. Perioperative mortality, bile leak, post-hepatectomy liver failure and long-term overall survival are equivalent between platforms.^{1,2}

These advantages are, however, of modest absolute magnitude and are systematically attenuated relative to those documented in the posterosuperior segments and in major hepatectomy, consistent with a technological ceiling effect in an anatomical domain where conventional laparoscopy already performs near its theoretical optimum. They are further offset by a uniform and substantial economic penalty, by longer operative times in the majority of series, and by a modest but reproducible excess of 30-day readmission. The certainty of the evidence is low to moderate across all outcome domains, constrained by the predominance of non-randomised designs, residual confounding, era and learning-curve effects, and the availability of only a single small randomised trial powered for a patient-reported endpoint.^{1,19,29,30}

The clinically defensible conclusion is therefore one of qualified, patient-selective superiority rather than categorical platform preference. Neither approach should be regarded as obsolete for anterior-segment hepatectomy. Laparoscopy remains an appropriate and cost-efficient default for straightforward anterolateral resection, while the robotic platform is best justified where the anterior-segment operation carries features that erode the laparoscopic advantage — cirrhosis with portal hypertension, the reoperative abdomen, bulky or centrally located segment IVb/V lesions requiring anatomical resection, proximity to major intrahepatic vasculature, and institutional programme development towards complex minimally invasive hepatectomy.^{17,39,43}

Recommendations

For clinical practice. (1) Platform selection for anterior-segment resection should be individualised on the basis of patient hepatic reserve, lesion characteristics, prior abdominal surgery

and institutional expertise rather than applied categorically. (2) Robotic assistance should be prioritised for anterolateral resections in patients with compensated cirrhosis or portal hypertension, in whom reductions in blood loss and inflow occlusion duration carry disproportionate physiological benefit. (3) Laparoscopy should remain the default for uncomplicated left lateral sectionectomy in the non-cirrhotic liver, where no perioperative gain is demonstrable and the economic penalty is unmitigated. (4) Both approaches should be conducted within high-volume specialist hepatobiliary units with structured proctorship, given that all supporting evidence derives from such settings. (5) Institutions must maintain adequate individual surgeon volume on whichever platform is adopted, since volume dilution across two platforms may abolish the advantages of both.

For research. (1) A multicentre randomised controlled trial restricted to anterolateral-segment resection, powered on open conversion or textbook outcome with cost-effectiveness and patient-reported outcomes as co-primary endpoints, is the single highest research priority. (2) Weighted randomisation ratios should be employed to preserve robotic case volume above proficiency thresholds. (3) Discharge criteria must be prospectively standardised to resolve the readmission signal. (4) Segment IVb, V and VI resections, and anatomical versus non-anatomical anterolateral resection, warrant dedicated analysis. (5) Uniform adoption of ISGLS definitions, the Clavien–Dindo and Comprehensive Complication Index taxonomies, the IWATE difficulty score and the textbook outcome composite should be mandated in all future comparative reports to enable valid quantitative pooling.

For health policy and education. (1) Investment decisions regarding robotic capacity should be evaluated against the full institutional case-mix across surgical specialties rather than against liver surgery alone, since capital amortisation across a broad portfolio is the principal determinant of per-case cost. (2) In resource-constrained settings, the demonstrated cost-efficiency of laparoscopy for straightforward anterolateral resection should be explicitly recognised in procurement and clinical pathway design. (3) Training curricula should exploit the shorter proficiency curve of robotic hepatectomy and its role as a bridge to complex minimally invasive liver surgery, with formal credentialling anchored to validated difficulty scoring rather than to raw case counts.

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