Conversion in Minimally Invasive Liver Surgery

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Conversion in Minimally Invasive Liver Surgery: The Impact of Conversion Urgency and Surgical Approach

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Abstract

Background Conversion to open surgery forfeits any potential benefits of minimally invasive liver surgery (MILS), however, it remains uncertain whether the conversion itself introduces additional risk. The impact may differ depending on urgency (emergency or elective) and surgical approach (robotic or laparoscopic liver resection). This study aimed to evaluate outcomes of emergency and elective conversions in robotic liver resection (RLR) and laparoscopic liver resection (LLR).

Patients and Methods Data from 34 international centers of patients undergoing converted MILS procedures (stratified for conversion urgency) were retrospectively compared with patients who underwent elective open liver surgery using propensity score matching. Additionally, RLR and LLR conversions were compared. Conversion risk factors were identified using multivariable logistic regression in RLR and LLR separately.

Results Among 10,548 MILS procedures ($n = 1626$ RLR and $n = 8922$ LLR), 719 (6.8%) were converted. Both emergency ($n = 226$) and elective ($n = 472$) conversions were associated with longer operative time and more Pringle use compared with open surgery. Emergency conversions additionally showed higher blood loss, transfusion rates, severe morbidity, and even mortality. Matched analysis of 40 pairs of RLR and LLR conversions identified no significant differences in perioperative outcomes, although mortality following RLR conversion was remarkably high (7.7%). RLR conversion risk factors were bilobar disease and anatomically major resection; whereas LLR risk factors included cirrhosis, history of previous liver surgery, tumor size, technically complex, and anatomically major resection.

Conclusions Emergency conversions in MILS are associated with worse outcomes, whereas elective conversions appear safe, highlighting the importance of timely, controlled conversion. Further investigation into the safety of robotic conversions is warranted.

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Keywords Conversion · Hepatectomy · Minimally invasive liver surgery · Robotic liver surgery · Laparoscopic liver surgery

Minimally invasive liver surgery (MILS) offers distinct advantages over its open counterpart, including reduced morbidity and faster recovery.[1–7] However, technical challenges such as constrained maneuverability and diminished tactile feedback can impede intraoperative disease assessment and management of unfavorable intraoperative incidents. In the case of intraoperative complications or when progression of the minimally invasive procedure is not possible, surgeons may elect to convert.

Conversions may extend operative time and introduce safety concerns, especially in urgent situations where time is critical.[8–10] This challenge is accentuated in robotic-assisted surgeries where converting entails additional complexities due to the need for undocking and team repositioning.[8] Naturally, the advantages of a minimally invasive approach are forfeited when converting to open surgery.[8,11–13] However, it remains unclear whether the conversion event impacts outcomes, as few studies directly compare converted procedures with planned open surgery.[13–16] Furthermore, previous studies find that the conditions under which the conversion occurs (emergency or elective) can be predictive for patient outcomes, with emergency conversions associated with poorer results.[9,10,12] However, previous studies comparing conversions from MILS versus elective open surgery have been small and did not stratify for conversion reasons.

Understanding the impact of emergency and elective conversions on surgical outcomes, as well as risk factors for conversion, is critical for decisions regarding patient selection and surgical strategy. By comparing outcomes of emergency and elective conversions with those of planned open liver resections, this study seeks to elucidate the implications of conversions on both short-term perioperative and long-term patient outcomes. Additionally, outcomes of conversion in robotic liver resection (RLR) and laparoscopic liver resection (LLR) are compared, and risk factors for conversion are analyzed separately per approach. Such insights can help guide decision-making and surgical management in MILS.

Patients and Methods

Study Design

This is a retrospective analysis of prospectively collected data from the International Consortium of Minimally Invasive Liver Surgery database, including consecutive patients undergoing liver resection across 34 centers in 15 countries between January 2009 and December 2022. Outcomes of minimally invasive liver resections converted to open surgery were compared with a retrospective cohort of open liver resections from 13 centers. Adult patients (≥ 18 years) who underwent elective liver resection for benign and malignant indications were included. Patients who underwent thoracoscopic procedures or hand-assisted approaches, did not undergo formal liver resection (i.e., cyst fenestrations and biopsies), underwent associating liver partition and portal vein ligation for staged hepatectomy (ALPPS), underwent major concurrent operation (i.e. vascular or biliary reconstructions, colorectal, diaphragmatic or pancreatic resections), or underwent transplant hepatectomies were excluded. Patients were divided into two groups: minimally invasive surgery converted to open (converted) or planned open surgery (open). The converted group was further stratified into emergency conversions and elective conversions on the basis of the definition from the Brescia Internationally Validated European Guidelines on Minimally Invasive Liver Surgery.[17] Emergency conversion is defined as a necessary decision required to fix potentially life-threatening conditions or serious intraoperative complications that cannot be properly handled while maintaining the laparoscopic or robotic approach. Elective conversions are those that occur in hemodynamically stable patients because of unanticipated conditions (e.g., concerns about resection margins, failure to progress, technology failure, etc.) that require a switch to a different surgical approach. Minimally invasive procedures were subdivided into two groups on the basis of approach (robotic or laparoscopic). Baseline characteristics and perioperative outcomes were compared between the following groups: (1) emergency conversion versus open surgery, (2) elective conversion versus open surgery, (3) elective conversion versus emergency conversion, (4) RLR conversion versus LLR conversion, (5) converted versus nonconverted in RLR, and (6) converted versus nonconverted in LLR. Long-term oncologic outcomes were compared between open and converted procedures stratified for conversion reasons. Propensity score matching (PSM) was applied to mitigate the influence of selection bias. Risk factors for conversion were identified using multivariable logistic regression for RLR and LLR separately. The medical ethics committee of Amsterdam UMC granted approval for the study (2025.0181). This report adheres to the Strengthening The Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[18]

Outcomes and Definitions

Data were collected from electronic patient records. Collected baseline characteristics were age, sex, body mass index (BMI; kg/m^2), American Society of Anesthesiologists (ASA) classification, cirrhosis (based on pathology), neoadjuvant chemotherapy, history of previous extrahepatic abdominal surgery, history of previous hepatic surgery, pathological diagnosis, size of largest lesion, number of lesions, presence of bilobar disease, type and extent of resection. Resection type was classified according to the Brisbane 2000 nomenclature. Resection extent was based on the location and number of segments resected; minor resections are resections involving less than three adjacent liver segments and major resections those involving three or more adjacent segments. The term technically complex is used to refer to minor resections in the posterosuperior segments (I, IVa, VII, VIII); resections involving the anterolateral segments (II, III, IVb, V, VI) are referred to as minor.[17,19] Intraoperative outcomes were intraoperative blood loss in milliliters, major blood loss (≥ 500 ml), operative time in min, utilization of the Pringle maneuver and duration when applied, and use of intraoperative transfusion. All postoperative outcomes, apart from mortality, which was reported with a follow-up length of 90 days, were reported with a follow-up length of 30 days. Postoperative outcomes were composed of length of hospital stay in days, complications (classified according to the Clavien–Dindo classification),[20] severe postoperative morbidity (Clavien–Dindo grade ≥ 3A), bile leak [according to the International Study Group of Liver Surgery (ISGLS) definition],[21] post-hepatectomy liver failure (according to the ISGLS definition),[22] readmission, and in-hospital or 90-day mortality. Oncologic outcomes were assessed in patients with malignant disease; these included resection margin status, disease-free survival (DFS), and overall survival (OS). DFS and OS were defined as the interval (in months) between the date of surgery and the date when there was clinical evidence of disease recurrence or date of death, respectively. Resection margin was classified as following: R0 corresponding to a microscopically tumor-free margin of ≥ 1 mm, R1 with a macroscopic tumor-free margin with the microscopic presence of tumor cells within 1 mm of the resection margin (R1), and R2 a macroscopically incomplete resection.

Preoperative Assessment and Surgical Technique

In preparation for surgery, patients underwent routine blood tests and imaging with triphasic thoracal/abdominal computed tomography (CT) scans and/or magnetic resonance imaging (MRI) scans. Each patient's treatment plan was reviewed by a multidisciplinary team consisting of at least surgeons, oncologists, and radiologists. All patients received preoperative anesthesiologic consultations. Surgical technique was not standardized and was performed according to institutional practice. Surgical steps consisted of intraoperative disease and lesion assessment using ultrasound, parenchymal transection with bipolar energy devices, and/or ultrasonic aspirator. Vessels and biliary structures were sealed and divided using the dissector device, metallic clips, self-locking clips, sutures, or staplers on the basis of their diameter. The Pringle maneuver was applied intermittently at the operating surgeon's discretion.

Statistical Analysis

All analyses were performed using IBM SPSS Statistics for Windows version 26.0 (SPSS V26.0, Inc., Chicago, IL, USA) and R for Windows version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria). Categorical variables were reported as absolute numbers with percentages, continuous normally distributed variables as means with standard deviation, and continuous not normally distributed variables as medians with interquartile range (IQR). Normality of data was evaluated by visual inspection of histograms and Q–Q plots. Comparisons between categorical variables were performed using chi-squared or Fisher's exact test, when appropriate. Comparisons between continuous variables were performed using unpaired *t*-test for normally distributed data and Mann–Whitney *U* test for not normally distributed data. Missing baseline data for variables used in the matching procedure was imputed by means of single imputation for the matched analyses. The amount of missing data per variable, corresponding with the extent of imputation, is found in Supplementary Table 1. Data were assumed to be missing at random. Propensity scores were calculated using a logistic regression model on the basis of the following variables: age, sex, ASA classification, presence of cirrhosis, use of neoadjuvant chemotherapy, history of previous hepatic surgery, pathological diagnosis, type of resection, extent of resection, single or multiple tumors, and presence of bilobar disease. Procedures in the converted and planned surgery groups were matched in a 1:1 ratio using a nearest neighbor matching algorithm, without replacement. Balance between the groups was assessed using standardized mean differences (SMD); SMD ≤ 0.1 indicated optimal balance. A calliper of 0.05 was used for comparisons of open versus converted procedures and a calliper of 0.01 for matching of converted versus nonconverted procedures as well as RLR versus LLR to achieve optimal balance while maintaining the highest possible sample size. Matched categorical data were compared using McNemar's test, or McNemar–Bowker test when appropriate. Continuous matched data were compared using Wilcoxon signed rank test. Kaplan–Meier curves were plotted for time-to-event outcomes, specifically DFS and OS, using matched data to correct for baseline covariates. Differences were evaluated using a stratified log-rank test to account for the paired nature of the data.[23]

A univariable analysis identified factors significantly associated ($p < 0.1$) with conversion to open surgery. These variables were subsequently entered into a multivariable logistic regression model to determine independent associations with conversion. For logistic regression analyses, multiple imputation was applied for missing data of baseline predictors. The quantity of missing data is reported in Supplementary Table 1. A total of 20 imputed datasets

Table 1 Reasons for conversion in minimally invasive (robotic and laparoscopic) liver resection

Conversion reason, *n* (%)	All (*n* = 10548)	Laparoscopic (*n* = 8922)	Robotic (*n* = 1626)	*p*-value
Conversion	719 (6.8)	665 (7.5)	54 (3.3)	< 0.001
Emergent	226 (32.4)	208 (31.3)	18 (33.3)	0.432*
Bleeding	222 (30.9)	207 (31.1)	15 (27.8)	
Air embolus	4 (0.6)	1 (0.2)	3 (5.5)	
Nonemergent	472 (67.6)	442 (66.5)	30 (55.5)	
Technical reason	148 (20.6)	138 (20.8)	10 (18.5)	
Adhesions	124 (17.2)	119 (17.9)	5 (9.3)	
Oncological concern	138 (19.2)	131 (19.7)	7 (13.0)	
Impaired visualization	14 (1.9)	12 (1.8)	2 (3.7)	
Anesthesiologic reason	17 (2.4)	14 (2.1)	3 (5.6)	
Difficulty identifying tumor	12 (1.7)	11 (1.7)	1 (1.9)	
Disease progression	10 (1.4)	9 (1.4)	1 (1.9)	
Biliostasis	5 (0.7)	5 (0.8)	0 (0.0)	
Iatrogenic bowel lesion	3 (0.4)	2 (0.3)	1 (1.9)	
Equipment problem	1 (0.1)	1 (0.2)	0 (0.0)	
Other				
Unknown	21 (2.9)	15 (2.3)	6 (11.1)	

**p*-value refers to the comparison of proportion of emergent conversions in robotic versus laparoscopic liver resection.

Percentages for conversion reasons are given as proportions of the number of conversions

were generated from which pooled results were attained. The results are reported as adjusted odds ratios (aOR) along with their 95% confidence intervals (CI).

Results

Overall, 5894 open procedures and 10548 minimally invasive procedures (1626 RLR and 8922 LLR) met the study criteria. A total of 719 procedures (6.8%) were converted ($n = 226$ emergency, $n = 472$ elective, and $n = 21$ unknown). Reasons for conversion are presented in Table 1. Overall, MILS procedures were most often converted electively ($n = 472$; 65.6%), with technical reasons cited most frequently. Bleeding was the leading cause of emergency conversion. The baseline characteristics and perioperative outcomes of unmatched data are found in the Supplementary Materials.

Impact of Conversion Urgency

Emergency Conversions versus Open Surgery

Baseline characteristics of 225 matched pairs of emergency conversions and planned open surgeries are shown in the Supplementary Materials; perioperative outcomes are presented in Table 2. Emergency conversions were associated with poorer intraoperative outcomes, including greater blood loss (median 800 mL [IQR 400–1500 mL] vs. 300 mL [IQR 150–550 mL], $p < 0.001$), a higher incidence of major blood loss (70.1% vs. 33.0%, $p < 0.001$), increased transfusion rates (49.7% vs. 13.9%, $p < 0.001$), more Pringle maneuver use (62.8% vs. 45.6%, $p = 0.003$), and longer operative time (median 285 min [IQR 195–371 min] vs. 222 min [IQR 180–292 min], $p < 0.001$). Notably, postoperatively, they also had a higher rate of severe morbidity (21.4% vs. 9.0%, $p = 0.001$) and mortality (5.0% vs. 1.4%, $p = 0.046$). Compared with elective open surgery, emergency conversion was not associated with worse oncologic outcomes (OS, $p = 0.261$; DFS, $p = 0.102$) (Figs. 1A, 1B).

Elective Conversions versus Open Surgery

A total of 471 matched pairs of electively converted procedures and planned open surgeries were obtained for analysis. Baseline characteristics were well balanced between groups (Supplementary Materials). Perioperative outcomes are reported in Table 2. Intraoperatively, when compared with open surgery, elective conversions showed only a higher frequency and longer duration of Pringle maneuver use (59.7% vs. 40.2%, $p < 0.001$; 35 min [IQR 25–50 min] vs. 30 min [IQR 15–50 min], $p = 0.002$), as well as longer operative times (276 min [IQR 200–360 min] vs. 237 min [IQR 182–330 min], $p = 0.008$). All other perioperative outcomes, as well as OS ($p = 0.885$) and DFS ($p = 0.499$), were comparable between elective conversions and planned open surgery (Fig. 1C, D).

Table 2 Perioperative outcomes after propensity score matching of emergent conversion versus open surgery, nonemergent conversion versus open surgery, and nonemergent versus emergent conversion

	Emergency $n = 225$	Open $n = 225$	p-value	Elective $n = 471$	Open $n = 471$	p-value	Elective $n = 210$	Emergency $n = 210$	p-value
Intraoperative blood loss (median [IQR])	800 [400–1500]	300 [150–550]	**< 0.001**	400 [200–663]	360 [200–678]	0.382	400 [200–613]	800 [375–1500]	**< 0.001**
Major blood loss (> 500 mL) (%)	124 (70.1)	35 (33.0)	**< 0.001**	143 (40.2)	85 (39.4)	0.630	58 (40.3)	117 (70.1)	**< 0.001**
Pringle (%)	135 (62.8)	83 (45.6)	**0.003**	276 (59.7)	155 (40.2)	**< 0.001**	133 (64.9)	128 (63.7)	0.682
Pringle duration* (median [IQR])	35 [25–58]	30 [17–50]	0.185	35 [25–50]	30 [15–50]	**0.002**	35 [26–49]	35 [25–57]	0.484
Transfusion (%)	89 (49.7)	16 (13.9)	**< 0.001**	63 (15.3)	43 (18.9)	0.890	25 (14.2)	84 (50.0)	**< 0.001**
Operative time (median [IQR])	285 [195–371]	222 [180–292]	**< 0.001**	276 [200–360]	237 [182–330]	**0.008**	270 [200–335]	288 [195–367]	0.565
LOS (median [IQR])	7 [5–10]	7 [6–10]	0.595	7 [5–9]	7 [6–10]	0.060	7 [5–10]	7 [5–10]	0.268
Overall morbidity (%)	100 (45.2)	82 (38.5)	0.171	191 (40.8)	169 (37.3)	0.277	80 (38.5)	92 (44.4)	0.262
Severe morbidity (Clavien–Dindo ≥ 3A) (%)	47 (21.4)	19 (9.0)	**0.001**	58 (12.4)	57 (12.7)	1000	28 (13.5)	43 (20.9)	0.077
Readmission (%)	8 (4.1)	8 (9.2)	0.131	21 (5.7)	10 (6.2)	0.773	10 (6.5)	8 (4.3)	1.000
90-day/in-hospital mortality (%)	11 (5.0)	3 (1.4)	**0.046**	7 (1.5)	15 (3.4)	0.136	2 (1.0)	9 (4.4)	0.070
Resection margin (%)			0.572			0.141			0.344
R0	152 (81.3)	149 (84.2)		317 (83.0)	298 (81.2)		138 (85.2)	140 (80.9)	
R1	35 (18.7)	27 (15.3)		63 (16.5)	65 (17.7)		22 (13.6)	33 (19.1)	
R2	0 (0.0)	1 (0.6)		2 (0.5)	4 (1.1)		2 (1.2)	0 (0.0)	

Bold values indicate statistical significance

Emergency versus Elective Conversions

After PSM, 214 emergency conversions were well matched to an equal number of elective conversions (Supplementary Materials). Perioperative outcomes are presented in Table 2. Emergency conversions were associated with greater blood loss (800 mL [IQR 375–1500 mL] vs. 400 mL [IQR 200–613 mL], $p < 0.001$), higher incidence of major blood loss (70.1% vs. 40.3%, $p < 0.001$), and increased transfusion rate (50.0% vs. 14.2%, $p < 0.001$) intraoperatively. Notably, they also showed a trend toward higher rates of severe morbidity (20.9% vs. 13.5%, $p = 0.077$) and mortality (4.4% vs. 1.0%, $p = 0.070$) compared with elective conversions. Emergency conversions also trended toward poorer oncologic outcomes, including OS ($p = 0.089$; Fig. 1E) and DFS ($p = 0.076$; Fig. 1F).

Impact of Surgical Approach on Conversions

Robotic Versus Laparoscopic Conversions

Overall, RLR was associated with a significantly lower conversion rate than LLR (3.3% vs. 7.5%, $p < 0.001$), with a similar proportion of emergency conversions across both approaches (33.3% vs. 31.3%, $p = 0.432$) (Table 1). In unmatched analyses, conversions from RLR were linked

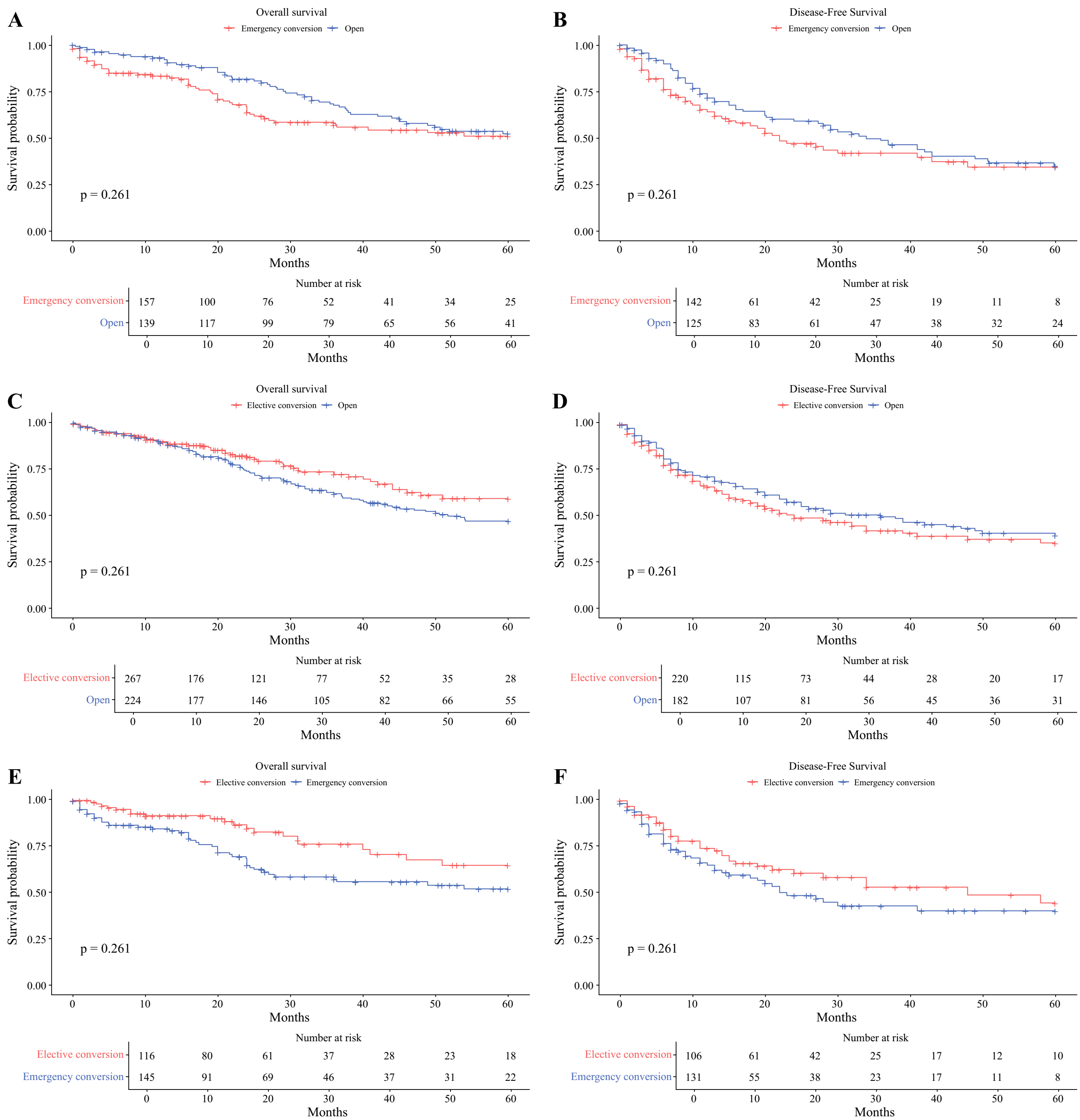

Fig. 1 Oncological outcomes: overall survival (**A**) and disease-free survival (**B**) in emergent conversions versus open surgery; overall survival (**C**) and disease-free survival (**D**) in elective conversions versus open surgery; overall survival (**D**) and disease-free survival (**E**) in elective versus emergent conversions

to longer operative time (340 min [IQR 240–435 min] vs. 275 min [IQR 195–360 min], $p = 0.006$) and higher mortality (7.7% vs. 2.6%, $p = 0.040$) compared with conversions from LLR (Table 3). In the matched cohort, no significant differences in perioperative outcomes were found between conversions from RLR and LLR. However, PSM could not fully balance baseline variables, as optimal SMD (< 0.1) was not achieved for several factors (Supplementary Materials). Matching did result in generally smaller SMDs indicating smaller differences between the groups.

Table 3 Perioperative outcomes of conversions from robotic versus laparoscopic liver resection in unmatched and matched analyses

	Unmatched			Matched		
	Laparoscopic	Robotic	*p*-value	Laparoscopic	Robotic	*p*-value
	$n = 665$	$n = 54$		$n = 40$	$n = 40$	
Emergency conversion (%)	207 (31.9)	17 (36.2)	0.549	8 (20.5)	13 (35.1)	0.243
Intraoperative blood loss (median [IQR])	475 [235–900]	450 [300–950]	0.870	400 [250–700]	400 [163–688]	0.939
Major blood loss (> 500 mL) (%)	248 (49.8)	25 (50.0)	0.978	13 (41.9)	17 (44.7)	1.000
Pringle (%)	394 (61.1)	32 (60.4)	0.919	24 (64.9)	25 (62.5)	0.814
Pringle duration* (median [IQR])	35 [25–52]	35 [22–45]	0.861	34 [20–61]	36 [25–45]	0.906
Transfusion (%)	141 (25.1)	16 (32.0)	0.287	6 (17.6)	9 (23.7)	0.752
Operative time (median [IQR])	275 [195–360]	340 [240–435]	**0.006**	290 [225–373]	286 [224–405]	0.101
LOS (median [IQR])	7 [5–9]	7 [5–12]	0.140	6 [5–9]	7 [5–10]	0.063
Overall morbidity (%)	282 (42.9)	20 (37.0)	0.400	14 (35.9)	14 (35.0)	1.000
Severe morbidity (Clavien–Dindo ≥ 3A) (%)	99 (15.1)	12 (22.2)	0.167	2 (5.1)	7 (17.5)	0.182
Readmission (%)	30 (5.7)	1 (2.1)	0.303	1 (3.0)	0 (0.0)	
90-day/in-hospital mortality (%)	17 (2.6)	4 (7.7)	**0.040**	0 (0.0)	3 (7.7)	0.248
Resection margin (%)			0.279			0.515
R0	443 (81.4)	40 (90.9)		26 (81.2)	33 (91.7)	
R1	98 (18.0)	4 (9.1)		5 (15.6)	3 (8.3)	
R2	3 (0.6)	0 (0.0)		1 (3.1)	0 (0.0)	

Bold values indicate statistical significance

Converted versus Nonconverted Procedures in RLR

A total of 47 converted RLR procedures were matched with an equal number of procedures completed robotically. Optimal matching (SMD < 0.1) was not achieved, as nonconverted procedures still had higher rate of previous hepatic surgery (SMD 0.245), bilobar disease (SMD 0.249), less anatomically major resections, and more technically complex resections (SMD 0.360) after matching (Supplementary Materials). In RLR, conversions were associated with poorer outcomes, including greater blood loss (400 mL [IQR 300–800 mL] vs. 200 mL [IQR 50–400 mL], $p < 0.001$), higher incidence of major blood loss (48.9% vs. 21.3%, $p = 0.019$), increased transfusion rates (28.9% vs. 4.3%, $p = 0.009$), longer operative time (299 min vs. 230 min, $p = 0.048$), and postoperatively longer hospital stays (7 days [IQR 5–12 days] vs. 5 days [IQR 3–6 days], $p < 0.001$) (Table 4).

Converted versus Nonconverted Procedures in LLR

After PSM, converted ($n = 652$) and nonconverted ($n = 652$) LLR procedures had well-balanced baseline characteristics (Supplementary Materials). In LLR, conversions were associated with poorer perioperative outcomes compared with procedures completed laparoscopically (Table 4). This included greater blood loss (470 mL [IQR 223–975 mL] vs. 200 mL [IQR 100–400 mL], $p < 0.001$), higher incidence of major blood loss (49.9% vs. 22.1%, $p < 0.001$), more Pringle application (60.8% vs. 52.4%, $p = 0.002$) though shorter Pringle duration (35 min [IQR 25–53 min]) vs. 40 min [IQR 25–63 min], $p = 0.015$), increased transfusion rates (25.3% vs. 4.8%, $p < 0.001$), and longer operative time (274 min [IQR 195–360 min] vs. 215 min [IQR 150–300 min]). Postoperatively, LLR conversions had longer hospital stays (7 days [IQR 5–9 days] vs. 5 days [IQR 3–7 days], $p < 0.001$) and higher overall as well as severe morbidity (42.4% vs. 24.9%, $p < 0.001$; 15.1% vs. 8.6%, $p < 0.001$).

Risk Factors for Conversion in RLR and LLR

Results of multivariable logistic regression analyses are summarized in the Supplementary Materials. Bilobar disease (aOR 2.44 [95% CI 1.31–4.55]) and anatomically major resection (aOR 2.20 [95% CI 1.13–4.29]) were independently associated with conversion in RLR. Independent risk factors for conversion in LLR were presence of cirrhosis (aOR 1.45 [95% CI 1.18–1.76]), history of previous liver surgery (aOR 1.59 [95% CI 1.24–2.05]), largest lesion size (aOR 1.01 [95% CI 1.01–1.01]), technically complex resection (aOR 1.86 [95% CI 1.53–2.25]) and anatomically major resection (aOR 2.47 [95% CI 2.01–3.04]).

Table 4 Perioperative outcomes of converted versus not converted procedures stratified by approach (robotic and laparoscopic) in unmatched and matched analyses

	Robotic liver resection						Laparoscopic liver resection					
	Unmatched			Matched			Unmatched			Matched		
	Not converted	Converted	*p*-value	Not converted	Converted	*p*-Value	Not converted	Converted	*p*-value	Not converted	Converted	*p*-value
	n = 1626	*n* = 54		*n* = 47	*n* = 47		*n* = 8922	*n* = 665		*n* = 652	*n* = 652	
Intraoperative blood loss (median [IQR])	100 [50–250]	450 [300–950]	**< 0.001**	200 [50–400]	400 [300–800]	**< 0.001**	200 [76–400]	475 [235–900]	**< 0.001**	200 [100–400]	470 [223–975]	**< 0.001**
Major blood loss (> 500 mL) (%)	193 (12.4)	25 (50.0)	**< 0.001**	10 (21.3)	22 (48.9)	**0.019**	1292 (18.5)	248 (49.8)	**< 0.001**	117 (22.1)	243 (49.9)	**< 0.001**
Pringle (%)	615 (37.9)	32 (60.4)	**0.001**	23 (48.9)	30 (63.8)	0.248	3734 (43.4)	394 (61.1)	**< 0.001**	334 (52.4)	384 (60.8)	**0.002**
Pringle duration* (median [IQR])	30 [20–46]	35 [22–45]	0.266	36 [24–49]	35 [23–45]	0.477	40 [25–61]	35 [25–52]	**0.007**	40 [25–63]	35 [25–53]	**0.015**
Transfusion (%)	71 (4.5)	16 (32.0)	**< 0.001**	2 (4.3)	13 (28.9)	**0.009**	384 (4.9)	141 (25.1)	**< 0.001**	27 (4.8)	139 (25.3)	**< 0.001**
Operative time (median [IQR])	191 [139–280]	340 [240–435]	**< 0.001**	230 [153–341]	299 [229–396]	**0.048**	190 [121–275]	275 [195–360]	**< 0.001**	215 [150–300]	274 [195–360]	**< 0.001**
LOS (median [IQR])	4 [3–9]	7 [5–12]	**< 0.001**	5 [3–6]	7 [5–12]	**< 0.001**	4 [3–5]	7 [5–9]	**< 0.001**	5 [3–7]	7 [5–9]	**< 0.001**
Overall morbidity (%)	306 (18.8)	20 (37.0)	**0.001**	12 (25.5)	17 (36.2)	0.359	1754 (19.8)	282 (42.9)	**< 0.001**	162 (24.9)	273 (42.4)	**< 0.001**
Severe morbidity (Clavien–Dindo ≥ 3A) (%)	88 (5.4)	12 (22.2)	**< 0.001**	4 (8.5)	9 (19.1)	0.182	540 (6.1)	99 (15.1)	**< 0.001**	56 (8.6)	97 (15.1)	**< 0.001**
Readmission (%)	100 (6.3)	1 (2.1)	0.239	4 (8.9)	1 (2.4)	0.617	290 (3.9)	30 (5.7)	0.052	22 (4.2)	30 (5.8)	0.522
90-day/in-hospital mortality (%)	23 (1.4)	4 (7.7)	**< 0.001**	2 (4.3)	3 (6.7)	1.000	109 (1.2)	17 (2.6)	**0.003**	11 (1.7)	16 (2.5)	0.327
Resection margin (%)			0.885			0.978			0.082			0.428
R0	967 (88.6)	40 (90.9)		35 (92.1)	36 (92.3)		5779 (84.0)	443 (81.4)		460 (85.7)	432 (81.4)	
R1	123 (11.3)	4 (9.1)		3 (7.9)	3 (7.7)		1088 (15.8)	98 (18.0)		76 (14.2)	96 (18.1)	
R2	1 (0.1)	0 (0.0)		0 (0.0)	0 (0.0)		13 (0.2)	3 (0.6)		1 (0.2)	3 (0.6)	

Bold values indicate statistical significance

Discussion

This international, multicenter retrospective study demonstrated that emergency conversions in MILS are associated with poorer perioperative outcomes, including higher morbidity and mortality compared with open surgery, whereas elective conversions show postoperative outcomes comparable to those of planned open surgery. Hence, the present results support the notion that controlled conversions can be performed without detriment to the patient. Though naturally, in both RLR and LLR, procedures completed minimally invasively achieve better outcomes.

Numerous studies have demonstrated advantages of the minimally invasive approach over open surgery for liver resection.[1–4] Unfortunately, these advantages are inherently forfeited during a conversion. Understanding the impact of conversion events on patient outcomes is crucial for surgical decision-making. During patient selection, the benefits of a minimally invasive approach should be weighed against the potential risks of converting. The outcomes of elective conversions in the present study are reassuring, suggesting that timely conversion results in similar outcomes as planned open surgery. Worryingly, emergency conversions were associated with poorer outcomes including higher morbidity and mortality. These findings stress the importance of adequate patient selection for MILS. Particularly alarming is that emergency conversions trended toward worse long-term outcomes compared with elective conversions. Procedures completed minimally invasively have the potential of offering patients the best results. However, when unable to progress safely in MILS, the second-best alternative is a controlled, elective conversion. Surgeons should consider converting early to avoid complications and poor oncologic results.

Previous studies did not identify differences in postoperative outcomes between converted MILS procedures and planned open surgery.[13–16] However, they did not account for conversion urgency and were limited by small sample sizes. In the present study, elective conversions indeed exhibited postoperative outcomes comparable to planned open surgery, whereas emergency conversions were associated with significantly worse outcomes. This is unsurprising, given that electively converted procedures are in essence not different to an open procedure, except for the initial minimally invasive approach. These findings corroborate the study by Halls et al., which reported worse postoperative outcomes for patients undergoing emergency conversions compared with elective conversions.[9] Similar findings have also been observed in pancreatic and colorectal surgery.[24,25]

The present study identified risk factors for conversion in RLR and LLR, helping to refine patient selection criteria for MILS. Consistent with previous reports, independent risk factors for conversion in LLR included cirrhosis, prior liver surgery, lesion size, and resection complexity (both technically complex and anatomically major resection).[9,12,26] Risk factors for conversion in RLR were bilobar disease and anatomically major resection, both known to increase resection difficulty.[27] Notably, the identified risk factors for RLR and LLR do not entirely overlap, suggesting that the technical challenges in RLR may differ in nature from those in LLR. Interestingly, minor resections in the posterosuperior segments were independently associated with conversion in LLR but not in RLR. This is indicative that the robotic platform may help overcome certain technical obstacles associated with LLR. Adhesions may be another example of this, given that previous liver surgery was a risk factor during LLR and not for RLR. Illustratively, 17.9% of the conversions during LLR occurred because of adhesions, while in RLR this was 9.3%. Conversely, the study found that presence of bilobar disease leads to increased risk for conversion in RLR but not in LLR. This difference can likely be attributed to the increased flexibility surgeons have during LLR, allowing them to reposition trocars and target both liver lobes more effectively throughout the procedure. In contrast, RLR involves docking the robot in a fixed position, making adjustments during surgery impractical, requiring redocking and/or a coupled operating table. Previous studies have not explored risk factors for conversion in RLR specifically and this should be investigated further. This knowledge can guide the allocation of patients to either RLR or LLR. Aligning procedure complexity to surgeon experience is important in ensuring patient safety and limiting conversions.[28,29] Additionally, identification of patients at higher risk for conversion plays an important role in patient counselling and informed decision-making.

The adoption of robotic liver surgery is increasing, with its main perceived advantage being a reduction in conversion rates.[30–36] The increased degrees of freedom, enhanced vision, and better ergonomics of the robotic platform facilitate complex minimally invasive resections, also improving management of intraoperative complications by easier suturing of vessels and bile ducts.[37] However, concerns exist regarding conversions in robotic surgery owing to delays caused by the undocking process. Mortality was notably higher in the group converted from RLR (RLR 7.7% vs. LLR 2.6%). While the difference was not statistically significant in the matched analysis, the study was underpowered to detect such differences given the small sample size of 40 patients per group. Conversion during RLR involves multiple steps including the surgeon scrubbing in and undocking of the robot, which may hamper quick control of hazardous situations. Failure to intervene quickly can have serious consequences for the patient, which could explain the high mortality rate during converted RLR. This finding also underscores the potential risks of performing RLR without an experienced bedside surgeon capable of intervening safely in an emergency. Given the relatively recent adoption of RLR, conversion techniques may still require further refinement. It is paramount that clear conversion protocols are established to ensure patient safety. Surgeons should be proficient in conversions, and surgical teams must be well trained to optimize coordination and minimize risk. Future robotic system designs should also prioritize features that facilitate rapid intraoperative intervention.

These results should be interpreted in light of several limitations. First, an inherent limitation of retrospective studies is selection bias, and although PSM functions to limit this, latent confounders cannot be corrected for. Second, given the later implementation of LLR and RLR, time bias can influence outcomes. Third, considering the limited sample size, particularly of the sensitivity and subgroup analyses, it is important to acknowledge the potential for type II errors. Fourth, owing to the available data, perioperative outcomes were only reported with a follow-up of 30 days. Fifth, analyses of oncologic outcomes (including DFS and OS) were limited by large amounts of missing data.

In conclusion, in nonemergent scenarios, conversions do not appear to impose additional harm when compared with planned open procedures. However, emergency conversions are associated with poorer outcomes. Therefore, MILS can still be considered in patients with higher conversion risk, provided that surgeons convert in a timely, controlled manner in response to intraoperative findings. Given the high mortality rate following conversion from RLR, further research into its safety is warranted.

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