Annals of Surgery Publish Ahead of Print
DOI:10.1097/SLA.0000000000007123

Learning Curves and Complexity Evolution in Robotic Liver Surgery: An International Multicenter Study with Comparison to Global Benchmark Outcomes

Christoph Kuemmerli, MD, MSc[°1], Gabriel F. Hess, MD[°1], Adrian T. Billeter, MD, PhD[°], Cristiano Guidetti, MD[$], Fabrizio di Benedetto, MD[$], Roberta Odorizzi, MD[£], Iswanto Sucandy, MD[£], Noa L.E. Aegerter, MD[°], Caroline Berchtold, MD[°], Lorenzo Bernardi, MD[+], Alessandra Cristaudi, MD[+], Emanuele Balzano, MD[*], Davide Ghinolfi, MD[*], Ye-Xin Koh, MD[§], Brian Goh, MD[§], Charles Chung-Wei Lin, MD[ς], Daisuke Fukumori, MD[&], Christoph Tschuor, MD, PhD[&], Sanjay Pandanaboyana, MD[°°], Steve White, MD[°°], Philipp von Kroge, MD[$$], Asmus Heumann, MD[$$], Celine De Meyere, MD[££], Mathieu D'Hondt, MD[££], Fabian Haak, MD[++], Daniel Seehofer, MD[++], Stefan Stättner, MD[**,§§], Florian Primavesi, MD[§§,ςς], Haluk Morgül, MD[&&], Andreas Andreou, MD[&&], Francesca Ratti, MD[°°°], Ignacio Sánchez Esquer, MD[$$$], Ricardo Robles-Campos, MD[$$$], Victor Lopez-Lopez, MD[$$$], Taiga Wakabayashi, MD[£££], Go Wakabayashi, MD[£££], Martina Nebbia, MD[+++], Stefan Gilg, MD[+++], Emrullah Birgin, MD[***], Nuh N. Rahbari, MD[***], Stefano Ferretti, MD[§§§], Giuseppe Maria Ettore, MD[§§§], Mirhasan Rahimli, MD[&&&], Roland Croner, MD[&&&], Yawen Dong, MD[ςςς], Patrick P. Starlinger, MD, PhD[ςςς], Felix Nickel, MD[$$], Beat P. Müller, MD[°], Philip C. Müller, MD[°]

[1] C. Kuemmerli and G.F. Hess shared first authorship

° Department of Surgery, Clarunis University Digestive Health Care Center, University Hospital Basel, Basel, Switzerland

$ Hepato-Pancreato-Biliary Surgery and Liver Transplantation Unit, University of Modena and Reggio Emilia, Modena, Italy.
£ Foregut and HPB Division, Digestive Health Institute Advent Health Tampa, 3000 Medical Park Drive, Suite #500, Tampa, FL, USA.
+ Department of Surgery, Lugano Regional Hospital, Ente Ospedaliero Cantonale (EOC), Via Tesserete 46, 6900, Lugano, Switzerland.
* Division of Hepatobiliary Surgery and Liver Transplantation, Azienda Ospedaliera Universitaria Pisana (AOUP), University of Pisa, Via Paradisa, 2, 56124, Pisa, Italy.
§ Hepato-pancreato-biliary and Transplant Surgery, Singapore General Hospital
ç Ircad-TAIWAN Show Chwan Memorial Cancer Center, Changhua Show Chwan Memorial Hospital
& Department of Surgery and Transplantation, Rigshospitalet, Copenhagen University Hospital, Copenhagen, Denmark.
°° HPB Surgery, Freeman Hospital, Newcastle, UK
$$ Klinik für Allgemein, Viszeral und Thoraxchirurgie Universitätsklinikum Hamburg-Eppendorf
££ Department of Digestive and Hepatobiliary/Pancreatic Surgery AZ Groeninge Hospital Kortrijk President Kennedylaan 4 8500 Kortrijk, Belgium
++ Department of Visceral, Transplant, Thoracic and Vascular Surgery, University Hospital of Leipzig, Leipzig, Germany
** Department of General and Visceral Surgery, Academic Hepatobiliary Centre, Kepler University Hospital, Linz, Austria
§§ Department of General, Visceral and Vascular Surgery, Salzkammergut Klinikum Vöcklabruck, Austria;
çç Department of Visceral, Transplant and Thoracic Surgery, Medical University of Innsbruck, Innsbruck, Austria
&& Universitätsklinikum Münster (UKM) Klinik für Allgemein-, Viszeral- und Transplantationschirurgie
°°° Hepatobiliary Surgery Division, San Raffaele Hospital, GSD Group, Via Olgettina 60, 20132, Milan, Italy

$$$ Department of Surgery and Transplantation, Virgen de la Arrixaca Clinic and University Hospital, Murcian Institute of Biosanitary Research (IMIB)
£££ Center for Advanced Treatment of Hepatobiliary and Pancreatic Diseases, Ageo Central General Hospital, Ageo, Saitama, Japan.
+++ Division of Surgery and Oncology, Department of Clinical Science, Intervention and Technology, Karolinska Institutet, Karolinska University Hospital, Stockholm, Sweden
*** Department of General and Visceral Surgery, Ulm University Hospital, Ulm, Germany
§§§ Department of General Surgery and Transplantation Unit, San Camillo Forlanini Hospital, Rome, Italy
ççç Department of Surgery, Division of Hepatobiliary and Pancreas Surgery, Mayo Clinic, Rochester, MN, USA;
&&& Klinik für Allgemein-, Viszeral-, Gefäß- und Transplantationschirurgie, Universitätsklinikum Magdeburg, Magdeburg, Deutschland.

Corresponding Author

Philip C. Müller, MD
Department of Surgery, Clarunis University Digestive Health Care Center, University Hospital Basel
Spitalstrasse 21
4031 Basel
Switzerland
e-mail: philip.mueller@clarunis.ch

Author contributions
PCM: conception and design, interpretation of data, creation of figures, drafting of article, and final approval. CK: conception and design, acquisition of data, statistical analysis, interpretation of data, creation of figures, drafting of article, and final approval. GFH: conception and design, acquisition of data, drafting of article, and final approval. ATB, CG, FDB, RO, IS, NLEA, CB, LB, AC, EB, DG, YXK, BG, CCWL, DF, CT SP, SW, PvK, AH, CDM, MDH, FH, DS, SS, FP, HM, AA, FR, ISE, RRC, VLL, TW, GW, MN, SG, EB, NNR SF, GME, MR, RC, YD, PPS, FN, BPM: conception and design, interpretation of data, critical revision of the article, and final approval. Data supporting this study's findings are available on request from the corresponding author.

Conflicts of Interest: FP shares of Intuitive Surgical Inc., Sunnyvale, CA, USA. There are no other conflicts of interest to declare. No grants and financial support were received for this study.

Short running head: Learning Curves in Robotic Liver Surgery

Abstract

Objective

To evaluate the institutional learning curve of robotic liver resection (RLR), its association with surgical complexity and outcomes in an international multicenter cohort.

Summary of Background Data

RLR is increasingly adopted worldwide, but the dynamics of the learning process and its impact on surgical outcomes remain poorly defined.

Methods

This international, multicenter, retrospective cohort study included consecutive patients who underwent RLR between 06/2013 and 12/2024 across 22 expert centers. Based on the first 150 cases at each center, three phases were used to define the learning curve: operative time for competency, major complications for proficiency, and textbook outcome for mastery. Risk-adjusted generalized additive models were used to assess the learning process. Benchmark performance was compared to international reference values.

Results

Among 2,331 patients, the most common indications were hepatocellular carcinoma (36%), benign lesions (23%) and colorectal liver metastases (21%). Operative time decreased after achieving competency (case #62), from 240 to 220 minutes ($P<0.001$). Major morbidity reached a plateau during the proficiency phase (cases #63–138; 9% vs. 11%, $P=0.144$), while progression to mastery (cases #139–150) was associated with a higher rate of textbook outcome (76% vs. 87%, $P=0.021$). In contrast, conversion (5.1% vs. 4.9% vs. 2%), bile leak (4.0% vs. 5.3% vs. 3.8%), and 90-day mortality (0.7% vs. 0.9% vs. 0.9%) remained low and stable across all learning phases. Importantly, benchmark criteria for operative time, hospital stay, and textbook outcome were met across all complexity groups, including during the early learning phase.

Conclusions

Robotic liver surgery shows progressive outcome improvement with early achievement of benchmark-level results and stable performance across increasing complexity. These findings indicate that, in experienced centers, RLR can be safely implemented and integrated into clinical practice, supporting its key role in modern hepatobiliary surgery.

Key words: Robotic Liver Resection; Learning Curve; Surgical Complexity; Minimally Invasive Hepatectomy; Benchmark Outcomes

Introduction

Minimally invasive liver surgery (MILS) has progressively replaced open liver surgery, supported by robust evidence demonstrating reduced morbidity, lower rates of postoperative liver failure, and faster recovery(1–9). Recent consensus statements have established recommendations for the safe implementation of robotic liver resection (RLR)(1).

The transition from open to minimally invasive approaches, referred to as the learning curve, appears shorter for robotic than for laparoscopic liver surgery(10). Nevertheless, in complex hepatectomies involving large tumors or proximity to major vascular structures, approximately 50–60 of such difficult resections are required to achieve mastery (1,11,12). Institutional pathways toward RLR vary; while some centers transitioned sequentially from open to laparoscopic and then to robotic surgery, others adopted RLR directly. As a result, learning trajectories are heterogeneous and influenced by institutional experience, availability of robotic resources, case complexity, and team composition. A structured three-phase model (competency, proficiency and mastery) has recently been proposed to standardize the learning process for MILS (13).

A comprehensive evaluation of the RLR learning curve requires the inclusion of all consecutive cases, as all contribute to learning and cannot be separated, to account for the multitude of influencing factors(13–15). Understanding this process is critical for ensuring safe implementation, guiding structured training and proctoring, and facilitating broader adoption of RLR. Therefore, the aim of this study was to evaluate the learning curve of robotic liver surgery, independent of the extent of resection, within a large, retrospective, international multicenter cohort(16).

Methods

Study Design

This international, multicenter study was conducted in accordance with the STROBE guidelines(17). Twenty-two high-volume hepatobiliary centers across three continents participated. Eligible institutions performed more than 80 liver resections annually and had prior experience with at least 70 RLR. Consecutive patients undergoing RLR between June 2013 and December 2024 were included. The study was approved by the Ethics Committee of Northwestern Switzerland (EKNZ, BASEC-ID 2024-01787).

Inclusion and Exclusion Criteria

From the first institutional RLR, all consecutive patients undergoing robotic liver resection for benign or malignant indications were included. Combined resections of any difficulty were analyzed to reflect a realistic learning trajectory. Patients undergoing procedures without liver parenchymal transection (e.g. cyst deroofing) were excluded.

Data Collection and Outcomes

Data was extracted from prospectively maintained institutional databases and anonymized in a secure management platform. Collected parameters included demographic data, underlying disease, tumor characteristics, prior treatments, surgical approach, extent of resection classified according to the Brisbane classification (18) and a modified IWATE score categorized as low (1–3), intermediate (4–6), advanced (7–9), or expert (10–11)(5,19).

Perioperative outcomes included operative time, conversion rates, morbidity and mortality, assessed according to the Clavien–Dindo classification and the Comprehensive

Complication Index (CCI) up to 90 days postoperatively(20–23). Major complications were defined as Clavien–Dindo grade ≥ IIIa. Liver-specific complications were categorized according to the International Study Group of Liver Surgery (ISGLS) definitions for post-hepatectomy liver failure (PHLF), post-hepatectomy hemorrhage (PHH), and bile leak (BL) (24–26). Reoperation rate, length of intensive care unit (ICU) stay, length of hospital stay (LOS) and 90-day readmission were analyzed. Textbook outcome was defined according to Görgec et al.(27).

Institutional variables included annual caseloads of open, laparoscopic, and robotic liver resections. Surgeon-specific variables included overall and minimally invasive liver surgery (MILS) experience. MILS specific training was defined as any form of external proctoring or MILS specific fellowship.

Three phases of the learning curve

The competency learning curve was based on operative time, the proficiency learning curve on major complications, and the mastery learning curve on textbook outcome, as previously proposed by Kuemmerli et al. (13,28)

Benchmark Comparison

Surgical outcomes were compared to the multinational benchmark values for robotic liver surgery, which were developed in low-risk patients. The low-risk, benchmark cohort included patients with an American Society of Anesthesiology (ASA) classification ≤2, absence of major comorbidities (recent myocardial infarction, advanced renal or obstructive pulmonary disease), absence of portal hypertension (>10 mm Hg), and Child-Pugh A liver function. According to the previous benchmark publication on robotic liver surgery, surgical complexity was classified based on the IWATE score in low (0-3), intermediate (4-6), and high (7-12) surgical complexity (15).

Statistical Analysis

Continuous variables are reported as means with standard deviation (SD) or medians with interquartile range (IQR) as appropriate. Categorical variables are presented as frequencies and percentages. Between-group comparisons were performed using the Student's t-test or Mann–Whitney U test for continuous variables, and the chi-square or Fisher's exact test for categorical variables, depending on sample size and data distribution. Analyses were performed using R version 4.2.3 (R Foundation for Statistical Computing, Vienna, Austria).

Learning Curve Analysis

The learning curve analysis included the first 150 institutional RLRs. Adjusted generalised additive models (GAM) were fit by using smoothing terms for procedures and allowed penalized center-specific deviations from the global learning curve. Operative time was right-skewed and followed a gamma distribution; a log link was used. Restricted maximum likelihood was used to estimate smoothing parameters. Derivatives of the smooth function were computed to quantify the rate of change in the outcome across the learning trajectory. Derivatives were obtained from the fitted GAM using finite difference approximations. Positive values indicate improvement, negative values indicate slowing, and values near zero indicate periods of minimal change. Confidence intervals around the derivatives were used to identify intervals where the rate of change differed significantly from zero. (8)

Results

Patient Demographics

Twenty-two centers from twelve countries contributed 2,331 patients, of whom 1,348 (57.8%) were male. The median age of these patients was 64 (IQR 55-73) years, and their median body mass index was 26 (IQR 23-29) kg/m^2. The most frequent indications for RLR were hepatocellular carcinoma (HCC) with 843 cases (36.2%), followed by 528 benign lesions (22.7%), 494 patients with colorectal liver metastases (CRLM) (21.2%), and 208 patients with cholangiocarcinoma (CC) (8.9%). The baseline characteristics of the population are shown in **Table 1**.

According to the IWATE surgical complexity, 520 (22.3%) were low, 918 (39.4%) intermediate, 620 (26.6%) advanced, and 273 (11.7%) expert resections. The most frequently performed procedure was atypical minor resection in 807 patients (37.0%), followed by 518 technically major cases (23.8%), 361 major (16.6%), and 228 left lateral resections (10.5%).

Institution- and surgeon-specific Characteristics

Surgeons in 15 of 22 centers had undergone specific MILS training (71.4%), and 19 centers had substantial prior experience in laparoscopic liver surgery (90.5%). The annual institutional volume of liver resections was 135 cases (IQR 100-200), with 55 robotic liver resections (IQR 36-78). The annual volume per surgeon was 50 cases (IQR 40-100) with 30 (IQR 17-39) robotic liver resections.

Evolution of complexity and outcomes along the learning curve

Along the learning curve, the proportions of low-difficulty and expert cases remained stable. However, there was an expansion of advanced cases rising from 23% during the first 50 cases to 31% from cases 100-150 ($P<0.001$) (**Figure 1).** The risk-adjusted learning curve analysis of the overall cohort for operative time, BL, textbook outcome, and major complications is shown in **Figure 2.**

Learning curve

Competency

The analysis of operative time revealed a cutoff for competency at 62 procedures. Operative time decreased from 240 minutes (171-340) before this point to 221 minutes (150-325) thereafter ($p=0.001$). The rates of conversion (5.1% vs. 5.1%; $p=1.000$), BL (2.5% vs. 3.3%; $p=0.858$) and R1 resections (8.3% vs. 7.3%; $p=0.479$) did not significantly change before and after reaching competency. The rate of major complications (9.4% vs. 11.6%; $p=0.133$) was similar and LOS decreased (5 days (3-7) vs. 4 days (3-7); $p=0.002$) after reaching competency (**Table 1**).

Proficiency and Mastery

The risk-adjusted evaluation of major morbidity revealed a cutoff for proficiency at 138 procedures reaching mastery after this cutoff. Major complications reached the plateau phase (11.6% vs 10.4%; $p=0.825$). Operative time (221 (IQR (150-325)) vs 210 (IQR 154-350) minutes, $p=0.852$), conversion rate (5.2% vs. 2.0%; $p=0.370$), BL (3.3% vs. 1.9%; $p=0.455$) did not differ between proficiency and mastery. However, patients with a textbook outcome (76.2%

vs 87.0%; p=0.021) and R1 resections (7.3% vs. 0.0%; p=0.027) improved significantly. (**Table 1**)

Learning curve according to surgical complexity

Within the different surgical complexity groups, no differences in intraoperative outcomes, such as blood loss, conversion, and R1 resection rate, were observed between the competency, proficiency and mastery phases of the learning curve (**Table 2)**. In low, intermediate and high IWATE cases, the operative time decreased from the competency to the proficiency phase, while from proficiency to mastery, operative time remained stable throughout all complexity groups.

Postoperative complications such as BL, PHLF, reinterventions and reoperations were similar between the competency, proficiency and mastery phases in all three surgical complexity groups. The rate of patients achieving a textbook outcome was similar in the low and intermediate complexity groups along all three phases of the learning curve. Interestingly, the rise of patients achieving textbook outcome was mainly driven by the high complexity group (74.1% vs. 70.3% vs. 90.7%).

Comparison with international benchmark values

Within an unselected cohort of low-risk (benchmark) and high-risk (non-benchmark) patients, international reference values were met through all three phases of the learning curve **(Table 2**) for operative time for all degrees of surgical complexity (Competency: Low IWATE: 186min, benchmark cut-off (BM) ≤234min; Intermediate IWATE: 222min, BM ≤354min; High

IWATE: 305min, BM ≤357min). The reference values for conversion were met through all three phases of the learning curve for more complex procedures (Competency: Intermediate IWATE: 3.8% BM ≤3.5%; High IWATE: 7.7% BM ≤9.4%); however, not for low-complexity cases (Competency Low IWATE: 4.1% BM ≤0%). Likewise, the benchmark values for the R1 rate were met for more complex procedures (Competency: Intermediate IWATE: 4.7% BM ≤5.7%; High IWATE: 11.2% BM ≤14.1%), but not for low-complexity cases (Competency: Low IWATE: 8.6% BM ≤5.7%).

Summarizing the postoperative course, international reference values were met during the early learning curve for patients achieving textbook outcomes across all degrees of complexity (Competency: Low IWATE: 83.8%, BM ≥84.2%; Intermediate IWATE: 86.9%, BM ≥76.2%; High IWATE: 74.1%, BM ≥67.9%). However, benchmark values for major complications were not met for any complexity group during competency (Competency: Low IWATE: 7.5%, BM ≤2.2%; Intermediate IWATE: 9.8%, BM ≤5.9%; High IWATE: 14.2%, BM ≤9.5%) and proficiency phase (Proficiency: Low IWATE: 7.0%, BM ≤2.2%; Intermediate IWATE: 9.8%, BM ≤5.9%; High IWATE: 15.6%, BM ≤9.5%). 90-day mortality benchmarks were 0% for all complexity groups and a mortality of 0.2%-1.1% was reported for all complexity groups (**Table 2**).

Discussion

In this large, international, multicenter study of more than 2,300 robotic liver resections performed at 22 expert centers, we provide a comprehensive evaluation of the learning curve in robotic hepatectomy establishing a risk-adjusted three-phase model of competency, proficiency, and mastery. The following principal findings should be noted: First, while case complexity increased throughout the learning curve, surgical outcomes showed clinically relevant improvements along this process. Reaching competency (case #62) was associated with a decrease in operative time from 240 to 221 minutes, during proficiency (case #63-138) major complications plateaued and mastery (case #139-150) was associated with an increased rate of patients reaching textbook outcome from 76% to 87%. These changes along the learning curve were consistently shown for all complexity groups. Second, already during the initial learning phase - defined by the first 62 institutional procedures, outcomes of unselected patients were mostly within international reference values, especially for more complex resections. Together, these findings indicate that RLR can be implemented safely across expert centers, still our study suggest an extended and relevant process to finally master robotic liver surgery.

The progressive increase in advanced resections from 23% to 31% over the first 150 cases demonstrates that surgical teams expanded indications for RLR as institutional confidence, team familiarity, and robotic expertise grew. This pattern reflects a controlled, stepwise transition from minor to major hepatectomies—a hallmark of safe innovation(29,30). Unlike prior single-center reports describing a discrete inflection point at 10–50 cases(13,16,31), our findings support a continuous and longer evolution of learning across a risk-adjusted multicenter, high-volume context. The stable proportion of expert-level resections could be explained by the fact that highly complex procedures were performed laparoscopically before the transition to RLR and that MILS institutional expertise could be transferred to the robotic surgical approach (32,33). Importantly, these results were achieved in centers with substantial prior laparoscopic experience. In settings lacking such expertise, the learning process may differ considerably, potentially requiring longer adaptation phases and alternative implementation strategies.

Among intraoperative parameters, only operative time decreased relevantly in the initial learning phase, while both blood loss and conversion rate remained stable. The complete resection (R0) rate improved in the late mastery phase (7% to 0%) suggesting that technical precision still evolved as procedural complexity increased. This is in line with the evaluation of learning curves of laparoscopic liver surgery, where intraoperative outcomes typically improve with experience (13). Prior laparoscopic studies have reported learning curves of 20–35 cases for minor hepatectomies and up to 120 for major resections(13,34). The robotic platform's stability, visualization, and enhanced dexterity may substantially mitigate the learning effect. Postoperatively, overall morbidity was low, with 10% major complications and 80% of the patients achieving textbook outcomes. Importantly, rates of liver specific complications like BL, PHH and PHLF as well as reoperations were low and remained stable between the three learning phases, whereas major morbidity increased moderately until reaching the mastery phase (**Figure 2B**). This trend coincided with a rise in case complexity, indicating that more challenging procedures—rather than loss of proficiency—could account for the higher major complication rates.

While major complications and textbook outcome are not perfect surrogates to define proficiency and mastery, prior studies on surgical learning curves have consistently shown that these composite and outcome-based parameters improve later than intraoperative metrics and therefore represent more robust indicators of advanced surgical maturation. Even with the late plateau of major complications, outcomes in both benchmark and non-benchmark patients mostly met or exceeded international reference values for robotic liver surgery (15,35). Collectively, these findings reinforce that RLR is characterized by a relevant learning curve of 63-138 cases especially for patient relevant morbidity. These results mostly reflect the outcomes of RLR pioneers and the adoption of the new robotic technique in second- and third-generation MILS surgeons is still ongoing (36,37).

Especially in the intermediate and high surgical difficulty groups, early-phase RLR met international benchmark criteria (15) for operative time, conversion rate, and textbook outcome, confirming that especially centers with prior laparoscopic experience can achieve reference-level safety from the outset irrespective of patient comorbidities. However, benchmark values should be interpreted cautiously and are best understood as reference points rather than tools for credentialing, particularly in the context of evolving case-mix and learning effects. In the low difficulty group reference values were not met for conversion rate (BM ≤0%) and major complications (BM ≤2%). On one hand, this supports findings from laparoscopic liver surgery, where long learning curves and higher morbidity is common during the initial learning curve(38,39). On the other hand, near zero reference values like the ones for conversion, reoperation and 90-day mortality (all reference values ≤0% for all complexity groups) might not reflect realistic reference points. Taken together, these findings reinforce that benchmarks provide valuable context for performance assessment but should not be interpreted as absolute thresholds, particularly in heterogeneous, real-world cohorts.

Our findings provide several important lessons for clinical practice and surgical education. First, they affirm that robotic liver surgery can be safely adopted by expert centers especially with established MILS programs (40). Second, they advocate for learning models that move beyond case counts to include evolving case complexity, team dynamics, and institutional support. Third, the results underscore the importance of international collaboration and standardized surgical data reporting to monitor outcomes as robotic surgery disseminates globally at a fast pace(41). The concept of competency-based institutional expansion of RLR, integrating objective metrics such as textbook outcomes and benchmark compliance, may serve as the foundation for future credentialing and certification frameworks in robotic HPB surgery.

Some limitations should be acknowledged. First, this was a retrospective analysis, and unmeasured confounders may exist. For example, the study could not account for a change in selection criteria for RLR during the study period. Still, consecutive inclusion of all RLR cases across high-volume centers minimizes selection bias. Furthermore, surgical complexity was assessed using the IWATE classification, which, despite its limitations, currently represents the most established and widely adopted framework for stratifying procedural difficulty in minimally invasive liver surgery. However, it was not specifically developed for robotic approaches and may not fully capture platform-specific advantages or nuances of case selection. Third, because the participating centers were mostly experienced in laparoscopic liver surgery, generalizability to early-adopting or low-volume HPB hospitals and centers that directly adapt RLR from purely open surgery may be limited. Finally, over 75% of all resections were performed for oncologic indications. While the R0 resection rate is a marker for an oncologic adequate resection, long-term oncologic outcomes were beyond the scope of this analysis and warrant future evaluation.

Conclusions

In this large multicenter analysis of robotic liver surgery, the learning process was characterized by an increase in case complexity with a relevant learning curve reaching mastery after 138 cases. Benchmark-level safety was achieved from the beginning of the robotic implementation, especially for intermediate and high surgical difficulty resections. These findings indicate that, in experienced centers, RLR can be safely implemented and integrated into clinical practice, supporting its key role in modern hepatobiliary surgery.

Compliance with Ethical Standards

Conflict of interest: The authors declare that they have no conflict of interest. FP shares of Intuitive Surgical Inc., Sunnyvale, CA, USA.

Source of Funding: The study was funded by institutional means.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Approval was obtained from the ethical review board of the University of Basel (BASEC-ID 2024-01787).

Informed consent: Not applicable due to the nature of the study design**.**

References

1. Liu R, Abu Hilal M, Wakabayashi G, Han HS, Palanivelu C, Boggi U, et al. International experts consensus guidelines on robotic liver resection in 2023. World J Gastroenterol. 2023 Aug 28;29(32):4815–30. doi:10.3748/wjg.v29.i32.4815 PubMed PMID: 37701136; PubMed Central PMCID: PMC10494765.

2. Haney CM, Studier-Fischer A, Probst P, Fan C, Müller PC, Golriz M, et al. A systematic review and meta-analysis of randomized controlled trials comparing laparoscopic and open liver resection. HPB. 2021 Oct 1;23(10):1467–81. doi:10.1016/j.hpb.2021.03.006 PubMed PMID: 33820689.

3. Fretland ÅA, Dagenborg VJ, Bjørnelv GMW, Kazaryan AM, Kristiansen R, Fagerland MW, et al. Laparoscopic Versus Open Resection for Colorectal Liver Metastases: The OSLO-COMET Randomized Controlled Trial. Ann Surg. 2018 Feb;267(2):199–207. doi:10.1097/SLA.0000000000002353 PubMed PMID: 28657937.

4. Abu Hilal M, Aldrighetti L, Dagher I, Edwin B, Troisi RI, Alikhanov R, et al. The Southampton Consensus Guidelines for Laparoscopic Liver Surgery: From Indication to Implementation. Annals of Surgery. 2018 Jul;268(1):11. doi:10.1097/SLA.0000000000002524

5. Wakabayashi G, Cherqui D, Geller DA, Buell JF, Kaneko H, Han HS, et al. Recommendations for laparoscopic liver resection: a report from the second international consensus conference held in Morioka. Ann Surg. 2015 Apr;261(4):619–29. doi:10.1097/SLA.0000000000001184 PubMed PMID: 25742461.

6. Fichtinger RS, Aldrighetti LA, Abu Hilal M, Troisi RI, Sutcliffe RP, Besselink MG, et al. Laparoscopic Versus Open Hemihepatectomy: The ORANGE II PLUS Multicenter Randomized Controlled Trial. J Clin Oncol. 2024 May 20;42(15):1799–809. doi:10.1200/JCO.23.01019 PubMed PMID: 38640453; PubMed Central PMCID: PMC11107897.

7. Sijberden JP, Kuemmerli C, Ratti F, D'Hondt M, Sutcliffe RP, Troisi RI, et al. Laparoscopic versus open parenchymal preserving liver resections in the posterosuperior segments (ORANGE Segments): a multicentre, single-blind, randomised controlled trial. The Lancet Regional Health – Europe. 2025 Apr 1;51. doi:10.1016/j.lanepe.2025.101228 PubMed PMID: 40060302.

8. Abu Hilal M, Hoogteijling TJ, Edwin B, Dagher I, D'Hondt M, Marques HP, et al. The Brescia internationally validated European guidelines on minimally invasive liver surgery. Br J Surg. 2025 Jun 26;112(6):znaf113. doi:10.1093/bjs/znaf113 PubMed PMID: 40568914; PubMed Central PMCID: PMC12199258.

9. Hobeika C, Pfister M, Geller D, Tsung A, Chan ACY, Troisi RI, et al. Recommendations on Robotic Hepato-Pancreato-Biliary Surgery. The Paris Jury-Based Consensus Conference. Annals of Surgery. 2025 Jan;281(1):136. doi:10.1097/SLA.0000000000006365

10. Fukumori D, Tschuor C, Penninga L, Hillingsø J, Svendsen LB, Larsen PN. Learning curves in robot-assisted minimally invasive liver surgery at a high-volume center in Denmark: Report of the first 100 patients and review of literature. Scand J Surg. 2023 Sep 1;112(3):164–72. doi:10.1177/14574969221146003

11. Duong LM, Cai H, Shrubsole MJ, Bailey C, Idrees K, Shu XO. Outcomes of robotic-assisted liver surgery versus laparoscopic liver surgery for treatment of stage I hepatocellular carcinoma. Cancer. 2022 Feb 15;128(4):762–9. doi:10.1002/cncr.33979 PubMed PMID: 34674225; PubMed Central PMCID: PMC9248018.

12. Di Benedetto F, Magistri P, Di Sandro S, Sposito C, Oberkofler C, Brandon E, et al. Safety and Efficacy of Robotic vs Open Liver Resection for Hepatocellular Carcinoma. JAMA Surgery. 2023 Jan 1;158(1):46–54. doi:10.1001/jamasurg.2022.5697

13. Kuemmerli C, Toti JMA, Haak F, Billeter AT, Nickel F, Guidetti C, et al. Toward a Standardization of Learning Curve Assessment in Minimally Invasive Liver Surgery. Ann Surg. 2025 Feb;281(2):252–64. doi:10.1097/SLA.0000000000006417 PubMed PMID: 38920042; PubMed Central PMCID: PMC11723502.

14. Guilbaud T, Birnbaum DJ, Berdah S, Farges O, Beyer Berjot L. Learning Curve in Laparoscopic Liver Resection, Educational Value of Simulation and Training Programmes: A Systematic Review. World Journal of Surgery. 2019;43(11):1. doi:10.1007/s00268-019-05111-x

15. Li Z, Pfister M, Raptis DA, Ma Y, Yang G, Li L, et al. Novel Benchmark for Robotic Liver Resection – Bridging Tradition with Innovation. Annals of Surgery. 10.1097/SLA.0000000000006759. doi:10.1097/SLA.0000000000006759

16. Dugan MM, Christodoulou M, Ross SB, Pattilachan T, Rosemurgy A, Sucandy I. Learning curve analysis after 500 robotic hepatectomies. Journal of Gastrointestinal Surgery. 2024 Jul 1;28(7):1039–44. doi:10.1016/j.gassur.2024.04.012

17. Elm E von, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Journal of Clinical Epidemiology. 2008 Apr 1;61(4):344–9. doi:10.1016/j.jclinepi.2007.11.008 PubMed PMID: 18313558.

18. Strasberg SM, Belghiti J, Clavien PA, Gadzijev E, Garden JO, Lau WY, et al. The Brisbane 2000 Terminology of Liver Anatomy and Resections. HPB. 2000 Jan 1;2(3):333–9. doi:10.1016/S1365-182X(17)30755-4

19. Tanaka S, Kawaguchi Y, Kubo S, Kanazawa A, Takeda Y, Hirokawa F, et al. Validation of index-based IWATE criteria as an improved difficulty scoring system for laparoscopic liver resection. Surgery. 2019 Apr 1;165(4):731–40. doi:10.1016/j.surg.2018.10.012 PubMed PMID: 30446171.

20. Dindo D, Demartines N, Clavien PA. Classification of Surgical Complications. Ann Surg. 2004 Aug;240(2):205–13. doi:10.1097/01.sla.0000133083.54934.ae PubMed PMID: 15273542; PubMed Central PMCID: PMC1360123.

21. Clavien PA, Barkun J, de Oliveira ML, Vauthey JN, Dindo D, Schulick RD, et al. The Clavien-Dindo classification of surgical complications: five-year experience. Ann Surg. 2009 Aug;250(2):187–96. doi:10.1097/SLA.0b013e3181b13ca2 PubMed PMID: 19638912.

22. Clavien PA, Vetter D, Staiger RD, Slankamenac K, Mehra T, Graf R, et al. The Comprehensive Complication Index (CCI®): Added Value and Clinical Perspectives 3 Years "Down the Line." Annals of Surgery. 2017 Jun;265(6):1045. doi:10.1097/SLA.0000000000002132

23. Slankamenac K, Graf R, Barkun J, Puhan MA, Clavien PA. The Comprehensive Complication Index: A Novel Continuous Scale to Measure Surgical Morbidity. Annals of Surgery. 2013 Jul;258(1):1. doi:10.1097/SLA.0b013e318296c732

24. Rahbari NN, Garden OJ, Padbury R, Brooke-Smith M, Crawford M, Adam R, et al. Posthepatectomy liver failure: A definition and grading by the International Study Group of Liver Surgery (ISGLS). Surgery. 2011 May 1;149(5):713–24. doi:10.1016/j.surg.2010.10.001 PubMed PMID: 21236455.

25. Rahbari NN, Garden OJ, Padbury R, Maddern G, Koch M, Hugh TJ, et al. Post-hepatectomy haemorrhage: a definition and grading by the International Study Group of Liver Surgery (ISGLS). HPB (Oxford). 2011 Aug;13(8):528–35. doi:10.1111/j.1477-2574.2011.00319.x PubMed PMID: 21762295; PubMed Central PMCID: PMC3163274.

26. Rahbari NN, Elbers H, Koch M, Kirchberg J, Dutlu M, Mehrabi A, et al. Bilirubin level in the drainage fluid is an early and independent predictor of clinically relevant bile leakage after hepatic resection. Surgery. 2012 Nov 1;152(5):821–31. doi:10.1016/j.surg.2012.03.012 PubMed PMID: 22657729.

27. Görgec B, Benedetti Cacciaguerra A, Pawlik TM, Aldrighetti LA, Alseidi AA, Cillo U, et al. An International Expert Delphi Consensus on Defining Textbook Outcome in Liver Surgery (TOLS). Annals of Surgery. 2023 May;277(5):821. doi:10.1097/SLA.0000000000005668

28. Müller PC, Kuemmerli C, Cizmic A, Sinz S, Probst P, de Santibanes M, et al. Learning Curves in Open, Laparoscopic, and Robotic Pancreatic Surgery. Ann Surg Open. 2022 Jan 27;3(1):e111. doi:10.1097/AS9.0000000000000111 PubMed PMID: 37600094; PubMed Central PMCID: PMC10431463.

29. Haugen C, Noriega M, Andy C, Waite C, Halazun K, Samstein B, et al. Transitioning from Laparoscopic to Robotic Liver Surgery Increases Access of Complex Operations to the Superior Outcomes of Minimally Invasive Liver Surgery. American Journal of Transplantation. 2025 Jan 1;25(1):S114–5. doi:10.1016/j.ajt.2024.12.225

30. Hawksworth J, Radkani P, Shoucair S, Gogna S, Fishbein T, Winslow E. One hundred and fifty-two robotic hepatectomies at a North American hepatobiliary program: Evolution of

practice, learning curve, appraisal of outcomes, and cost analysis. Surg Endosc. 2025 Mar 1;39(3):2136–46. doi:10.1007/s00464-025-11570-2

31. Rahimli M, Gumbs AA, Perrakis A, Al-Madhi S, Dölling M, Stelter F, et al. Learning curve analysis of 100 consecutive robotic liver resections. Surg Endosc. 2025 Apr 1;39(4):2512–22. doi:10.1007/s00464-025-11551-5

32. D'Hondt M, Devooght A, Willems E, Wicherts D, De Meyere C, Parmentier I, et al. Transition from laparoscopic to robotic liver surgery: clinical outcomes, learning curve effect, and cost-effectiveness. J Robotic Surg. 2023 Feb 1;17(1):79–88. doi:10.1007/s11701-022-01405-w

33. Ratti F, Ingallinella S, Catena M, Corallino D, Marino R, Aldrighetti L. Learning curve in robotic liver surgery: easily achievable, evolving from laparoscopic background and team-based. HPB. 2025 Jan 1;27(1):45–55. doi:10.1016/j.hpb.2024.10.007

34. Chua D, Syn N, Koh YX, Goh BKP. Learning curves in minimally invasive hepatectomy: systematic review and meta-regression analysis. Br J Surg. 2021 Apr 1;108(4):351–8. doi:10.1093/bjs/znaa118

35. Müller PC, Aegerter NLE, Billeter AT, Eden J, Moeckli B, Lin CCW, et al. International Benchmark Values for Robotic Right Hepatectomy: Multicenter Study From 22 Expert Centers. Annals of Surgery Open. 2025 Dec;6(4):e625. doi:10.1097/AS9.0000000000000625

36. Vignot L, Khene ZE, Mellouki A, Morrone A, Bernhard JC, Bensalah K, et al. Does the transfer of knowledge from the pioneer generation to the second-generation speed-up the learning curve of robot-assisted partial nephrectomies? TRANSFER trial (UroCCR n°83). BJUI Compass. 2025;6(1):e477. doi:10.1002/bco2.477

37. Rice MK, Hodges JC, Bellon J, Borrebach J, Al Abbas AI, Hamad A, et al. Association of Mentorship and a Formal Robotic Proficiency Skills Curriculum With Subsequent Generations' Learning Curve and Safety for Robotic Pancreaticoduodenectomy. JAMA Surg. 2020 Jul 1;155(7):607–15. doi:10.1001/jamasurg.2020.1040

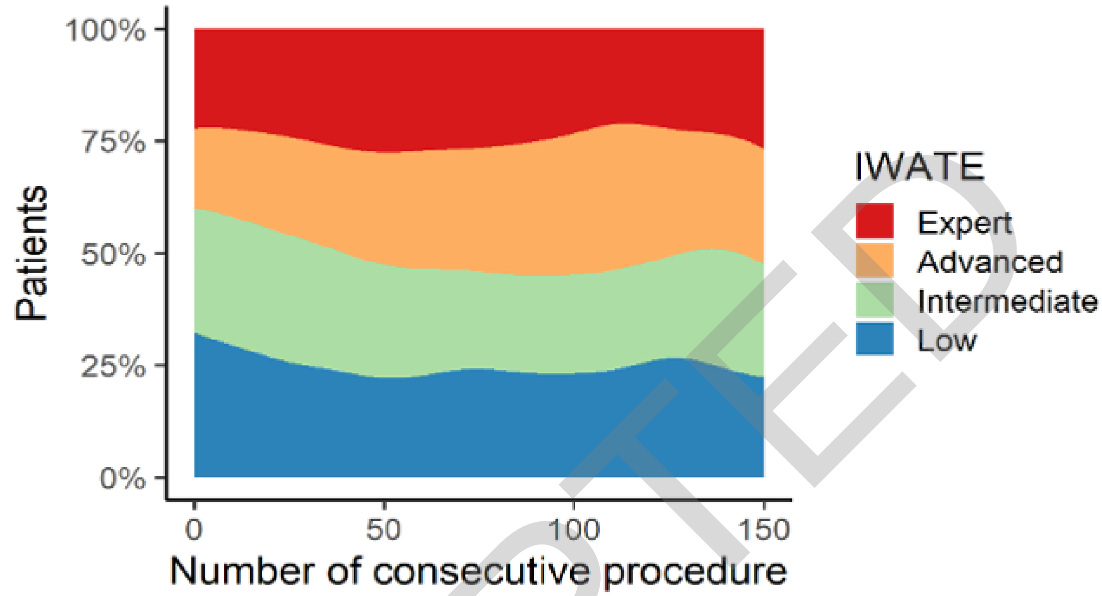
38. Berardi G, Aghayan D, Fretland ÅA, Elberm H, Cipriani F, Spagnoli A, et al. Multicentre analysis of the learning curve for laparoscopic liver resection of the posterosuperior segments. Br J Surg. 2019 Oct 1;106(11):1512–22. doi:10.1002/bjs.11286

39. Cannon RM, Brock GN, Marvin MR, Buell JF. Laparoscopic Liver Resection: An Examination of Our First 300 Patients. Journal of the American College of Surgeons. 2011 Oct;213(4):501. doi:10.1016/j.jamcollsurg.2011.04.032

40. Aegerter NLE, Kuemmerli C, Nickel F, Guidetti C, Tschuor C, Lopez-Lopez V, et al. Key steps of complex robotic liver surgery: an international expert survey. Surg Endosc. 2025 Aug 21. doi:10.1007/s00464-025-12020-9

41. Domenghino A, Walbert C, Birrer DL, Puhan MA, Clavien PA. Consensus recommendations on how to assess the quality of surgical interventions. Nat Med. 2023 Apr;29(4):811–22. doi:10.1038/s41591-023-02237-3

Figure 1: Development of surgical complexity along the learning curve



	0-50	50-100	100-150
Expert	12%	13%	10%
Advanced	23%	30%	31%
Intermediate	42%	37%	37%
Low	23%	21%	22%

Figure 2: Learning curve analysis for operative time (A), bile leak (B), textbook outcome (C), and major complications (D). Competency (red), proficiency (blue), and mastery (green) are shown in different colors.

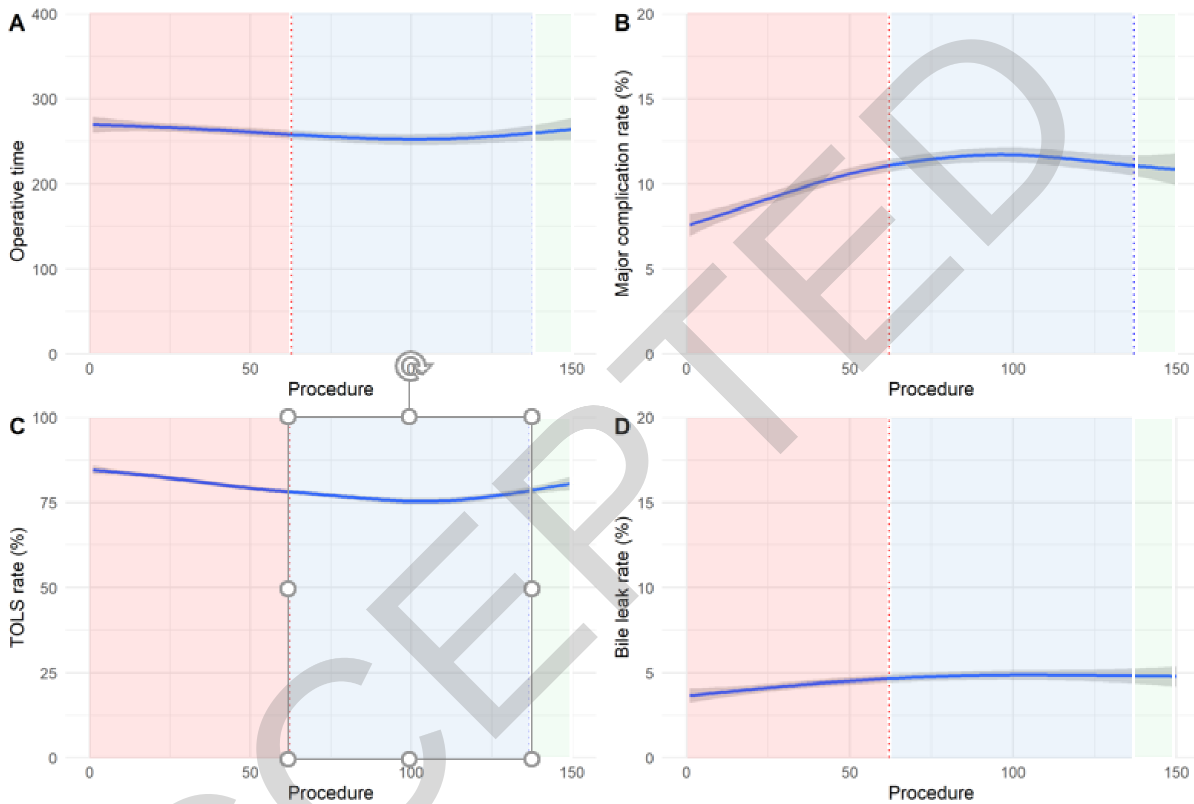


Table 1: Baseline characteristics and surgical outcomes during the learning curve.					
	Competency (n=1'303)	**Proficiency** (n=903)	**Mastery** (n=106)	***P*¹**	***P*²**
Age, *years*	64 (55-72)	65 (56-73)	64 (53-75)	0.046	0.693
Gender, *male*	738 (56.6)	539 (59.7)	61 (57.5)	0.186	0.749
Body mass index, *kg/m*^{2}	26 (23-29)	26 (23-30)	25 (23-28)	0.117	0.103
Benchmark patients	487 (38.4)	337 (37.3)	43 (40.6)	0.571	0.585
Cirrhosis	403 (30.9)	333 (37.6)	42 (39.6)	0.004	0.745
Previous liver surgery	176 (13.6)	96 (10.9)	9 (8.5)	0.001	0.300
Histological diagnosis				<.001	0.128
Colorectal liver metastasis	309 (23.7)	161 (17.8)	18 (17.0)		
Hepatocellular carcinoma	475 (36.5)	329 (36.4)	31 (29.2)		
Cholangiocarcinoma	96 (7.4)	98 (10.9)	14 (13.2)		
NCRLM	107 (8.2)	87 (9.6)	5 (4.7)		
Benign	298 (22.9)	196 (21.7)	31 (29.2)		
IWATE				<.001	0.786
Expert	154 (11.8)	105 (11.6)	13 (12.3)		
Advanced	303 (23.3)	280 (31.0)	30 (28.3)		
Intermediate	553 (42.4)	317 (35.1)	42 (39.6)		
Low	293 (22.5)	201 (22.3)	21 (19.8)		
Operative time, *min*	240 (171-340)	221 (150-325)	210 (154-350)	0.001	0.852
Blood loss, ml	150 (50- 350)	150 (50-300)	100 (50-300)	0.966	0.086
Conversion	67 (5.1)	90 (5.1)	2 (2.0)	0.858	0.370

R1 resection	78 (8.3)	49 (7.3)	0 (0.0)	0.479	0.027
Liver failure (grade B+C)	11 (0.9)	16 (1.8)	1 (0.9)	0.059	0.531
Bleeding (grade B+C)	7 (0.6)	7 (0.8)	1 (0.9)	0.514	0.854
Bile leak (grade B+C)	33 (2.5)	29 (3.3)	2 (1.9)	0.387	0.455
Reoperation	24 (1.8)	18 (2.0)	1 (0.9)	0.976	0.708
Reintervention	67 (5.1)	54 (6.0)	5 (4.7)	0.456	0.760
Major complications	123 (9.4)	105 (11.6)	11 (10.4)	0.133	0.825
Readmission	82 (6.3)	67 (7.5)	9 (8.5)	0.405	0.851
Mortality	9 (0.7)	8 (0.9)	1 (0.9)	0.822	1.000
CCI	0 (0-8.7)	0 (0-8.7)	0 (0-8.7)	0.342	0.506
Textbook outcome	1051 (81.7)	671 (76.2)	87 (87.0)	0.004	0.021
Hospital stay, *days*	5 (3-7)	4 (3-7)	4 (2-5)	0.002	0.001

Note: Data are given as n (%) and median (IQR). CCI: comprehensive complication index; NCRLM: non-colorectal liver metastasis

Table 2: Comparison of surgical outcomes with international benchmark values.

	Low IWATE			**BM**	**Intermediate IWATE**			**BM**	**High IWATE**			**BM**
	Competency (n=293)	**Proficiency** (n=201)	**Mastery** (n=21)		**Competency** (n=553)	**Proficiency** (n=317)	**Mastery** (n=42)		**Competency** (n=457)	**Proficiency** (n=385)	**Mastery** (n=43)	
Age, *years*	65 (55-73)	67 (57-74)	64 (55-68)		63 (55-71)	66 (56-74)	62 (49-75)		64 (54-72)	64 (55-72)	65 (57-78)	
Benchmark patients	92 (32.2)	73 (36.3)	12 (57.1)		207 (38.8)	117 (36.9)	13 (31.0)		188 (41.8)	147 (38.2)	18 (41.9)	
Intraoperative outcomes												
Operative time, *min*	186 (130-270)	150 (112-210)	165 (103-240)	≤234	222 (162-305)	200 (140-283)	180 (140-246)	≤354	305 (219-409)	288 (210-381)	326 (203-421)	≤357
Blood loss, ml	100 (30-250)	100 (50-250)	50 (50-125)	≤83	100 (50-300)	150 (50-300)	100 (50-250)	≤138	200 (100-500)	200 (80-430)	150 (50-413)	≤200
Conversion	12 (4.1)	7 (3.5)	0 (0)	≤0	20 (3.8)	12 (2.7)	1 (2.4)	≤3.5	35 (7.7)	25 (6.5)	1 (2.3)	≤9.4
R1 resection	17 (8.6)	10 (7.9)	0 (0)	≤5.7	24 (4.7)	15 (4.9)	0 (0)	≤5.7	39 (11.2)	28 (9.4)	0 (0)	≤14.1
Postoperative outcomes												
Liver failure (B/C)	1 (0.3)	0 (0)	0 (0)	≤0	3 (0.5)	6 (1.9)	0 (0)	≤0	7 (1.5)	10 (2.6)	1 (2.3)	≤0.3

Bile leak (B/C)	1 (0.3)	1 (0.5)	0 (0)	≤0	12 (2.2)	8 (2.5)	0 (0)	≤1.8	20 (4.4)	20 (5.2)	2 (4.7)	≤7.1
Reoperation	4 (1.4)	4 (2.0)	0 (0.0)	≤0	6 (1.1)	3 (0.9)	1 (2.4)	≤0.2	14 (3.1)	11 (2.9)	0 (0)	≤0
Major complications	22 (7.5)	14 (7.0)	1 (4.8)	≤2.2	36 (6.5)	31 (9.8)	6 (14.3)	≤5.9	65 (14.2)	60 (15.6)	4 (9.3)	≤9.5
Readmission	18 (6.1)	11 (5.5)	1 (4.8)	≤4.2	28 (5.1)	21 (6.6)	3 (7.1)	≤5.0	36 (7.9)	35 (9.2)	5 (11.6)	≤5.0
Mortality	3 (1.0)	1 (0.5)	0 (0.0)	≤0	1 (0.2)	3 (0.9)	1 (2.4)	≤0	5 (1.1)	4 (1.0)	0 (0)	≤0
CCI	0 (0-8.7)	0 (0-8.7)	8.7 (0-8.7)	≤0	0 (0-8.7)	0 (0-8.7)	0 (0-8.7)	≤0	6.7 (0-20.9)	0 (0-20.9)	0 (0-8.7)	≤0
Textbook outcome	244 (83.8)	161 (81.3)	16 (88.9)	≥84.2	472 (86.9)	247 (80.2)	32 (82.1)	≥76.2	335 (74.1)	263 (70.3)	39 (90.7)	≥67.9
Hospital stay, days	4 (3-7)	4 (3-5)	3 (2-4)	≤5	5 (3-7)	4 (3-6)	3 (2-5)	≤6	6 (4-9)	5 (3-8)	4 (3-7)	≤7

Note: Data are given as n (%) and median (IQR).
Abbreviations: BM, Benchmark; CCI, Comprehensive Complication Index.