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Robotic Versus Laparoscopic Liver Resection

A Nationwide Propensity Score Matched Analysis

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Objective: To compare nationwide outcomes of robotic liver resection (RLR) with laparoscopic liver resection (LLR).

Background: Minimally invasive liver resection is increasingly performed using the robotic approach as this could help overcome inherent technical limitations of laparoscopy. It is unknown if this translates to improved patient outcomes.

Methods: Data from the mandatory Dutch Hepatobiliary Audit were used to compare perioperative outcomes of RLR and LLR in 20 centers in the Netherlands (2014–2022). Propensity score matching (PSM) was used to mitigate selection bias. Sensitivity analyses assessed the impact of the learning curve (≥50 procedures for LLR and ≥25 procedures for RLR), concurrent noncholecystectomy operations, high-volume centers, and conversion on outcomes.

Results: Overall, 792 RLR and 2738 LLR were included. After PSM (781 RLR vs 781 LLR), RLR was associated with less blood loss (median: 100 mL [interquartile range (IQR): 50–300] vs 200 mL [IQR: 50–500], $P = 0.002$), less major blood loss (≥500 mL,18.6% vs 25.2%, $P = 0.011$), less conversions (4.9% vs 12.8%, $P < 0.001$), and shorter hospital stay (median: 3 days [IQR: 2–5] vs 4 days [IQR: 2–6], $P < 0.001$), compared with LLR. There were no significant differences in overall and severe morbidity, readmissions, mortality, and R0 resection rate. Sensitivity analyses yielded similar results. When excluding conversions, RLR was only associated with a reduction in reoperations (1.1% vs 2.7%, $P = 0.038$).

Conclusion: In this nationwide analysis, RLR was associated with a reduction in conversion, blood loss and length of hospital stay without compromising patient safety, also when excluding a learning curve effect. The benefits of RLR seem to be mostly related to a reduction in conversions.

Keywords: hepatectomy, laparoscopy, minimally invasive, propensity score matching, robotic liver surgery

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INTRODUCTION

More than 1200 liver resections are performed in the Netherlands annually.[1] Since the introduction of minimally invasive liver surgery (MILS) in the Netherlands, it has been increasingly adopted.[1–3] MILS may offer improved outcomes in selected patients without compromising oncological outcomes.[4–6] The most recent innovation in MILS is robotic liver resection (RLR). In 2020, a third of all MILS procedures in the Netherlands were performed using the robotic platform.[1] Valuable features of the robot are increased instrument range of motion, improved dexterity, magnified 3-dimensional vision, elimination of tremors, and the ability to integrate digital interfaces into the cockpit.[7,8] It is supposed that the robotic platform may help overcome certain limitations of laparoscopy, hereby broadening the indications for MILS. It is conceivable that these features will result in a shorter learning curve for RLR compared with laparoscopic liver resection (LLR).[9,10] The safety and feasibility of RLR have been well-documented; however, the complexity of the technique demands experienced hands.[1,11] The advantages of MILS over open surgery have been studied extensively; however, comparisons between RLR and LLR remain limited to data from high-volume expert centers.[12–16] Investigation of population-based outcomes is warranted as this could help guide choices regarding treatment approaches and ultimately healthcare policies. This study aimed to compare the Dutch nationwide perioperative outcomes of RLR and LLR.

METHODS

Study Design and Patient Selection

This study is a multicenter, retrospective, propensity score matched (PSM) analysis comparing the perioperative outcomes of all consecutive RLR and LLR procedures in Dutch centers (January 2014–December 2022) for any indication. All 22 centers for liver surgery in the Netherlands were approached with the study protocol, whereafter 20 centers agreed to participate and share their data. The 2 centers that did not join were centers with a low volume of MILS. Transplant hepatectomy and emergency procedures were excluded. Patients in whom no formal liver resection was performed (eg, fenestration/deroofing of cysts, biopsies, diagnostic laparoscopy) were excluded. Preoperatively, the indication for surgery was discussed in a multidisciplinary team meeting with hepato-pancreato-biliary surgeons, oncologists, gastroenterologists, radiologists, and pathologists. Patient and tumor characteristics as well as surgeon and center experience determined the surgical approach. LLR technique was based on a standardized method from a national training program.[3] RLR surgical technique was not standardized and performed at the discretion of the surgeon. All centers applied an enhanced recovery after surgery protocol.[17] The implementation of RLR and LLR in the Netherlands has been described previously.[1,3]

Ethics and Privacy

The study is reported in compliance with the Strengthening of Reporting of Observational Studies in Epidemiology (STROBE) statement and performed in accordance with the Declaration of Helsinki.[18,19] A statement was obtained from the ethics committee of the Amsterdam UMC determining that the study is not subject to the Medical Research Involving Human Subjects Act, exempting it from requiring informed consent (W22_470 # 23.018). Patient data were pseudonymized. Survey responses were treated confidentially.

Data Collection

Data from the Dutch Hepatobiliary Audit (DHBA) were utilized. Since January 2014, the DHBA has been a mandatory, data-verified, prospectively maintained registry of all liver resections performed in the Netherlands.[20] Participating centers requested extraction of their data from the DHBA. Missing data were collected from the electronic patient records at the respective centers. Consequently, the pseudonymized data from all centers were pooled and analyzed centrally at the Amsterdam UMC. To obtain information on experience and training, surgical technique, and case selection, an online survey was sent out to all centers via Qualtrics (Qualtrics, Provo, UT, USA) (Supplement 1, see http://links.lww.com/AOSO/A437).

Outcomes and Definitions

Segment nomenclature followed the Couinaud classification.[21] Liver resections were categorized into minor, technically major, and anatomically major.[22,23] Minor and technically major resections were defined as any resection involving less than 3 adjacent anterolateral (2, 3, 4b, 5, and 6) or posterosuperior (1, 4a, 7, and 8) segments, respectively. Anatomically major resections were resections involving 3 or more adjacent segments. The terms segmentectomy, bisegmentectomy, trisegmentectomy, and left/right hemihepatectomy were defined according to the Brisbane 2000 nomenclature.[24]

Collected baseline patient characteristics included age at the time of surgery, sex, body mass index (kg/m^2), American Society of Anesthesiologists (ASA) grade, Charlson Comorbidity Index, use of neoadjuvant chemotherapy, presence of cirrhosis, history of extrahepatic abdominal surgery, and history of liver surgery. The following disease characteristics were recorded: histological diagnosis, size of the largest lesion, number of lesions on computed tomography, location of lesions (by Couinaud segments), and presence of bilobar disease. Procedure characteristics consisted of surgical approach (robotic or laparoscopic), resection year, hepatectomy type (wedge, segmentectomy, bisegmentectomy, trisegmentectomy, left or right [extended] hemihepatectomy, or other anatomically major procedure), classification (minor, technically major, anatomically major), and concurrent other abdominal surgery except cholecystectomy.

Intraoperative outcomes were intraoperative blood loss and conversion to open surgery. Postoperative outcomes were length of hospital stay, intensive care unit stay, overall postoperative morbidity (classified according to the Clavien–Dindo classification[25]), severe morbidity (defined by Clavien–Dindo classification grade IIIa or higher),[25] presence or absence of bile leakage and/or liver failure (defined according to the International Study Group of Liver Surgery[26]), readmission, percutaneous/endoscopic reintervention, reoperation, and mortality. Postoperative outcomes were reported with a follow-up of 30 days. Oncological outcomes were resection margin status, reported as microscopically radical (R0, ≥1 mm tumor-free margin from the transection surface), microscopically irradical (R1, <1 mm tumor-free margin from the transection surface), or macroscopically irradical (R2).

A center's learning curve was defined as 50 minimally invasive procedures for LLR and 25 for RLR based on a systematic review.[27] High-volume centers were defined as centers with an average volume of ≥20 MILS procedures annually since implementing MILS.[3]

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics version 29.0 (IBM, Armonk, NY, USA) and R for Mac OS X version 4.2.1 (R Foundation for Statistical Computing, Vienna, Austria). Nonparametric data are expressed as medians with interquartile range (IQR). Normality was assessed by visually inspecting histograms and Q–Q plots. Categorical variables are reported as counts and percentages. Independent samples *t* test was applied to normally distributed variables and the Mann–Whitney *U* test to nonparametric data. Categorical variables were analyzed using chi-squared tests or Fisher exact test where appropriate. PSM was performed, to minimize selection bias, in a 1:1 ratio using nearest-neighbor matching with a caliper of 0.2, without replacement using the 'MatchIt' package.[28] The following covariates were used for matching: sex, age, ASA score, Charlson Comorbidity Index, history of previous extrahepatic abdominal surgery, history of liver surgery, uni or bilobar disease, number of lesions, size of the largest lesion, pathological diagnosis, presence of cirrhosis, performance of a concurrent abdominal surgery, except cholecystectomy, and hepatectomy type and classification. Missing data were present in a small number of the covariates in a missing-at-random pattern and ranged from 0% to 10.7%. Prior to PSM, missing data in the baseline characteristics were handled by means of single imputation. Outcome data were not imputed. After matching, the balance was assessed using standardized differences. A standardized mean difference ≤ 0.1 is considered optimal balance. Categorical data were compared using McNemar test. Ordinal and continuous data were compared using the Wilcoxon signed rank test. Subgroup analyses were performed after stratification for hepatectomy type (minor, technically major, and anatomically major). Several sensitivity analyses were performed, of the procedures performed after the completion of a center's learning curve, in high-volume centers, procedures performed between 2019 and 2022, and when excluding patients that underwent concurrent abdominal surgery, excluding cholecystectomy. Additionally, a sensitivity analysis was performed, excluding procedures in which conversion to open surgery occurred. Statistical significance was considered as a 2-tailed *P* value <0.05.

RESULTS

Center Characteristics

The annual volume of RLR and LLR is depicted in Figure 1. The majority of MILS procedures are performed laparoscopically (58.7% in 2022). Eight centers (40%) began performing laparoscopy during the early study period (2014–2018) while the other centers had already implemented it prior to 2014. Implementation of RLR increased from 2.2% of MILS procedures in 2014 to 41.3% in 2022. The median annual center volume of MILS was 19 (IQR: 8–27) throughout the study period. Nine (45%) of the included centers were high volume (≥20 MILS procedures per year). As of 2022, only 5 centers perform solely LLR. Of the centers performing both RLR and LLR (n = 11), there is only one center with surgeons dedicated to either one of the approaches. The median number of surgeons performing MILS per center is 2, ranging from 1 to 6 (Supplement 2, see http://links.lww.com/AOSO/A437).

Surgeon Experience and Training

Among the participating surgeons, training and experience for minimally invasive procedures were largely heterogeneous (Supplement 3, see http://links.lww.com/AOSO/A437). Twelve surgeons (80%) reported having previous robotic surgery experience with other abdominal procedures prior to starting with RLR (Supplement 3, see http://links.lww.com/AOSO/A437).

Patient Selection

Reported contraindications for MILS per center included Klatskin tumors (n = 18, 90%), central location of lesion (n = 10, 50%), extended hemihepatectomy (n = 8, 40%), proximity to large vessels or biliary structures (n = 6, 30%), anatomically major resection (n = 3, 15%), previous liver surgery (n = 1, 5%), tumor location in the posterosuperior segments (n = 1, 5%) and need for more than 2 large wedge resections (n = 1, 5%) (Supplement 4, see http://links.lww.com/AOSO/A437).

Surgical Technique

Robotic procedures were performed using the Da Vinci Xi (n = 9, 60%), Da Vinci X (n = 4, 27%), and Da Vinci Si (n = 2, 13%) robotic systems (Supplement 5, see http://links.lww.com/AOSO/A437). An overview of the instruments utilized is available in Supplement 5, see http://links.lww.com/AOSO/A437. Laparoscopic-assisted RLR using an ultrasonic aspirator device was performed in just 2 centers (10%), for specific indications. About 20% of centers reported using an ultrasonic aspirator for all LLRs, while another 35% used it on indication. In centers performing RLR, ultrasound was performed robotically in 8 centers (53%) and otherwise laparoscopically (Supplement 6, see http://links.lww.com/AOSO/A437). Indocyanine green (ICG) fluorescence imaging was used in most centers (n = 14, 70%). ICG was primarily used for tumor imaging (Supplement 5, see http://links.lww.com/AOSO/A437). Of the 6 centers (30%) not using ICG, 4 were laparoscopy-only centers. Three-dimensional vision was used

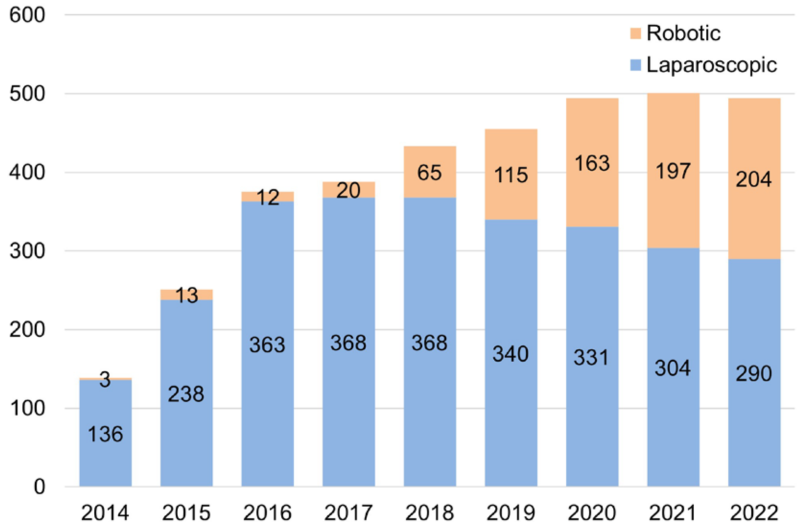

FIGURE 1. Annual volume of laparoscopic and robotic liver surgery in the Netherlands.

TABLE 1.

Baseline, Disease, and Procedural Characteristics in the Overall Cohort Stratified by the Used Surgical Approach, Before and After Propensity Score Matching

	Before PSM				After PSM			
	Robotic	Laparoscopic			Robotic	Laparoscopic		
	n = 792	n = 2738	*P*	SMD	n = 781	n = 781	*P*	SMD
Age, y	65 (54–73)	65 (56–73)	0.724	0.028	65 (54–73)	65 (55–73)	0.791	0.012
Male gender	438 (55.3)	1569 (57.3)	0.317	0.040	434 (55.6)	441 (56.5)	0.760	0.018
BMI	26.2 (23.4–29.4)	26 (23.4–29.1)	0.221	0.065	26.2 (23.4–29.4)	25.9 (23.4–28.7)	0.123	0.077
ASA score ≥ 3	241 (30.4)	734 (26.8)	0.045*	0.080	234 (30.0)	243 (31.1)	0.656	0.025
Charlson Comorbidity Index	3 (2–4)	3 (1–4)	0.058	0.075	3 (2–4)	3 (1–5)	0.666	0.042
Presence of liver cirrhosis	48 (6.1)	152 (5.6)	0.585	0.022	48 (6.1)	42 (5.4)	0.585	0.033
Pathological diagnosis			<0.001*	0.238			0.849	0.056
Colorectal metastases	469 (59.2)	1793 (65.5)			468 (59.9)	478 (61.2)		
Hepatocellular carcinoma	93 (11.7)	226 (8.3)			91 (11.7)	89 (11.4)		
Cholangiocarcinoma	25 (3.2)	41 (1.5)			23 (2.9)	23 (2.9)		
Gallbladder carcinoma	15 (1.9)	12 (0.4)			10 (1.3)	10 (1.3)		
Noncolorectal metastases	46 (5.8)	210 (7.7)			46 (5.9)	39 (5.0)		
Other malignancy	5 (0.6)	10 (0.4)			5 (0.6)	3 (0.4)		
Benign	139 (17.6)	446 (16.3)			138 (17.7)	139 (17.8)		
Neoadjuvant chemotherapy	146 (18.4)	437 (16.0)	0.099	0.066	145 (18.6)	107 (13.7)	0.010	0.133
Previous abdominal surgery								
Extrahepatic	428 (54.0)	1663 (60.7)	0.001*	0.136	427 (54.7)	445 (57.0)	0.372	0.046
Hepatic	76 (9.6)	263 (9.6)	0.994	<0.001	75 (9.6)	68 (8.7)	0.600	0.031
Size largest lesion, mm	28 (17–44)	26 (16–43.5)	0.303	0.034	28 (17–43.2)	27 (16–44)	0.848	0.017
No. lesions	1 (1–2)	1 (1–2)	0.577	0.008	1 (1–2)	1 (1–2)	0.911	0.036
Bilobar disease	141 (17.8)	766 (28.0)	<0.001*	0.244	141 (18.1)	145 (18.6)	0.825	0.013
Complexity of resection			<0.001*	0.221			0.904	0.036
Minor	415 (52.4)	1722 (62.9)			410 (52.5)	406 (52.0)		
Technically major	281 (35.5)	796 (29.1)			280 (35.9)	291 (37.3)		
Major	96 (12.1)	220 (8.0)			91 (11.7)	84 (10.8)		
Type of resection			0.001*	0.194			0.509	0.088
Wedge	434 (54.8)	1695 (61.9)			429 (54.9)	441 (56.5)		
Segmentectomy	124 (15.7)	356 (13.0)			123 (15.7)	123 (15.7)		
Bisegmentectomy	138 (17.4)	467 (17.1)			138 (17.7)	133 (17.0)		
Trisegmentectomy	10 (1.3)	31 (1.1)			10 (1.3)	5 (0.6)		
Left hemi hepatectomy	33 (4.2)	55 (2.0)			31 (4.0)	26 (3.3)		
Right hemihepatectomy	45 (5.7)	117 (4.3)			43 (5.5)	46 (5.9)		
Extended left hemi hepatectomy	1 (0.1)	2 (0.1)			1 (0.1)	2 (0.3)		
Extended right hemi hepatectomy	4 (0.5)	4 (0.1)			3 (0.4)	3 (0.4)		
Other anatomically major	3 (0.4)	11 (0.4)			3 (0.4)	2 (0.3)		
Anatomical resection	350 (44.2)	1036 (37.8)	0.001*	0.129	344 (44.0)	339 (43.4)	0.833	0.013
Concurrent ablation	44 (5.6)	222 (8.1)	0.017*	0.101	44 (5.6)	44 (5.6)	1	<0.001
Concurrent colorectal operation	40 (5.1)	217 (7.9)	0.006*	0.117	40 (5.1)	42 (5.4)	0.905	0.011
Concurrent noncholecystectomy operation	91 (11.5)	517 (18.9)	<0.001*	0.207	91 (11.7)	93 (11.9)	0.930	0.008

Values are expressed in counts (percentages) or median (IQR).Counts may not add up due to missing data.
BMI indicates body mass index; SMD, standardized mean difference. *statistically significant

during LLR for all cases in 4 centers (20%) and on indication in 4 others (20%). The specimen was primarily extracted through a trocar site following minor liver resection (80%) and through a Pfannenstiel (94.7%) following major liver resection (Supplement 5, see http://links.lww.com/AOSO/A437).

Before Matching

Between January 2014 and December 2022, 3530 MILS procedures met the eligibility criteria, of which 2738 LLR and 792 RLR. The median age was 65 years (IQR: 55–73) and 56.9% were male. Most resections (64.1%) were performed for colorectal liver metastasis. Baseline characteristics are presented in Table 1. A higher proportion of patients in the LLR group had previously undergone extrahepatic abdominal surgery (60.7% vs 54%, *P* = 0.001), had bilobar disease (28% vs 17.8%, *P* < 0.001), and underwent concurrent ablations (8.1% vs 5.6%, *P* = 0.017) as well as concurrent other abdominal surgery, excluding cholecystectomy (18.9% vs 11.5%, *P* < 0.001). RLRs were more often of higher technical complexity; with more technically major (35.5% vs 29.1%) and anatomically major resections (12.1% vs 8.0%), *P* < 0.001. The RLR group had advantageous perioperative outcomes regarding intraoperative blood loss (median, 100 [IQR: 50–300] vs 180 mL [50–450], *P* = 0.003), rate of conversion to open surgery (4.9% vs 13.5%, *P* < 0.001), and length of hospital stay (median, 3 [2–5] vs 4 [2–6] days, *P* < 0.001) (Table 2).

After Matching

PSM resulted in 781 pairs for analysis (1562 patients). Baseline variables were well-matched after PSM (Table 1). Perioperative outcomes are reported in Table 2. RLR was associated with reduced median intraoperative blood loss (100 mL [50–300]) vs 200 mL [50–500], *P* = 0.002) and a lower conversion rate (4.9% vs 12.8%, *P* < 0.001), compared with LLR. Postoperatively, the median length of hospital stay was 1 day shorter for RLR (*P* < 0.001). No statistically significant differences were observed for other postoperative outcomes including morbidity (19.6% vs 20.7%, *P* = 0.626) and mortality (0.6% vs 0.9%, *P* = 0.773). There was no significant

TABLE 2.

Intra- and Postoperative Outcomes in the Overall Cohort Stratified by the Used Surgical Approach, Before and After Propensity Score Matching

	Before PSM			After PSM		
	Robotic	Laparoscopic		Robotic	Laparoscopic	
	n = 792	n = 2738	*P*	n = 781	n = 781	*P*
Intraoperative						
Blood loss, mL	100 (50–300)	180 (50–450)	0.003*	100 (50–300)	200 (50–500)	0.002*
Major blood loss (≥500 mL)	135 (18.8)	596 (23.8)	0.005*	132 (18.6)	178 (25.2)	0.011*
Conversion to an open procedure	39 (4.9)	369 (13.5)	<0.001*	38 (4.9)	100 (12.8)	<0.001*
Postoperative						
Postoperative length of stay, days	3 (2–5)	4 (2–6)	<0.001*	3 (2–5)	4 (2–6)	<0.001*
Intensive care unit admission	55 (7.0)	242 (9.1)	0.065	53 (6.8)	58 (7.7)	0.617
Overall morbidity	156 (19.7)	559 (20.4)	0.665	153 (19.6)	162 (20.7)	0.626
Liver failure	5 (0.7)	20 (0.7)	0.844	5 (0.7)	4 (0.5)	1
Bile leak	17 (2.3)	68 (2.5)	0.710	17 (2.3)	16 (2.1)	1
Severe morbidity	74 (9.4)	255 (9.4)	0.978	73 (9.4)	70 (9.0)	0.862
Highest Clavien–Dindo grade			0.596			0.888
Grade 1	25 (3.2)	77 (2.8)		25 (3.2)	26 (3.4)	
Grade 2	54 (6.9)	192 (7.1)		52 (6.7)	59 (7.6)	
Grade 3a	46 (5.8)	132 (4.9)		46 (5.9)	40 (5.2)	
Grade 3b	10 (1.3)	66 (2.4)		10 (1.3)	18 (2.3)	
Grade 4a	11 (1.4)	38 (1.4)		11 (1.4)	4 (0.5)	
Grade 4b	1 (0.1)	2 (0.1)		1 (0.1)	1 (0.1)	
Grade 5	6 (0.8)	19 (0.7)		5 (0.6)	7 (0.9)	
Readmission	45 (5.7)	145 (5.5)	0.857	45 (5.8)	36 (4.8)	0.368
Reintervention	70 (8.8)	210 (7.7)	0.284	70 (9.0)	62 (7.9)	0.533
Reoperation	8 (1.0)	67 (2.5)	0.013*	8 (1.0)	14 (1.8)	0.286
Mortality	6 (0.8)	20 (0.7)	0.937	5 (0.6)	7 (0.9)	0.773
Resection margin status			0.084			0.090
Microscopically radical (R0)	546 (85.7)	1946 (88.5)		539 (85.8)	544 (87.6)	
Microscopically irradical (R1)	89 (14.0)	240 (10.9)		87 (13.9)	76 (12.2)	
Macroscopically irradical (R2)	2 (0.3)	12 (0.5)		2 (0.3)	1 (0.2)	

Values are expressed in counts (percentages) or median (IQR). *statistically significant

difference in the R0 rate following RLR and LLR (85.8% vs 87.6%, respectively, *P* = 0.090).

Sensitivity Analysis Excluding Conversions

After the exclusion of the converted cases, PSM resulted in a well-matched cohort with 735 patients in each group (Table 3). In this analysis, RLR was solely associated with significantly less reoperations (1.1% vs 2.7%, *P* = 0.038), other perioperative outcomes were similar.

Minor, Technically Major, and Anatomically Major Resections

The unmatched baseline characteristics and outcomes of the subgroups are summarized in Supplementary Tables 1 and 2, see http://links.lww.com/AOSO/A437. PSM yielded 408, 272, and 82 matched pairs of minor, technically major, and anatomically major resections, respectively (Supplementary Table 3, see http://links.lww.com/AOSO/A437). Some imbalance remained after PSM. In the minor and technically major resections, RLR was associated with less intraoperative blood loss (respectively, median: 100 mL [IQR: 40–200] vs 100 mL [IQR: 50–300], *P* < 0.001 and 150 mL [IQR: 50–400] vs 250 mL [IQR: 100–600], *P* = 0.007) (Table 4). The conversion rate was lower with RLR for both minor (2.5% vs 11.3%, *P* < 0.001) and technically major resections (6.6% vs 15.4%, *P* < 0.001), compared with LLR. Length of hospital stay was also shorter for RLR in the minor (3 [IQR: 2–4] vs 4 [IQR: 2–5] days, *P* < 0.001) and technically major subgroups (3 [IQR: 2–5] vs 4 [IQR: 3–6] days, *P* < 0.001). No differences were observed between RLR and LLR regarding other postoperative outcomes across all subgroups.

Sensitivity Analyses

Baseline characteristics and outcomes of the sensitivity analysis are displayed in Supplementary Tables 4 and 5, see http://links.lww.com/AOSO/A437. When excluding patients who underwent concurrent abdominal surgery, excluding cholecystectomy (n=688 per group), similar benefits of RLR were observed as in the primary analysis. The sensitivity analysis of patients operated after the centers' learning curve (n = 508 per group) and between 2019 and 2022 (n = 669 per group) also yielded comparable results as the primary analysis, although the median length of stay was 3 days following both RLR (IQR: 2–5) and LLR (IQR: 2–5), *P* = 0.053 in the most recent years (2019–2022). In high-volume centers, RLR was associated with less blood loss (median: 100 mL [IQR: 50–300] vs 200 mL [50–500], *P* < 0.001), major blood loss (17.9% vs 25.6%, *P* = 0.007), conversions to open surgery (3.6% vs 11.7%, *P* < 0.001) but a similar length of stay as LLR (median: 4 [IQR: 2–5] vs 4 days [IQR: 2–5], *P* = 0.596).

DISCUSSION

This nationwide study comparing population-based outcomes of RLR and LLR utilizing PSM found that RLR was associated with decreased intraoperative blood loss, less conversions, and shorter hospital stays. Patient safety was not compromised as evidenced by similar morbidity and mortality rates compared to LLR. Less intraoperative blood loss, major blood loss, and conversions in RLR were consistent findings across all sensitivity analyses, including in procedures without concurrent abdominal surgery except cholecystectomy, in high-volume centers, in recent years (2019–2022), and post-centers' learning curve.

TABLE 3.

Baseline, Disease, Procedural Characteristics, and Intra- and Postoperative Outcomes in the Sensitivity Analysis Excluding Conversions Stratified by the Used Surgical Approach, After Propensity Score Matching

	Robotic	Laparoscopic		
	n = 735	n = 735	*P*	SMD
Characteristics				
Age, y	65 (54–73)	65 (54–73)	0.814	0.031
Male gender	408 (55.5)	407 (55.4)	1	0.003
BMI	26.1 (23.3–29.3)	26 (23.4–28.7)	0.089	0.104
ASA score ≥ 3	216 (29.4)	220 (29.9)	0.864	0.012
Charlson Comorbidity Index	3 (2–4)	3 (1–4)	0.903	0.009
Presence of liver cirrhosis	43 (5.9)	48 (6.5)	0.664	0.028
Pathological diagnosis			0.869	0.064
Colorectal metastases	449 (61.1)	439 (59.7)		
Hepatocellular carcinoma	85 (11.6)	84 (11.4)		
Cholangiocarcinoma	20 (2.7)	20 (2.7)		
Gallbladder carcinoma	4 (0.5)	3 (0.4)		
Noncolorectal metastases	42 (5.7)	39 (5.3)		
Other malignancy	3 (0.4)	5 (0.7)		
Benign	132 (18.0)	145 (19.7)		
Neoadjuvant chemotherapy	135 (18.4)	103 (14.0)	0.025*	0.118
Previous abdominal surgery				
Extrahepatic	403 (54.8)	412 (56.1)	0.661	0.025
Hepatic	73 (9.9)	72 (9.8)	1	0.005
Size largest lesion, mm	28 (17–42.5)	25 (16–41)	0.134	0.030
No. lesions	1 (1–2)	1 (1–2)	0.492	0.003
Bilobar disease	133 (18.1)	124 (16.9)	0.554	0.032
Complexity of resection			0.182	0.044
Minor	394 (53.6)	410 (55.8)		
Technically major	260 (35.4)	249 (33.9)		
Major	81 (11.0)	76 (10.3)		
Type of resection			0.552	0.048
Wedge	408 (55.5)	415 (56.5)		
Segmentectomy	115 (15.6)	120 (16.3)		
Bisegmentectomy	131 (17.8)	124 (16.9)		
Trisegmentectomy	9 (1.2)	9 (1.2)		
Left hemi hepatectomy	28 (3.8)	29 (3.9)		
Right hemihepatectomy	40 (5.4)	34 (4.6)		
Extended right hemi hepatectomy	2 (0.3)	2 (0.3)		
Other anatomically major	2 (0.3)	2 (0.3)		
Anatomical resection	322 (43.8)	317 (43.1)	0.818	0.014
Concurrent ablation	40 (5.4)	46 (6.3)	0.571	0.035
Concurrent colorectal operation	39 (5.3)	36 (4.9)	0.804	0.019
Concurrent noncholecystectomy operation	84 (11.4)	85 (11.6)	1	0.004
Intraoperative outcomes				
Blood loss, mL	100 (50–300)	150 (50–350)	0.160	
Major blood loss (≥500 mL)	106 (15.8)	129 (18.9)	0.227	
Postoperative outcomes				
Postoperative length of stay, days	3 (2–5)	3 (2–5)	0.006*	
Intensive care unit admission	45 (6.2)	53 (7.4)	0.594	
Overall morbidity	138 (18.8)	129 (17.6)	0.589	
Liver failure	3 (0.4)	5 (0.7)	0.724	
Bile leak	13 (1.9)	20 (2.8)	0.473	
Severe morbidity	65 (8.9)	67 (9.2)	0.926	
Highest Clavien–Dindo grade			0.864	
Grade 1	25 (3.4)	21 (2.9)		
Grade 2	45 (6.2)	36 (4.9)		
Grade 3a	39 (5.3)	33 (4.5)		
Grade 3b	9 (1.2)	22 (3.0)		
Grade 4a	11 (1.5)	6 (0.8)		
Grade 4b	1 (0.1)	0 (0.0)		
Grade 5	5 (0.7)	6 (0.8)		
Readmission	41 (5.6)	33 (4.7)	0.403	
Reintervention	61 (8.3)	59 (8.0)	0.923	
Reoperation	8 (1.1)	20 (2.7)	0.038*	
Mortality	5 (0.7)	6 (0.8)	1	
Resection margin status			0.366	
Microscopically radical (R0)	507 (85.9)	504 (88.1)		
Microscopically irradical (R1)	81 (13.7)	65 (11.4)		
Macroscopically irradical (R2)	2 (0.3)	3 (0.5)		

Values are expressed in counts (percentages) or median (IQR). Counts may not add up due to missing data.

BMI indicates body mass index; SMD, standardized mean difference. *statistically significant

TABLE 4.

Intra- and Postoperative Outcomes in the Different Procedure Subgroups Stratified by the Used Surgical Approach, After Propensity Score Matching

	Minor			Technically Major			Major		
	Robotic	Laparoscopic		Robotic	Laparoscopic		Robotic	Laparoscopic	
	n = 408	n = 408	*P*	n = 272	n = 272	*P*	n = 82	n = 82	*P*
Intraoperative outcomes									
Blood loss, mL	100 (40–200)	100 (50–300)	<0.001*	150 (50–400)	250 (100–600)	0.007*	400 (200–1000)	450 (150–700)	0.203
Major blood loss (≥500 mL)	37 (10.1)	66 (18.0)	0.001*	53 (21.4)	87 (33.6)	0.002*	37 (46.2)	36 (44.4)	0.868
Conversion to an open procedure	10 (2.5)	46 (11.3)	<0.001*	18 (6.6)	42 (15.4)	0.003*	11 (13.4)	15 (18.3)	0.540
Postoperative outcomes									
Postoperative length of stay, days	3 (2–4)	4 (2–5)	<0.001*	3 (2–5)	4 (3–6)	<0.001*	5 (4–8)	5 (4–7)	0.504
Intensive care unit admission	19 (4.7)	31 (7.9)	0.105	18 (6.7)	19 (7.2)	1	16 (19.5)	13 (16.0)	0.710
Overall morbidity	69 (16.9)	69 (16.9)	1	46 (17.0)	55 (20.2)	0.428	31 (37.8)	29 (35.4)	0.874
Liver failure	0	0	NA	2 (0.8)	0	0.480	3 (4.0)	4 (4.9)	1
Bile leak	8 (2.1)	7 (1.7)	0.789	2 (0.8)	3 (1.1)	1	6 (7.9)	3 (3.8)	0.505
Severe morbidity	29 (7.1)	32 (8.0)	0.795	27 (10)	22 (8.2)	0.532	14 (17.3)	14 (17.9)	1
Highest Clavien–Dindo grade			0.764			0.713			0.874
Grade 1	15 (3.7)	12 (3.0)		6 (2.2)	9 (3.3)		2 (2.5)	3 (3.8)	
Grade 2	23 (5.7)	19 (4.7)		13 (4.8)	21 (7.8)		14 (17.3)	8 (10.1)	
Grade 3a	17 (4.2)	16 (4.0)		18 (6.6)	14 (5.2)		9 (11.1)	6 (7.6)	
Grade 3b	7 (1.7)	11 (2.7)		1 (0.4)	6 (2.2)		2 (2.5)	4 (5.1)	
Grade 4a	3 (0.7)	5 (1.2)		5 (1.8)	2 (0.7)		2 (2.5)	0	
Grade 4b	1 (0.2)	0		0	0		0	0	
Grade 5	1 (0.2)	1 (0.2)		3 (1.1)	0		1 (1.2)	5 (6.3)	
Readmission	18 (4.4)	13 (3.4)	0.473	13 (4.8)	13 (5)	1	11 (13.4)	4 (5.3)	0.121
Reintervention	29 (7.1)	26 (6.4)	0.779	26 (9.6)	20 (7.4)	0.451	13 (15.9)	13 (15.9)	1
Reoperation	4 (1.0)	11 (2.7)	0.121	4 (1.5)	5 (1.9)	1	0 (0.0)	4 (4.9)	0.134
Mortality	1 (0.2)	1 (0.2)	1	3 (1.1)	0	0.248	1 (1.2)	5 (6.1)	0.221
Resection margin status			0.462			0.690			1
Microscopically radical (R0)	273 (86.9)	264 (89.8)		207 (87.0)	211 (88.3)		49 (79)	51 (79.7)	
Microscopically irradical (R1)	39 (12.4)	29 (9.9)		31 (13.0)	26 (10.9)		13 (21.0)	13 (20.3)	
Macroscopically irradical (R2)	2 (0.6)	1 (0.3)		0	2 (0.8)		0	0	

Values are expressed in counts (percentages) or median (IQR). Counts may not add up due to missing data. *statistically significant

A dramatic surge in the proportion of MILS procedures performed robotically in the Netherlands was observed during the study period (2.2%–41.3%). Similar trends have also been observed in North America and Italy.[29,30] Current evidence on RLR versus LLR is mainly comprised of small single-center experiences and a few large multicenter studies with mixed results.[12–14,29,31–36] One randomized controlled trial performed in a single high-volume expert center found no differences between RLR and LLR; however, it is limited in its generalizability because of its small sample size and expertise of the hospital it was conducted in.[16] Moreover, the sample size for this trial was calculated based on an anticipated difference in quality of life between RLR and LLR, which may not be the most suitable primary outcome for comparing 2 minimally invasive approaches.[37] In the present study, RLR was associated with a reduced conversion rate (4.9% vs 12.8%, $P < 0.001$), affirming the findings in the existing literature.[12,14,15,31–34] The modest decrease in blood loss with RLR aligns with other comparative studies.[12,14,15,32,33] More importantly, the present study reports that less patients in RLR group had major blood loss during surgery (18.6% vs 25.2%, $P = 0.011$).

The benefits of RLR such as less intraoperative blood loss and shorter length of stay in this cohort could likely largely be attributed to the decreased conversion rate, as objectified in the sensitivity analysis excluding converted cases. This is the first study to demonstrate this, as previous studies that reported favorable outcomes for RLR did not perform such analyses. These findings suggest that the ability to complete more procedures minimally invasive is the primary factor contributing to the benefits of RLR. This consequently implies that for procedures where the chance of conversion is low, the use of the robot might have limited added value. However, this is difficult to determine preoperatively, and in the present study, RLR was still associated with substantially less conversions during minor resections in the anterolateral segments, which are perceived as the easiest resections. The consequences of conversion to open surgery and its association with poorer intra- and postoperative outcomes have been extensively documented in the literature.[38–42] Conversions have even been shown to be associated with poorer oncological outcomes[39,43,44] as well as higher costs.[45,46]

It is important to note that the differences in length of hospital stay observed in the primary analysis may be a result of the later implementation of RLR and surgeons becoming comfortable with earlier discharge. This notion is supported by the sensitivity analyses in the later study period (2019–2022) and in high-volume centers where no difference in hospital stay between RLR and LLR is observed. However, the similar length of stay in these analyses might also be due to the smaller sizes of these groups, which could limit the impact of outcomes from converted procedures on the overall findings.

The differences in baseline characteristics prior to PSM are interesting as they indicate that RLR is applied more broadly to technically complex cases than LLR. Conversely, it seems LLR is favored in patients with prior extrahepatic abdominal surgery, bilobar disease, and when concurrent procedures are indicated. This is possibly because of greater flexibility regarding port placement in LLR. Each approach offers distinct advantages, and by carefully selecting the most suitable technique for each patient, a broader population can benefit from the advantages of MILS.

Patients undergoing minor and technically major hepatectomy had a reduced hospital stay following RLR compared with LLR. For anatomically major resections, no significant differences were found regarding length of stay. However, analyses of the anatomically major subgroup were limited by its small size. Studies from the International Robotic and Laparoscopic Liver Resection Study Group found that RLR was associated with a reduced length of stay in resections of higher technical complexity[33–35] but not in minor anterolateral resections.[12,34,36] This contrasts with our results, in which benefits of RLR were observed for both these types of resections. This can be explained by the reduction of conversions in RLR, also for minor anterolateral resections.

RLR appears to be safe, exhibiting similar rates of morbidity and mortality as LLR. The morbidity and mortality rates in the overall cohort are in line with benchmark outcomes and other large population-based studies.[47,48] Along with the use of minimally invasive techniques, a plethora of factors likely contribute to these positive outcomes, such as patient selection, surgeon training, Dutch annual volume requirement (≥20 procedures per year), and compliance with enhanced recovery after surgery protocols.

The field of robotic surgery is presently in a phase of innovation, offering opportunities for improvement. A Pan-European survey revealed that most surgeons are dissatisfied with the available instrumentation for robotic parenchymal transection.[49] Moreover, we observed large heterogeneity in the instruments used for RLR across centers. In LLR and open surgery, the Cavitron Ultrasonic Aspirator has been the instrument of choice for performing this part of the operation. Despite the lack of a similar robotic device, the intraoperative and short-term postoperative outcomes of RLR are favorable. This implies that the currently available devices along with the high degree of control facilitated by robotic assistance allow satisfactory transection of the liver parenchyma. In addition, the bedside surgeon can provide assistance with an ultrasonic dissector, with good results.[50,51] Few centers (10%) opted for this method in the current cohort. Furthermore, the robotic system offers an optimal platform for integrating new technologies such as intraoperative fluorescence imaging with ICG and image-guided surgical navigation.[7,52,53]

The outcomes of robotic liver surgery are promising; however, its widespread implementation faces substantial hurdles owing to the high costs associated with purchasing and maintaining the robotic system, as well as the costs involved in training specialized robotic teams. Consequently, accessibility to robotic platforms remains an issue, especially in less wealthy nations.

Several limitations of this study need to be acknowledged. First, its retrospective design introduces potential selection and time bias, especially considering that the robotic approach was adopted later, and easier cases are often selected during the initial learning curve. PSM was used but does not account for unidentified confounding variables. Some remaining imbalances following PSM in the subgroup and sensitivity analyses may have contributed to bias. Post learning curve and time-dependent sensitivity analyses were conducted, revealing similar results as the primary analysis. Unfortunately, the data at hand did not allow for a correction of the learning curve per surgeon; instead, corrections were made on a per-center basis. Similarly, previous laparoscopic experience in robotic surgery could not be corrected. Second, the study was limited by the set of available variables from the DHBA. Third, even though the study included a large nationwide sample, the number of anatomically major resections was low (12.6% in the matched sample). Therefore, the analysis of this subgroup was limited by a low statistical power, which could lead to type 1 and type 2 errors. A randomized trial is needed to address these limitations. Strengths of this study include its nationwide coverage based on mandatory audit data. PSM aided in limiting selection bias.

CONCLUSION

This nationwide study found that RLR is associated with less conversions, less intraoperative blood loss, and shorter hospitalization. These results favor continued implementation of the robotic platform. However, large, multicenter, randomized controlled trials are needed to verify these findings.

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