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Advances and Current Evidence in Minimally Invasive Hepatobiliary Surgery: A Review of Laparoscopic and Robotic Approaches

[1] Xudayberganova Nasiba Shakirovna
[2] Erkinov Javohir Abdulhamid ugli
[3] Irisov Ortiqali Tulayevich
[4] Mardonov Jamshid Normurotovich
[5] Khalikulov Khusan Gazihanovich

[1] PhD, Associate Professor, Department of Surgery and Transplantology, Tashkent State Medical University, Uzbekistan
[2] Master's degree, Department of Surgery and Transplantology, Tashkent State Medical University, Uzbekistan
[3] DSc, Associate Professor, Department of Surgery and Transplantology, Tashkent State Medical University, Uzbekistan
[4] PhD, Associate Professor, Department of Surgery and Transplantology, Tashkent State Medical University, Uzbekistan
[5] PhD, Associate Professor, Department of Surgery and Transplantology, Tashkent State Medical University, Uzbekistan

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Abstract

The field of hepatobiliary surgery is undergoing a significant paradigm shift, transitioning from conventional open approaches toward increasingly sophisticated minimally invasive techniques, including laparoscopic and robotic surgery. This review critically examines the contemporary evidence supporting minimally invasive liver surgery (MILS), tracing its progression from minor resections to complex oncologic procedures and applications in liver transplantation. Current data consistently demonstrate that laparoscopic and robotic liver resections are associated with improved short-term perioperative outcomes compared with open surgery. These benefits include reduced intraoperative blood loss, lower transfusion requirements, and shorter lengths of hospital stay. Importantly, in both primary and secondary hepatic malignancies—such as hepatocellular carcinoma and colorectal liver metastases—MILS achieves oncological outcomes equivalent to open surgery, with comparable rates of margin negativity, recurrence, and long-term survival. The advent of robotic-assisted surgery represents a further evolution in MILS, addressing several technical constraints of conventional laparoscopy. Enhanced three-dimensional visualization, tremor suppression, and articulated instrumentation facilitate precise dissection and suturing, particularly in technically demanding hepatectomies, including resections of posterosuperior segments and complex staged procedures such as associating liver partition and portal vein ligation for staged hepatectomy (ALPPS). These advantages may translate into reduced operative difficulty and physiological stress in selected patients. Despite its growing adoption and recognition as a standard approach in high-volume centers, the widespread implementation of MILS remains limited by cost considerations, unequal access to advanced technology, and a steep learning curve. This review concludes that while minimally invasive liver surgery is firmly established, further high-quality randomized controlled trials and standardized training pathways are essential to optimize outcomes, ensure oncological rigor, and promote safe global dissemination of these techniques.

Keywords: Minimally invasive liver surgery; Laparoscopic hepatectomy; Robotic liver surgery; Hepatobiliary malignancy; Oncological outcomes; ALPPS; Surgical innovation.

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1. Introduction

Over the past three decades, surgical practice has undergone a substantial shift toward minimally invasive approaches, driven by the goal of reducing surgical trauma while maintaining clinical efficacy. These techniques are consistently associated with decreased postoperative pain, shorter hospital stays, and improved cosmetic outcomes. In hepatobiliary surgery, this transition began with the first laparoscopic liver resection in 1992 and was further advanced by the introduction of robotic surgical platforms in 2003 [4,11]. Initially confined to minor resections for benign disease, minimally invasive techniques have progressively expanded to encompass major hepatectomies and complex oncological procedures [4,11]. Surgical resection remains the primary curative treatment for hepatocellular carcinoma (HCC) and colorectal liver metastases (CRLM). A growing body of evidence demonstrates that minimally invasive liver surgery (MILS) achieves oncological outcomes comparable to those of open hepatectomy, including equivalent rates of margin-negative resection and long-term survival [2,10]. In addition to maintaining oncological integrity, laparoscopic and robotic approaches provide significant perioperative advantages, such as reduced intraoperative blood loss, lower transfusion requirements, and decreased rates of major postoperative complications [3,5,10].

The adoption of robotic-assisted liver surgery has further broadened the applicability of minimally invasive techniques by overcoming several technical limitations of conventional laparoscopy. Enhanced three-dimensional visualization, tremor suppression, and articulated instruments allow for precise dissection and suturing in anatomically complex regions [7]. These advantages are particularly relevant for resections involving the posterosuperior liver segments and for technically demanding procedures such as associating liver partition and portal vein ligation for staged hepatectomy (ALPPS) and living donor liver transplantation [7,9].

Despite these advances, the dissemination of minimally invasive hepatobiliary surgery remains uneven. Barriers include high capital and maintenance costs, a steep learning curve, and the lack of standardized, competency-based training programs [1]. This review aims to critically synthesize the current evidence to define the safety, efficacy, and evolving role of minimally invasive techniques in the contemporary management of hepatobiliary diseases.

2. Methods

Search Strategy and Study Selection: A comprehensive literature search was conducted across PubMed, Embase, and the Cochrane Library to identify relevant studies evaluating minimally invasive hepatobiliary surgery [3,9]. Both controlled vocabulary terms and free-text keywords were used, including laparoscopy, robotic surgery, hepatectomy, associating liver partition and portal vein ligation for staged hepatectomy (ALPPS), hepatocellular carcinoma, and cholangiocarcinoma [4,3,9]. Eligible studies included original comparative studies, systematic reviews, and meta-analyses published between 1992 and 2024 that evaluated laparoscopic, robotic, or open hepatectomy [4]. Studies with fewer than five patients were excluded when specified to reduce the risk of bias associated with small sample sizes and inflated effect estimates [3].

Data Extraction and Outcome Measures: Data extraction focused on patient demographics, operative variables, and postoperative outcomes [3,5]. Outcomes were grouped into three predefined categories:

- **Perioperative outcomes**, including operative time, estimated blood loss, transfusion requirements, and use of the Pringle maneuver [3,5,10].
- **Short-term postoperative outcomes**, including length of hospital stay, overall morbidity, major complications, and 90-day mortality. When reported, postoperative complications were classified using the Clavien–Dindo grading system [8,3,5].
- **Oncological outcomes**, including rates of R0 resection, tumor recurrence, disease-free survival (DFS), and overall survival (OS) [2,3,10].

Quality Assessment: The methodological quality of non-randomized studies was assessed using the Newcastle–Ottawa Scale (NOS). The overall certainty of evidence for key outcomes, including morbidity and mortality, was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE)

framework [3].

Statistical Synthesis and Analysis: Where appropriate, data were synthesized using meta-analytic techniques. Dichotomous outcomes were reported as odds ratios (OR) or risk ratios (RR), while continuous variables were expressed as mean differences (MD) [3,9]. To address confounding and selection bias inherent in observational studies, several included analyses employed propensity score matching (PSM) to balance baseline patient and disease characteristics between comparison groups [4,2,10]. Additionally, E-values were calculated in selected studies to estimate the potential impact of unmeasured confounding on observed survival outcomes [2].

3. Results

Perioperative and Short-Term Clinical Outcomes: Across the included studies, minimally invasive liver surgery (MILS) demonstrated consistent perioperative advantages compared with open hepatectomy. In elderly patients (≥70 years) undergoing resection for hepatocellular carcinoma (HCC), MILS was associated with significantly lower median intraoperative blood loss (200 mL vs. 440 mL, $p < 0.001$), shorter postoperative hospital stay (5 vs. 7 days, $p < 0.001$), and reduced overall morbidity (26.4% vs. 43.6%) [10]. Comparable benefits were observed in octogenarian patients, in whom the median length of stay was reduced from 8 days following open surgery to 6 days after minimally invasive resection [10]. In patients with cholangiocarcinoma, systematic reviews reported improved short-term outcomes with minimally invasive approaches, including shorter hospital stays (8.0 vs. 10.9 days), lower rates of major postoperative morbidity (13.3% vs. 18.8%), and reduced 90-day mortality (3.0% vs. 4.5%) compared with open hepatectomy [3]. At the health-system level, expansion of minimally invasive hepatobiliary programs was associated with a significant reduction in readmission rates (21% vs. 37%) and shorter length of hospital stay (4 vs. 7 days) [5]. In the setting of benign liver disease, minimally invasive techniques were also associated with significantly lower estimated blood loss compared with open surgery (200 mL vs. 600 mL) [8].

Oncological Safety and Long-Term Survival: Oncological outcomes following MILS were comparable to, and in selected cohorts superior to, those observed after open hepatectomy. In patients with early to intermediate-stage HCC, minimally invasive hepatectomy was associated with improved overall survival (hazard ratio 0.62) and higher 5-year overall survival rates (84.0% vs. 78.5%) [2]. For cholangiocarcinoma, minimally invasive approaches achieved higher rates of margin-negative (R0) resection compared with open surgery (90.4% vs. 81.4%), alongside improved 3-year disease-free survival (49.9% vs. 38.5%) [3]. In the treatment of recurrent liver tumors, laparoscopic resection resulted in significantly higher R0 resection rates than open surgery (92% vs. 81.2%) [3].

Robotic Versus Laparoscopic Approaches: Comparative analyses highlighted several advantages of robotic liver resection (RLR) over laparoscopic liver resection (LLR). In a large international cohort of over 10,000 patients, RLR was associated with higher R0 resection rates (89.8% vs. 84.7%), shorter operative times, and a significantly lower conversion rate to open surgery (2.7% vs. 8.8%) [7]. In anatomically complex procedures such as right posterior sectionectomy, robotic assistance resulted in markedly reduced intraoperative blood loss (40 mL vs. 200 mL) and lower rates of transfusion and conversion compared with laparoscopy [7]. Additionally, the robotic platform demonstrated a shorter learning curve, with surgical proficiency achieved after approximately 20 cases compared with more than 40 cases for laparoscopic liver resection [7].

Advanced and Specialized Procedures: The application of minimally invasive techniques to highly complex procedures yielded favorable outcomes. In patients undergoing associating liver partition and portal vein ligation for staged hepatectomy (ALPPS), minimally invasive approaches significantly reduced 90-day mortality (risk ratio 0.48), shortened total hospital stay by a mean of 8 days, and achieved higher rates of R0 resection compared with open ALPPS [9]. In the management of hepatobiliary cysts, laparoscopic approaches demonstrated high technical success rates (91.7%), lower recurrence rates, and durable symptom resolution compared with percutaneous aspiration techniques [8].

Table 1. Summary of key outcomes: minimally invasive vs open liver surgery

Clinical Context	Outcome	Minimally Invasive Surgery	Open Surgery	Key Finding
Elderly HCC (≥70 yrs)	Blood loss	200 mL	440 mL	Lower with MILS
	Hospital stay	5 days	7 days	Shorter stay
	Morbidity	26.4%	43.6%	Reduced complications
Cholangiocarcinoma	R0 resection	90.4%	81.4%	Higher margin-negative rate
	90-day mortality	3.0%	4.5%	Lower mortality
Early–Intermediate HCC	5-year overall survival	84.0%	78.5%	Improved survival
Robotic vs Laparoscopic	Conversion rate	2.7%	8.8%	Lower with robotics
ALPPS	90-day mortality	Reduced (RR 0.48)	—	Lower mortality

4. Discussion

The transition from open hepatectomy to minimally invasive liver surgery (MILS) represents a significant advancement in the surgical management of hepatobiliary diseases. Accumulating evidence demonstrates that reduced abdominal wall trauma and limited intraoperative organ manipulation attenuate the postoperative inflammatory response, resulting in improved perioperative recovery. Across multiple studies, MILS has consistently been associated with reduced intraoperative blood loss, lower transfusion requirements, decreased postoperative morbidity, and shorter hospital stays compared with open surgery [3,5,10]. Importantly, these advantages are achieved without compromising operative safety.

A critical concern in the adoption of minimally invasive approaches has been the preservation of oncological integrity. Current evidence indicates that MILS provides oncological outcomes comparable to open hepatectomy for both primary and secondary liver malignancies. Equivalent or improved rates of R0 resection, disease-free survival, and overall survival have been reported for hepatocellular carcinoma and cholangiocarcinoma, supporting the

oncological validity of minimally invasive techniques when applied in appropriately selected patients and high-volume centers [2,3,10].

The introduction of robotic-assisted liver surgery has further extended the applicability of minimally invasive techniques by addressing several inherent limitations of conventional laparoscopy. Enhanced three-dimensional visualization, tremor filtration, and articulated instruments facilitate precise dissection and suturing, particularly in anatomically complex resections and posterior segmentectomies [7]. These technological advantages are reflected in lower conversion rates to open surgery and improved technical performance in complex procedures.

Despite these advancements, several barriers continue to limit the widespread adoption of minimally invasive hepatobiliary surgery. High acquisition and maintenance costs, restricted access to advanced robotic platforms, and the absence of standardized, competency-based training pathways remain significant challenges [1,7]. Furthermore, although robotic surgery may reduce conversion rates and shorten learning curves, its cost-effectiveness requires further validation, particularly in healthcare systems with limited resources.

Overall, while minimally invasive liver surgery has become an integral component of contemporary hepatobiliary practice, continued efforts are necessary to optimize training, improve technological accessibility, and strengthen the evidence base through well-designed prospective studies.

5. Conclusion

Minimally invasive hepatobiliary surgery has evolved from a technically selective approach to a robust and evidence-supported standard of care in appropriately selected patients. Accumulating data from large multicenter studies, systematic reviews, and propensity-matched analyses consistently demonstrate that laparoscopic and robotic liver resections confer significant perioperative advantages over open surgery, including reduced blood loss, lower transfusion requirements, decreased postoperative morbidity, and shorter hospital stays. These short-term benefits translate into accelerated recovery without compromising surgical safety.

Crucially, contemporary evidence confirms that minimally invasive liver surgery maintains oncological integrity across a broad spectrum of hepatic malignancies. Comparable—and in some cohorts superior—rates of R0 resection, disease-free survival, and overall survival have been reported for hepatocellular carcinoma, colorectal liver metastases, and cholangiocarcinoma. These findings support the oncological equivalence of minimally invasive approaches when performed in high-volume centers with appropriate expertise and patient selection.

The introduction of robotic-assisted platforms represents a further technological advancement, expanding the feasibility of minimally invasive surgery to anatomically complex resections and high-risk procedures such as posterosuperior segmentectomy and ALPPS. Enhanced visualization, improved dexterity, and reduced conversion rates position robotic surgery as a valuable adjunct to conventional laparoscopy, particularly in technically demanding cases and during program expansion phases.

Despite these advances, widespread adoption remains constrained by high capital costs, unequal access to technology, and the absence of standardized, competency-based training pathways. Furthermore, the current evidence base is largely derived from retrospective and observational studies, underscoring the need for well-designed randomized controlled trials to validate long-term oncological outcomes, cost-effectiveness, and quality-of-life measures.

In conclusion, minimally invasive hepatobiliary surgery is a safe, effective, and oncologically sound approach that continues to redefine modern liver surgery. Future progress will depend on structured training, technological refinement, and rigorous prospective research to ensure equitable implementation and optimal patient outcomes worldwide.

6. Declarations

This study is a systematic review and did not involve direct research on human participants or animals; therefore, ethics approval and consent to participate are not applicable. No individual patient data are included, and consent for publication is not required. All data generated or analyzed during this study are provided within this article and its references. The authors declare no competing interests. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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