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Toward a Standardization of Learning Curve Assessment in Minimally Invasive Liver Surgery

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Objective: The aim was to analyze the learning curves of minimal invasive liver surgery (MILS) and propose standardized reporting.

Background: MILS offers benefits compared with open resections. For a safe introduction along the learning curve, formal training is recommended. However, definitions of learning curves and methods to assess it lack standardization.

Methods: A systematic review of PubMed, Web of Science, and CENTRAL databases identified studies on learning curves in MILS. The primary outcome was the number needed to overcome the learning curve. Secondary outcomes included endpoints defining learning curves and characterization of different learning phases (competency, proficiency, and mastery).

Results: Sixty articles with 12,241 patients and 102 learning curve analyses were included. The laparoscopic and robotic approach was evaluated in 71 and 18 analyses and both approaches combined in 13 analyses. Sixty-one analyses (60%) based the learning curve on statistical calculations. The most often used parameters to define learning curves were operative time ($n=64$), blood loss ($n=54$), conversion ($n=42$), and postoperative complications ($n=38$). Overall competency, proficiency, and mastery were reached after 34 [interquartile range (IQR) 19–56], 50 (IQR 24–74), and 58 (IQR 24–100) procedures, respectively. Intraoperative parameters improved earlier (operative time: competency to proficiency to mastery: −13%, 2%; blood loss: competency to proficiency to mastery: –33%, 0%; conversion rate (competency to proficiency to mastery; −21%, −29%), whereas postoperative complications improved later (competency to proficiency to mastery: −25%, −41%).

Conclusions: This review summarizes the highest evidence on learning curves in MILS taking into account different definitions and confounding factors. A standardized 3-phase reporting of learning phases (competency, proficiency, and mastery) is proposed and should be followed.

Keywords: minimally invasive liver surgery, robotic liver surgery, laparoscopic liver surgery, learning curve, surgical outcomes, surgical training

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Minimally invasive liver surgery (MILS) has significantly improved the outcomes of liver resections over the past 20 years. The minimally invasive approach presents a multitude of advantages over conventional open procedures, such as reduced postoperative complications, a shorter hospital stay, and an improved quality of life.[1–4] Importantly, in experienced centers, MILS yields comparable oncological outcomes compared with open approaches.[5–7] Given their perioperative benefits and oncologic safety, expert consensus guidelines advocate for a gradual implementation of MILS in benign and malignant indications.[2,8,9]

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Despite its growing worldwide adoption over the past decade,[10] MILS continues to present technical challenges with a demanding learning curve, especially in the context of complex resections.[11,12] However, definitions of learning curves vary greatly and have not been standardized in terms of procedures necessary to reach competency, the influence of surgeon training, and surgical complexity. Various thresholds to reach "the learning curve" have been proposed, spanning a wide range from 20 to over 80 cases, depending on the assessed outcome and the definition of the learning curve.[13]

In other surgical procedures, comprehensive definitions and proposals of standardized 3-phase learning curve models have recently been established, dividing the learning curve into the phases of competency, proficiency, and mastery.[14–16] Along those 3 phases, intraoperative, postoperative, and oncologic outcomes improve at different stages.[15] Interestingly, rather than time-based competency assessment, a modern way to evaluate surgical skills is based on the number of cases performed. Such a case-dependent international standardization of the different learning phases in MILS would be highly desirable.

The aim of this systematic review was to analyze the learning curves associated with both laparoscopic and robotic liver surgery and to establish the 3 phases of learning to standardize the reporting of learning curves in MILS.

METHODS

Systematic Literature Search Methodology

This review complies with the recommendations of the Cochrane Handbook for Systematic Reviews and Interventions and specific recommendations for surgical systematic reviews and is reported in line with the PRISMA guidelines (PRISMA checklist: Supplementary Table 1, Supplemental Digital Content 1, http://links.lww.com/SLA/F173).[17,18] A protocol was developed a priori and published on http://researchregistry.com on December 28, 2023 (Unique identifying number: reviewregistry1767). The systematic literature search was performed using MEDLINE, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL) databases.[19] The search terms were connected with Boolean operators and used in combination with medical subject headings. The systematic literature search included contributions listed in the abovementioned databases until December 29, 2023. No language restrictions were applied. Cross-referencing and manual search of the bibliographies of eligible publications were actively performed until January 2024 to identify further relevant studies for the review.

The following search strategy for Medline (via PubMed) was used: (Liver resection OR liver surgery) AND (laparoscop* OR minim* invasive OR robot* surgery OR robotic-assisted surgery OR da Vinci) AND (learning curve OR Proficiency OR Mastery OR Competency OR Learning phase) NOT (pancreatic surgery OR colorectal surgery OR animal).

Study Selection and Data Extraction

The selection of relevant articles was performed in 2 stages. Two of the authors (J.M.A.T. and F.H.) independently screened the titles and abstracts of all retrieved references. Duplicates were deleted before further review. Studies considered irrelevant were discarded. Full-text articles for each of the selected abstracts were analyzed. In cases where clarification was needed, a consensus was reached through discussion with the senior author of the study. For data extraction, a dedicated predefined spreadsheet was used. The study selection process is illustrated in the PRISMA flow diagram (Fig. 1).

Inclusion and Exclusion

Eligible for inclusion were comparative studies and case series (> 10 patients) with a specific number or range of procedures characterizing any learning curve MILS performed for benign or malignant hepatic pathologies. All parameters used to calculate- and describe the learning curve were included. The definition of the learning curve was adopted according to the definition of each individual study.

Exclusion criteria were (1) studies based on MILS living-donor operations, (2) articles not providing a case number or range at which the learning curve was attained, (3) articles that compared pre-existing data (systematic reviews and meta-analyses), (4) articles reporting emergency procedures. Abstracts and further material not associated with a full-text manuscript, such as congress abstracts were only included in the systematic review when sufficient data concerning the characteristics of the learning curve were available but were used carefully in further discussion. Studies reporting on experimental or cadaveric models were excluded.

Outcome Parameters

The number of procedures needed to surmount the "learning curve" according to the definition of each study was chosen as the primary outcome for this analysis. Secondary outcomes were the endpoints that were used for the definition of the learning curve, the methods of learning curve analysis (statistical calculation/arbitrary), and the classification of different learning phases. Further outcomes were extracted and evaluated according to availability: operative time, blood loss, conversion rate, postoperative complications, bile leakage, and posthepatectomy liver failure according to the International Study Group of Liver Surgery,[20,21] oncologic parameters (resection margin) and length of stay (LOS). If specified, surgeon-specific parameters were also captured, including surgical experience, yearly case volume, and specific training, including fellowships, mentoring, and proctoring.

Quality Assessment

The ROBINS-I tool was used for quality assessment. Seven domains —(1) confounding, (2) selection of participants, (3) classification of interventions, (4) deviations from intended interventions, (5) missing data, (6) measurement of outcomes, (7) selection of reported outcomes—were rated with either low, moderate, serious, critical risk of bias or no information.[22]

Statistical Analysis

Reported minimal numbers of the learning curves were displayed as median and range or interquartile range (IQR). Group comparison was performed by the Mann-Whitney *U* test. When studies reported more than one number of cases to overcome the learning curve, the lowest number mentioned was used. The analyses were stratified by the use of statistical methods to assess the learning curve and by approach (laparoscopic/robotic) and type of resection, respectively. The following parameters were assessed: (1) intraoperative (operative time, blood loss, and conversion rate) and (2) postoperative outcomes (overall-specific,

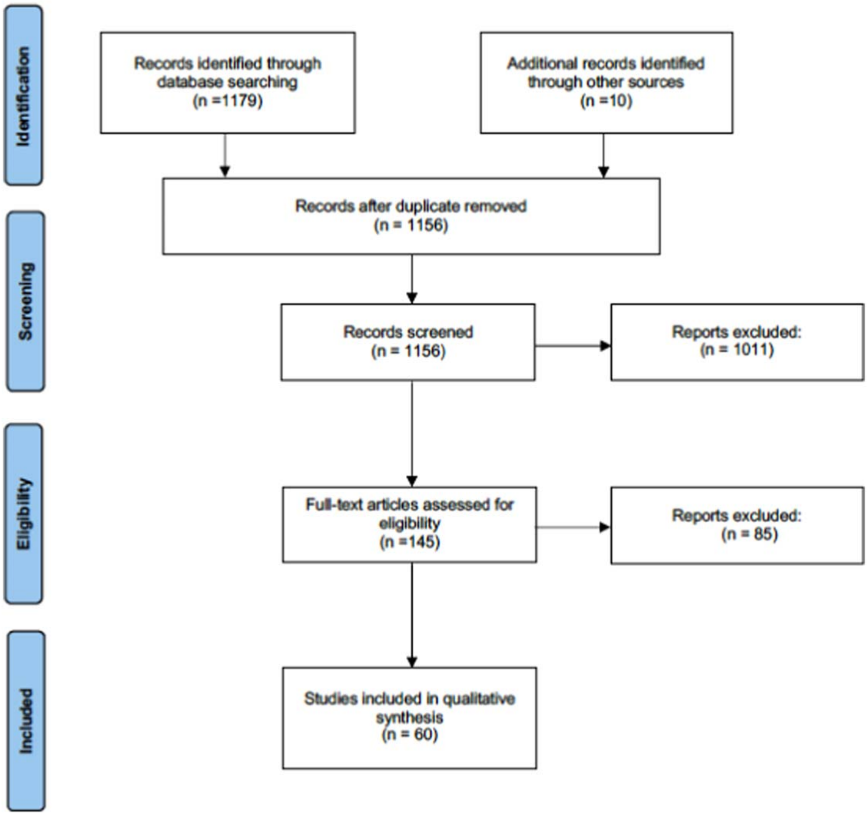

FIGURE 1. PRISMA flowchart.

disease-specific complications, and length of hospital stay). The correlation between learning curve numbers and the study sample size was assessed using the Spearman-rank coefficient. The association was considered weak (coefficient weak 0.1 to <0.3), moderate (0.3 to <0.5), or strong (≥0.5). R version 4.2.3, R Core Team, was used for all analyses and figures.[23]

RESULTS

Literature Search Results

The search yielded 1156 articles, and after full-text screening, 60 articles were included. The PRISMA flow diagram is presented in Figure 1. In total 12,241 patients were included (laparoscopic approach n = 8981, robotic approach n = 1190, both approaches n = 2070). From 60 studies, 102 individual learning curve analyses were included, which form the basis of the further analyses of this study. Table 1 shows the baseline characteristics of the included studies. Seventy-one analyses were reported on laparoscopic liver resections, 26 on laparoscopic minor, 19 on laparoscopic major, and 26 on laparoscopic mixed resections. Eighteen learning curve analyses were reported on robotic liver resections, 3 on minor, 8 on major, and 7 on mixed robotic resections. From the laparoscopic and robotic mixed analyses, 12/13 reported mainly minor liver resections.

How Is the Learning Curve Defined

In general, learning curves in MILS were heterogeneously defined. They were either based on a statistical calculation (60%) or an arbitrary split-group approach (40%) and the most frequently used statistical calculation method was the cumulative sum(CUSUM) (35%) or the risk-adjusted CUSUM analysis (8%). The majority of studies reported on 2 learning phases (64.7%), while 3 (25.5%) and up to 7 (3.9%) learning phases were also described (Supplementary Table 2, Supplemental Digital Content 1, http://links.lww.com/SLA/F173).

Most analyses reported on learning curves from individual surgeons (66.6%) or institutional learning curves (33.3%). However, the number of participating surgeons was only specified in half of the learning curve analyses (54.9%). Several important institutional baseline characteristics for the interpretation of the learning curve were not reported, such as institutional case volume (11.7%) or institutional MILS volume (28.3%). Likewise, information on surgeon-specific MILS training and previous MILS experience (20%) or MILS-specific training (45.0%) was reported in a minority of studies. In Table 2, the proposed baseline items for a standardized reporting of learning curves are presented.

The learning curve was defined by a single parameter in 60 analyses and by multiple endpoints in 42 analyses. For the definition of the learning curve, mainly intraoperative parameters were used, namely operative time (n = 64), blood loss (n = 54), and conversion rate (n = 47). Fewer studies used postoperative outcomes such as complications (n = 38) and LOS (n = 35) to define the learning curve, while none of the included studies specifically evaluated the learning curve for oncologic parameters.

What Changes Along the 3 Learning Phases

The phases of competency, proficiency, and mastery were analyzed to illustrate the change in intraoperative and

TABLE 1. Overview of the Baseline Characteristics of the Included Studies

References	Year	Surgeons (n)	Resection	Patients (n)	Analysis method	Learning curve phases (n)	Length of learning curve (n)	Factors
Laparoscopic								
Abu Hilal and Pearce[24]	2008	—	Minor	30	Arbitrary	2	15	OT
Aldrighetti et al[25]	2019	—	Mixed	1032	CUSUM	2	15	Conversion
Berardi et al[11]	2019	—	Minor	464	CUSUM	3	115	OT, EBL, conversion
Cai et al[26]	2009	—	Major	19	Arbitrary	2	8	Liver transection time
Cai et al[27]	2014	—	Major and minor	365	Arbitrary	7	15	OT, EBL, conversion, Comp, LOS
Cannon et al[28]	2011	—	Mixed	300	Arbitrary	3	100	OT, EBL, LOS, conversion, Comp
Chan et al[29]	2014	—	Mixed	100	Arbitrary	2	50	Conversion
Chan et al[30]	2016	2	Major	49	CUSUM	2	25	OT
Chang et al[31]	2007	—	Minor	36	Arbitrary	2	18	OT, EBL, LOS
Cho et al[32]	2019	—	Major	233	Arbitrary	2	5	OT, EBL, Conversion, Comp, LOS
D'Hondt et al[33]	2023	1	Mixed	240	Arbitrary	2	120	OT, EBL, Conversion, LOS, Comp
Fujikawa et al[34]	2023	5	Mixed	42	Regression	2	5	OT
Goh et al[35]	2014	2	Minor	147	Arbitrary	0	15	Conversion
Halls[36]	2019	4	Mixed	1736	RA CUSUM	3	17	LOS
Hasegawa et al[37]	2017	2	Mixed and major	245	Arbitrary	3	22	OT, EBL, LOS, Comp
Hasegawa et al[38]	2018	9	Major	120	Regression	2	14	OT
Homma et al[39]	2019	1	Minor	31	CUSUM	3	18	OT, EBL
Ivanecz et al[40]	2022	1	Mixed	171	Distribution function	3	-	EBL, Conversion,
Kim and Kim[41]	2020	1	Major	53	CUSUM	2	30	OT, EBL
Kluger et al[42]	2013	3	Mixed	174	Arbitrary	3	116	OT, EBL; Comp, reoperation
Komatsu et al[43]	2017	2	Minor and major	317	Arbitrary	2	15	Conversion
Lan et al[44]	2022	—	Minor and major	1098	CUSUM	3	17	EBL
Lee et al[45]	2016	1	Major and minor	170	CUSUM	2	25	OT, EBL
Lin et al[46]	2016	—	Mixed	126	CUSUM	4	22	Major operative events
Navarro et al[47]	2021	2	Mixed	106	RA CUSUM	2	42	Surgical failure
Navarro et al[48]	2020	1	Minor and major	272	RA CUSUM	3	19	Surgical failure
Nomi[49]	2015	1	Major	173	CUSUM	3	37	OT
Otsuka[50]	2009	—	Mixed	90	Arbitrary	2	45	OT, EBL, Comp
Ratti et al[51]	2016	—	Minor*	245	ROC	2	15	OT
Robinson et al[52]	2012	—	Mixed	37	Arbitrary	2	18	OT, conversion, Comp
Shanti et al[53]	2022	—	Mixed	286	RA CUSUM	2	50	EBL, conversion
Son et al[54]	2012	—	Mixed	138	Arbitrary	2	49	OT, EBL, LOS, Liver function
Spampinato et al[55]	2015	1	Major	70	Arbitrary	2	12	OT, EBL, transfusion, pringle time
Sultana et al[56]	2019	2	Minor	111	CUSUM	2	19	OT, conversion
Tomassini et al[57]	2016	1	Mixed	319	CUSUM	2	91	OT
Troisi et al[58]	2011	—	Minor	37	Arbitrary	2	10	OT, EBL
van der Poel[59]	2016	4	Major	159	Arbitrary	2	52	OT, EBL, conversion, Comp, LOS,
van der Poel et al[60]	2017	3	Mixed	135	CUSUM	3	19	Conversion

TABLE 1. (*continued*)

References	Year	Surgeons (n)	Resection	Patients (n)	Analysis method	Learning curve phases (n)	Length of learning curve (n)	Factors
Vigano et ak[61]	2009	4	Mixed and Minor	174	CUSUM and Arbitrary	3	58	OT, EBL, conversion, LOS, Comp
Villani et al[62]	2016	1	Mixed	150	Arbitrary	5	91	OT, EBL, Comp, LOS
Wang et al[63]	2013	—	Minor	49	Ordered sample cluster	2	18	OT, EBL
Yap and Bong[64]	2018	1	Mixed	44	CUSUM	2	17	Difficulty
Yoh[65]	2022	4	Mixed	382	Arbitrary	3	54	OT, EBL, Comp, transfusion, PHLF
Mixed								
Choi et al[66]	2014	—	Minor and major	100	Moving Average	2	10	OT, EBL
Efanov [67]	2017	2	Mixed	131	Correlation	2	16	Difficulty
Goh[68]	2018	10	Mixed	324	Arbitrary	2	20	OT, EBL, conversion
Goh[69]	2020	1	Mixed	200	RA CUSUM	2	65	OT, EBL, conversion, LOS, Transfusion
Marino et al[70]	2022	—	Mixed	212	CUSUM	3	40	OT, EBL, conversion
Patriti et al[71]	2015	1	Mixed	70	CUSUM	2	17	OT
Swaid et al[72]	2020	5	Mixed	1062	Arbitrary CUSUM	3	45	OT, conversion
Robotic								
Ahmad et al[73]	2023	1	Mixed and major	148	CUSUM	2	22	OT, EBL
Ceccarelli et al[74]	2018	—	Mixed	70	Arbitrary	—	70	Na
Fukumori et al[75]	2023	1	Mixed	100	Arbitrary	3	30	Conversion, LOS
Gravetz [76]	2019	—	Mixed	33	Arbitrary	3	11	OT, EBL, conversion, Comp, LOS
Görgec et alet al[77]	2023	19	Minor and major	400	CUSUM	3	19	LOS, EBL
Liu et al[78]	2020	3	Major	100	CUSUM	2	35	OT
Magistri et al[79]	2019	1	Mixed	60	CUSUM	2	30	OT
McCarron et al[80]	2023	6	Major	100	Arbitrary	2	50	OT, EBL, conversion, Comp, LOS, readmission, R0 rate
O'Connor et al[81]	2017	2	Minor	39	Arbitrary	3	15	EBL, Comp, LOS
Zhu et al[82]	2019	—	Mixed	140	CUSUM	3	30	OT, EBL, conversion, LOS, Comp

*Four centers, reported for each separately.
Comp indicates complications; OT, operative time.

TABLE 2. Standardized Reporting of Learning Curves in Minimally Invasive Liver Surgery and Adherence in Included Studies

	Reported (%)
Surgeon and institutional characteristics	
Annual volume of liver resections (institution/surgeon)	11.7
Annual volume of MILS (institution/surgeon)	28.3
Previous experience in open liver surgery (number of procedures)	50.0
Previous experience in MILS surgery (number of procedures)	20.0
Specific MILS training (proctoring/mentoring/ fellowship)	45.0
Patient characteristics	
BMI, ASA, comorbidities (division benchmark vs. non-benchmark patient[83,84])	98.3
Previous upper abdominal surgery or liver surgery	16.7
Liver cirrhosis	56.7
Complexity of the liver resection	
IWATE score[85,86]	28.3
Tumor size	96.8
Tumor location	100.0
Proximity to major vessels	10.0
Extent of liver resection	100.0
Perioperative outcomes (% within benchmark cutoffs)	
Intraoperative	100.0
Blood loss, operation time, conversion rate	
Postoperative	100.0
Complications according to Clavien-Dindo,[87] CCI[88]	
Liver surgery–specific complications such as PHLF,[20] bile leakage[21]	
Proportion reaching textbook outcomes[89]	
Oncologic	50.0
R0, recurrence-free survival, overall survival	

ASA indicates American society of anesthesiologists; BMI, body mass index; PHLF, posthepatectomy liver failure.

postoperative outcome parameters along the learning curve. Overall competency, proficiency, and mastery were reached after 34 (IQR 19–56), 50 (IQR 24–74), and 58 (IQR 24–100) procedures, respectively. From competency to proficiency, a marked improvement was mainly observed for intraoperative parameters, as demonstrated by a rapid reduction of operative time [competency to proficiency to mastery: 235 min (IQR 180–269) to 205 min (IQR 164–275) to 209 min (IQR 160–240)] and blood loss [competency to proficiency to mastery: 300 mL (IQR 195–409) to 200 mL (IQR 112–332) to 200 mL (IQR 129–258)]. From proficiency to mastery, postoperative complications [competency to proficiency to mastery: 12.0% (IQR 7.2–16.1) to 11.0% (IQR 6.1–17.2) to 5.3% (IQR 1.1–10)] and conversion rates [competency to proficiency to mastery: 9.5% (IQR 4.1–15.4) to 7.9% (IQR 2.7–10.0) to 5% (IQR 2.3–7.3)] decreased at a later stage (Fig. 2A–D).

Differences Between Statistically Calculated and Arbitrary Split Learning Curves

A total of 60% of analyses were based on statistical methods to define the phases of the learning curve, while the other 40% were arbitrarily split. When assessing the minimal number of cases needed to surpass the learning curve based on the approach used, there were minimal differences. The overall minimal number was 30 procedures (17–44) in the statistical group and 34 (18–57) in the arbitrary group ($P = 0.226$) (Fig. 3A). When looking at the different outcomes to define the learning curves, no difference was found for operative time [statistical: 30 (18–38) vs arbitrary: 40 (18–100); $P = 0.170$], EBL [statistical: 35 (21–50) vs arbitrary: 37 (23–51); $P = 0.918$], conversion [statistical: 45 (19–60) vs arbitrary: 25 (18–50); $P = 0.446$], and for LOS [statistical: 34 (22–65) vs arbitrary: 49 (30–90); $P = 0.595$], respectively.

Influence of Sample Size on Length of Learning Curve

There was a strong correlation between study sample size and the overall minimal number of cases reported (rho = 0.65) (Fig. 3B). Looking at the different outcome parameters of the learning curve analysis, this correlation remained strong for all operative time, EBL, and LOS (rho = 0.79, 0.89, and 0.73, respectively).

Differences Between the Laparoscopic and Robotic Approach

There was no difference in the number of procedures to surpass the first phase of the learning curve for minor resections [laparoscopic: 25 (10–106) vs robotic: 19 (15–109); $P = 0.903$] and mixed resections [laparoscopic: 47 (5–116) vs robotic: 30 (11–70); $P = 0.356$]. For major resections, the laparoscopic approach was associated with less procedures to surpass the first phase of the learning curve [laparoscopic: 19 (5–50) vs robotic: 40 (22–57); $P = 0.005$].

Risk of Bias Within Studies

Of the included studies most had a moderate or serious overall risk of bias. Moderate or serious overall risk of bias was mainly due to unclear reporting of items relevant to the assessment and analysis of the study. Supplementary Table 3, Supplemental Digital Content 1, http://links.lww.com/SLA/F173 depicts the risk of bias assessment.

DISCUSSION

This systematic review summarizes the best available evidence on learning curves in MILS. Furthermore, it proposes a standardized learning curve reporting as well as a 3-phase model with distinct changes of intraoperative and postoperative parameters along the learning curve.

Similar to other surgical fields, this systematic review defined a case dependent 3-phase learning model for MILS ie, competency, proficiency, mastery, with specific changes of intraoperative and postoperative outcomes along the learning curve (Fig. 4).[14,15,90,91] In the first phase, the surgical team or individual surgeon learns to carry out a procedure under the supervision of an experienced expert or proctor. This phase is characterized by selecting low-risk, benchmark patients with favorable anatomic and disease-specific conditions. Typically, a steep improvement of intraoperative metrics such as operative time or blood loss is observed. Interestingly, postoperative and oncologic outcomes improve less remarkably during the first phase. Reaching competency indicates that the surgeon is able to perform a procedure independently without supervision. In the second phase, a high standardization of the surgical approach is achieved and more complex cases are addressed through the already accumulated experience. Reaching proficiency is characterized by a less pronounced improvement of intraoperative parameters, while postoperative outcomes reach benchmark and textbook

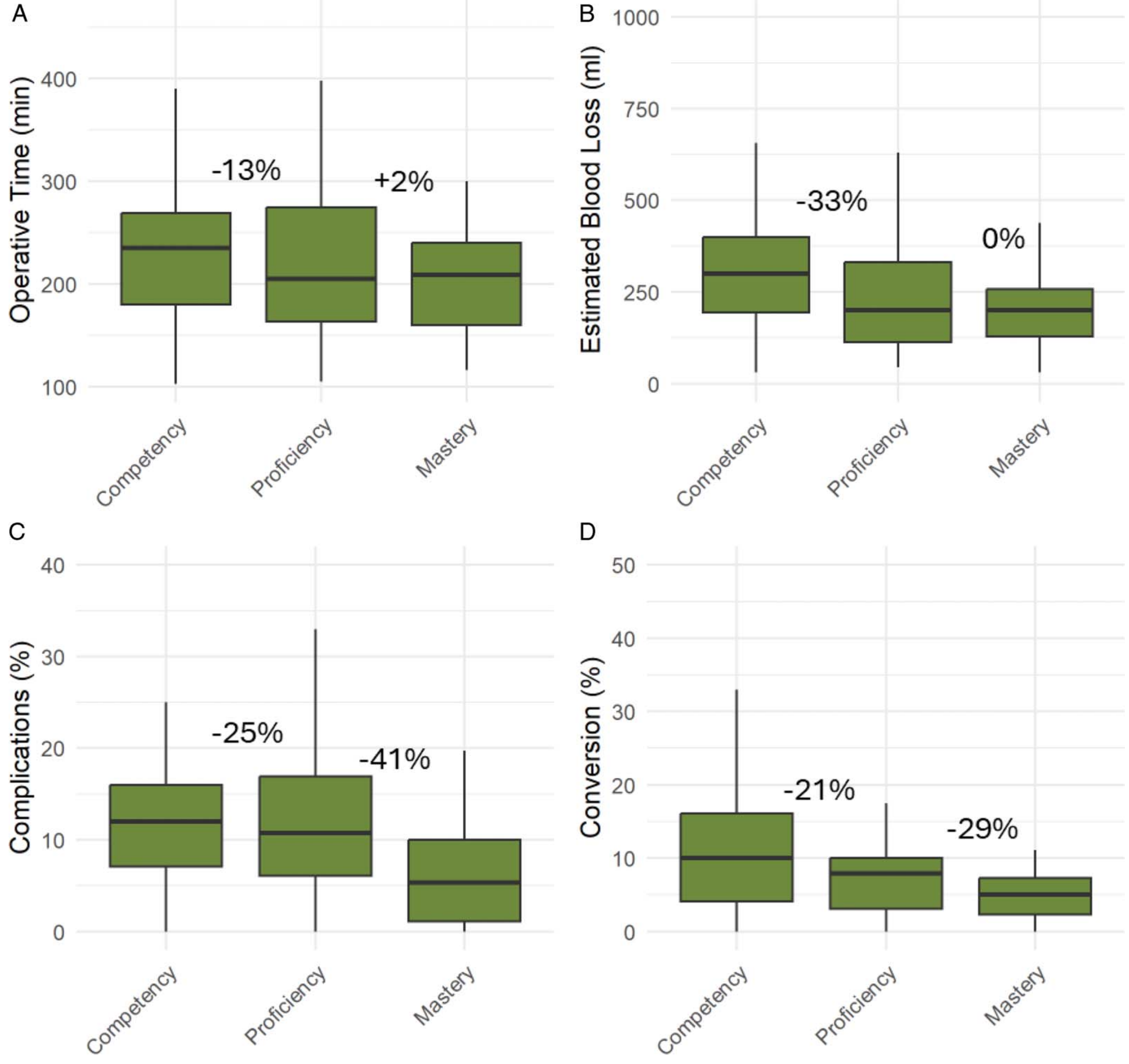

FIGURE 2. A–D, Changes in outcome parameters according to the 3 phases of the learning curve. Data are presented as median and interquartile range.

outcomes in a high percentage. In the third phase (mastery), complex indications are approached in difficult, comorbid, non-benchmark patients. Challenging intraoperative problems (eg, bleeding and vascular resections) may be solved by the minimally invasive approach without conversion; the surgeon can quickly and intuitively adapt to changing circumstances. Due to the selection of difficult cases, perioperative outcome improvement may initially stagnate in the mastery phase. However, later on, perioperative and oncological outcomes are clearly above benchmark or textbook outcomes even in complex patients. Contrary to time-dependent definitions of surgical proficiency, the suggested model strongly advocates for a case and not time-dependent evaluation of surgical learning.

The evolution of outcomes along the learning curve has far-reaching implications for clinical studies assessing novel surgical approaches, especially surgical robotics.[92] Most surgical innovations are introduced without the stepwise testing used in medical therapeutics and without taking into account the procedural learning curve with consequent risks to patient safety.[93,94] It is well known that intraoperative performance and the resulting surgical quality are strongly associated with postoperative outcomes and are important confounding factors when performing clinical studies or randomized controlled trials.[95,96] As an example of the influence of the learning curve, the LEOPARD-2 trial compared laparoscopic to open pancreatoduodenectomy (PD) and had to be prematurely terminated due to a 10% mortality in the laparoscopic group compared with 2% in the open group. Surgeons were only eligible after having performed at least 20 laparoscopic PD with a minimal institutional volume of 20 PD/year. Interestingly, the authors evaluated 41 videos from the laparoscopic group

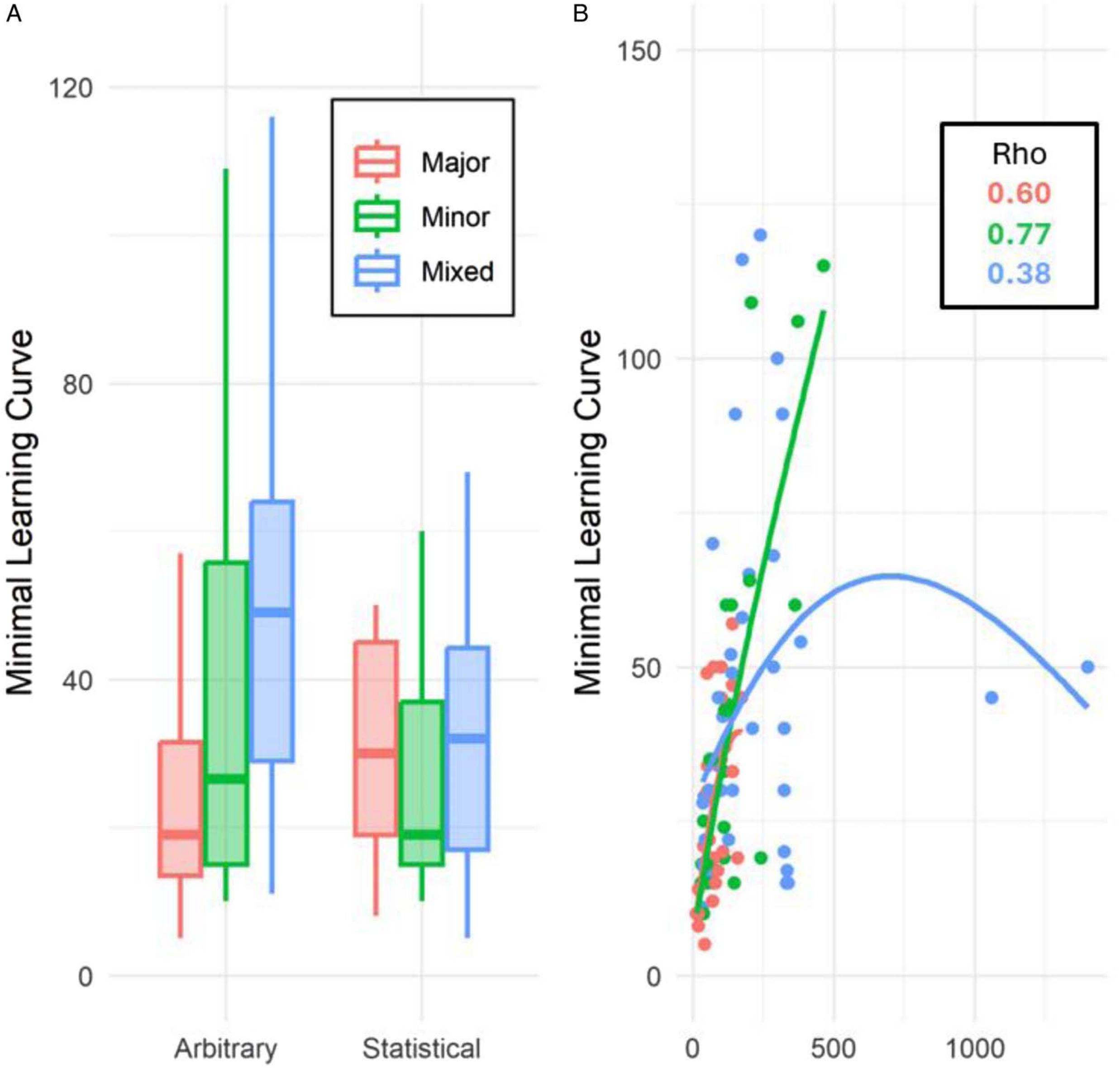

FIGURE 3. A, Minimal cases for the learning curve stratified by type of resection and type of statistical analysis. B, Correlation of study sample size and length of the learning curves. Data are presented as median and interquartile range.

and determined that every fifth video scored below the suggested minimum, meaning that the surgical quality could have significantly contributed to the main findings and termination of the study.[97]

Currently, most surgical RCTs do not account for learning curves or surgical quality, even though the IDEAL (Idea, Development, Exploration, Assessment, and Long-term monitoring) recommendations point out the importance of addressing this issue during the development and clinical introduction of novel techniques such as surgical robots.[92] A recent systematic review assessed the quality of 388 randomized surgical trials in high-impact journals and found that 78% of the studies did not control for surgical experience and < 5% assessed the quality of the surgical intervention.[98] In the few RCTs that reported surgical experience, predefined surgeon and center credentials were applied and mainly included a specific job level or prior number of years of surgical experience, definitions that are certainly inadequate to guarantee procedural quality.[99]

A modern, more objective approach to assessing surgical quality in clinical trials is video-based assessment (VBA), which was introduced especially in minimally invasive pancreatic, esophageal, and colorectal surgery.[100] VBA was shown to be a valid method for quality control, to display points for further improvement, and even predict postoperative outcomes.[101–104] In the near future, artificial intelligence assisted VBA-programs have the potential to implement an automated learning curve assessment with surgeon-tailored feedback and therefore dramatically improve the quality of the surgical training.[105,106]

For minor hepatectomies, the first phase of the learning curve was surpassed after 19 robotic and 25 laparoscopic

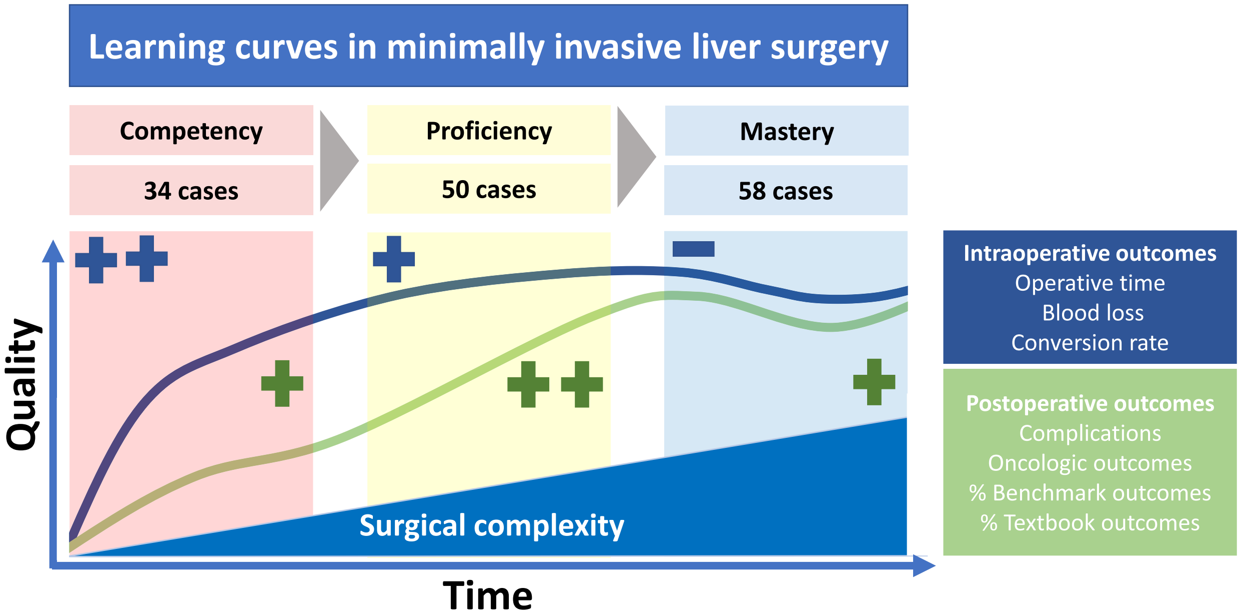

FIGURE 4. Changes in intraoperative and postoperative outcomes and selected surgical complexity along the 3 phases of the learning curve in minimally invasive liver surgery.

resections, in the mixed group after 30 robotic and 47 laparoscopic procedures, and in the major hepatectomy group after 40 robotic and 19 laparoscopic procedures. Those absolute numbers should be interpreted with caution as the definitions of learning curves varied greatly among the included studies, the methods to assess the learning curves were heterogenous and analyses did not adjust for the surgeons' previous experience or case complexity.

Some biases of the presented results should be kept in mind. Many analyses stem from pioneers in expert centers and do not factor in the optimization of the learning curve by targeted training and proctoring. Furthermore, little information was available about previous experience in open- or minimally invasive liver surgery.[107] Similar to the systematic review on learning curves in pancreatic surgery, only 60% of analyses based their learning curve on statistical analyses such as CUSUM.[15] Arbitrary split-group approaches may not allow for an adequate group comparison focusing on the relevant outcome changes over time. Furthermore, a strong correlation was found between study sample size and number of cases needed to surpass the learning curve. This presents an important bias when assessing learning phases and indicates that an adequate sample size is required to provide a realistic learning curve calculation, but even more that the currently used analytic strategies, including CUSUM, are highly influenced by the study sample size.[15]

To diminish bias and strengthen a standardized reporting of learning curves we propose to report the following confounding factors when reporting on MILS learning curves (Table 2):

- The institutional and individual surgeon's overall- and MILS case load as well as the surgeon's previous training and procedural experience.
- The patient's comorbidities, as they significantly influence the expected outcomes. A division in benchmark and non-benchmark patients could be presented based on comorbidities, underlying liver disease, and previous surgeries.[83,84]
- The technical complexity of the minimally invasive liver resection, preferentially based on the IWATE score. This difficulty-score takes into account tumor location and tumor size, proximity to major vessels, liver function as well as the extent of resection. The score is associated with intraoperative and postoperative outcomes in MILS.[85,86,108]

In addition to the presentation of the surgeon-, patient-, and procedural characteristics mentioned above, surgical outcome reporting must be standardized for a homogenous learning curve assessment. Reporting meaningful postoperative outcomes, such as complications and oncologic outcomes should be the focus of future learning curve research. Outcome reporting should further follow the Outcome4medicine consensus recommendations[109] and include both intraoperative, technical parameters such as blood loss and conversion rate as well as postoperative overall complications graded according to the Clavien-Dindo[110] classification and procedure-specific complications according to the international study group of liver surgery.[20,21,111] Furthermore, the overall burden of complications should be assessed with the Comprehensive Complication Index.[88,112,113] For an objective international comparison that takes into account the patient's risk profile, novel outcomes metrics should be integrated, eg, proportion of patients reaching international benchmark values.[84,114,115] Reporting learning curves in MILS with this standardized reporting system would highly enhance the comparability of learning curves between studies, institutions, and surgeons.

The present study is limited by the heterogenous definitions of the learning curve, which makes clinically meaningful comparisons difficult. Thus, this study is a qualitative review presenting the available evidence in an attempt to standardize reporting of learning curves in MILS. To diminish the heterogeneity of the included surgical procedures, we decided to exclude learning curve assessment of living-liver donation as this procedure is performed by expert liver surgeons in highly standardized settings.[116,117] Furthermore, the included studies were mostly of retrospective design, making them prone to significant selection bias. In addition, one has to keep in mind that most centers real learning curve consists of a mix of minor and major cases as well as laparoscopic and robotic surgeries as the centers gradually expand their indications. Therefore, the learning curves of mixed studies, although varying greatly, maybe closest to the real-life scenario of a "true" learning curve.

In conclusion, this review summarizes the best available evidence on learning curves in laparoscopic- and robotic liver surgery and their limitations such as different definitions, analysis methods, and various under-reported surgeon and patient-specific factors. A standardized 3-phase reporting of learning phases (competency, proficiency, and mastery) is proposed and showed a pronounced improvement of intraoperative parameters in the competency phase, while postoperative outcomes mainly improved in the proficiency and mastery phase. The assessment and analysis of learning curves of MILS have wide-ranging implications when conducting clinical studies or assessing novel surgical approaches (eg, robotic surgery) and should follow the herein proposed standardized reporting.

REFERENCES

1. Haney CM, Studier-Fischer A, Probst P, et al. A systematic review and meta-analysis of randomized controlled trials comparing laparoscopic and open liver resection. *HPB (Oxford)*. 2021;23:1467–1481.
2. Wakabayashi G, Cherqui D, Geller DA, et al. Recommendations for laparoscopic liver resection: a report from the second international consensus conference held in Morioka. *Ann Surg*. 2015;261:619–629.
3. Nguyen KT, Gamblin TC, Geller DA. World review of laparoscopic liver resection-2,804 patients. *Ann Surg*. 2009; 250:831–841.
4. Zhu P, Liao W, Zhang W-G, et al. A prospective study using propensity score matching to compare long-term survival outcomes after robotic-assisted, laparoscopic, or open liver resection for patients with BCLC stage 0-A hepatocellular carcinoma. *Ann Surg*. 2023;277:e103–e111.
5. Syn NL, Kabir T, Koh YX, et al. Survival advantage of laparoscopic versus open resection for colorectal liver metastases: a meta-analysis of individual patient data from randomized trials and propensity-score matched studies. *Ann Surg*. 2020;272:253–265.
6. Robles-Campos R, Lopez-Lopez V, Brusadin R, et al. Open versus minimally invasive liver surgery for colorectal liver metastases (LapOpHuva): a prospective randomized controlled trial. *Surg Endosc*. 2019;33:3926–3936.
7. Goh BKP, Syn N, Koh Y-X, et al. Comparison between short and long-term outcomes after minimally invasive versus open primary liver resections for hepatocellular carcinoma: a 1:1 matched analysis. *J Surg Oncol*. 2021;124:560–571
8. Buell JF, Cherqui D, Geller DA, et al. The international position on laparoscopic liver surgery: the Louisville Statement, 2008. *Ann Surg*. 2009;250:825–830.
9. Abu Hilal M, Aldrighetti L, Dagher I, et al. The Southampton Consensus Guidelines for Laparoscopic Liver Surgery: from indication to implementation. *Ann Surg*. 2018;268:11.
10. Zwart MJW, Görgec B, Arabiyat A, et al. Pan-European survey on the implementation of robotic and laparoscopic minimally invasive liver surgery. *HPB (Oxford)*. 2022;24: 322–331.
11. Berardi G, Aghayan D, Fretland ÅA, et al. Multicentre analysis of the learning curve for laparoscopic liver resection of the posterosuperior segments. *Br J Surg*. 2019;106: 1512–1522.
12. Cheek SM, Geller DA. The learning curve in laparoscopic major hepatectomy: what is the magic number? *JAMA Surgery*. 2016;151:929.
13. Chua D, Syn N, Koh Y-X, et al. Learning curves in minimally invasive hepatectomy: systematic review and meta-regression analysis. *Br J Surg*. 2021;108: 351–358.
14. Wehrtmann FS, de la Garza JR, Kowalewski KF, et al. Learning curves of laparoscopic Roux-en-Y gastric bypass and sleeve gastrectomy in bariatric surgery: a systematic review and introduction of a standardization. *Obes Surg*. 2020;30: 640–656.
15. Müller PC, Kuemmerli C, Cizmic A, et al. Learning curves in open, laparoscopic, and robotic pancreatic surgery: a systematic review and proposal of a standardization. *Ann Surg Open*. 2022;3:e111.
16. Nickel F, Distler M, Limen EF, et al. Initial learning curves of laparoscopic and robotic distal pancreatectomy compared with open distal pancreatectomy: multicentre analysis. *British Journal of Surgery*. 2023;110:1063–1067.
17. Shamseer L, Moher D, Clarke M, et al. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. *Brit Med J*. 2015;349:g7647.
18. Kalkum E, Klotz R, Seide S, et al. Systematic reviews in surgery-recommendations from the Study Center of the German Society of Surgery. *Langenbecks Arch Surg*. 2021; 406:1723–1731.
19. Goossen K, Tenckhoff S, Probst P, et al. Optimal literature search for systematic reviews in surgery. *Langenbecks Arch Surg*. 2018;403:119–129.
20. Rahbari NN, Garden OJ, Padbury R, et al. Posthepatectomy liver failure: a definition and grading by the International Study Group of Liver Surgery (ISGLS). *Surgery*. 2011;149: 713–724.
21. Koch M, Garden OJ, Padbury R, et al. Bile leakage after hepatobiliary and pancreatic surgery: a definition and grading of severity by the International Study Group of Liver Surgery. *Surgery*. 2011;149:680–688.
22. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *Brit Med J*. 2016;355:i4919.
23. Anonymous. R: a language and environment for statistical computing. *GBIF.ORG*. Accessed February 12, 2015. http://www.gbif.org/resource/81287
24. Abu Hilal M, Pearce NW. Laparoscopic left lateral liver sectionectomy: a safe, efficient, reproducible technique. *Dig Surg*. 2008;25:305–308.
25. Aldrighetti L, Cipriani F, Fiorentini G, et al. A stepwise learning curve to define the standard for technical improvement in laparoscopic liver resections: complexity-based analysis in 1032 procedures. *Updates Surg*. 2019;71: 273–283.
26. Cai X-J, Wang Y-F, Liang Y-L, et al. Laparoscopic left hemihepatectomy: a safety and feasibility study of 19 cases. *Surg Endosc*. 2009;23:2556–2562.
27. Cai X, Li Z, Zhang Y, et al. Laparoscopic liver resection and the learning curve: a 14-year, single-center experience. *Surg Endosc*. 2014;28:1334–1341.
28. Cannon RM, Brock GN, Marvin MR, et al. Laparoscopic liver resection: an examination of our first 300 patients. *J Am Coll Surg*. 2011;213:501–507.
29. Chan FKM, Cheng KC, Yeung YP. Laparoscopic liver resection: lessons learnt after 100 cases. *Hong Kong Med J*. 2014;20:386–392.
30. Chan FK-M, Cheng K-C, Yeung Y-P, et al. Learning curve for laparoscopic major hepatectomy: use of the cumulative sum method. *Surg Laparosc Endosc Percutan Tech*. 2016;26: e41–e45.

31. Chang S, Laurent A, Tayar C, et al. Laparoscopy as a routine approach for left lateral sectionectomy. *Br J Surg*. 2007;94: 58–63.
32. Cho W, Kwon CHD, Choi JY, et al. Impact of technical innovation on surgical outcome of laparoscopic major liver resection: 10 years' experience at a large-volume center. *Ann Surg Treat Res*. 2019;96:14–18.
33. D'Hondt M, Devooght A, Willems E, et al. Transition from laparoscopic to robotic liver surgery: clinical outcomes, learning curve effect, and cost-effectiveness. *J Robotic Surg*. 2023;17:79–88.
34. Fujikawa T, Uemoto Y, Matsuoka T. The impact of modified two-surgeon technique for laparoscopic liver resection on the training of surgeons-in-training. *Cureus*. 2023;15:e38865.
35. Goh BKP, Chan C-Y, Wong J-S, et al. Factors associated with and outcomes of open conversion after laparoscopic minor hepatectomy: initial experience at a single institution. *Surg Endosc*. 2015;29:2636–2642.
36. Halls MC, Alseidi A, Berardi G, et al. A comparison of the learning curves of laparoscopic liver surgeons in differing stages of the IDEAL Paradigm of Surgical Innovation: standing on the shoulders of pioneers. *Ann Surg*. 2019;269: 221–228.
37. Hasegawa Y, Nitta H, Takahara T, et al. Safely extending the indications of laparoscopic liver resection: when should we start laparoscopic major hepatectomy? *Surg Endosc*. 2017;31: 309–316.
38. Hasegawa Y, Nitta H, Takahara T, et al. Laparoscopic left hemihepatectomy is suitable as a first step in pure laparoscopic major hepatectomy. *Ann Gastroenterol Surg*. 2018;2:376–382.
39. Homma Y, Honda G, Kurata M, et al. Pure laparoscopic right posterior sectionectomy using the caudate lobe-first approach. *Surg Endosc*. 2019;33:3851–3857.
40. Ivanecz A, Plahuta I, Mencinger M, et al. The learning curve of laparoscopic liver resection utilising a difficulty score. *Radiol Oncol*. 2021;56:111–118.
41. Kim JH, Kim H. Modified liver hanging maneuver in laparoscopic major hepatectomy: the learning curve and evolution of indications. *Surg Endosc*. 2020;34:2742–2748.
42. Kluger MD, Vigano L, Barroso R, et al. The learning curve in laparoscopic major liver resection. *J Hepatobiliary Pancreat Sci*. 2013;20:131–136.
43. Komatsu S, Scatton O, Goumard C, et al. Development process and technical aspects of laparoscopic hepatectomy: learning curve based on 15 years of experience. *J Am Coll Surg*. 2017;224:841–850.
44. Lan X, Zhang H-L, Zhang H, et al. Four-year experience with more than 1000 cases of total laparoscopic liver resection in a single center. *World J Gastroenterol*. 2022;28:2968–2980.
45. Lee W, Woo J-W, Lee J-K, et al. Comparison of Learning Curves for Major and Minor Laparoscopic Liver Resection. *J Laparoendosc Adv Surg Tech A*. 2016;26:457–464.
46. Lin C-W, Tsai T-J, Cheng T-Y, et al. The learning curve of laparoscopic liver resection after the Louisville statement 2008: will it be more effective and smooth? *Surg Endosc*. 2016; 30:2895–2903.
47. Navarro JG, Kang I, Rho SY, et al. Major laparoscopic versus open resection for hepatocellular carcinoma: a propensity score-matched analysis based on surgeons' learning curve. *Ann Surg Oncol*. 2021;28:447–458.
48. Navarro JG, Kang I, Rho SY, et al. Stepwise development of laparoscopic liver resection skill using rubber traction technique. *HPB*. 2020;22:1174–1184.
49. Nomi T, Fuks D, Kawaguchi Y, et al. Learning curve for laparoscopic major hepatectomy. *Br J Surg*. 2015;102:796–804.
50. Otsuka Y, Tsuchiya M, Maeda T, et al. Laparoscopic hepatectomy for liver tumors: proposals for standardization. *J Hepatobiliary Pancreat Surg*. 2009;16:720–725.
51. Ratti F, Barkhatov LI, Tomassini F, et al. Learning curve of self-taught laparoscopic liver surgeons in left lateral sectionectomy: results from an international multi-institutional analysis on 245 cases. *Surg Endosc*. 2016;30:3618–3629.
52. Robinson SM, Hui KY, Amer A, et al. Laparoscopic liver resection: is there a learning curve? *Dig Surg*. 2012;29:62–69.
53. Shanti H, Raman R, Chakravartty S, et al. Effect of the learning curve on survival after laparoscopic liver resection for colorectal metastases. *BJS Open*. 2022;6:zrac020.
54. Son SH, Kim HJ, Yun SS, et al. Single center experience of laparoscopic hepatectomy: the comparison of perioperative outcomes between early and late period. *Korean J Hepatobiliary Pancreat Surg*. 2012;16:7–12.
55. Spampinato MG, Arvanitakis M, Puleo F, et al. Assessing the learning curve for totally laparoscopic major-complex liver resections: a single hepatobiliary surgeon experience. *Surg Laparosc Endosc Percutan Tech*. 2015;25:e45–e50.
56. Sultana A, Nightingale P, Marudanayagam R, et al. Evaluating the learning curve for laparoscopic liver resection: a comparative study between standard and learning curve CUSUM. *HPB*. 2019;21:1505–1512.
57. Tomassini F, Scuderi V, Colman R, et al. The single surgeon learning curve of laparoscopic liver resection: a continuous evolving process through stepwise difficulties. *Medicine (Baltimore)*. 2016;95:e5138.
58. Troisi RI, Van Huysse J, Berrevoet F, et al. Evolution of laparoscopic left lateral sectionectomy without the Pringle maneuver: through resection of benign and malignant tumors to living liver donation. *Surg Endosc*. 2011;25:79–87.
59. van der Poel MJ, Besselink MG, Cipriani F, et al. Outcome and learning curve in 159 consecutive patients undergoing total laparoscopic hemihepatectomy. *JAMA Surg*. 2016;151: 923–928.
60. van der Poel MJ, Huisman F, Busch OR, et al. Stepwise introduction of laparoscopic liver surgery: validation of guideline recommendations. *HPB (Oxford)*. 2017;19:894–900.
61. Vigano L, Laurent A, Tayar C, et al. The learning curve in laparoscopic liver resection: improved feasibility and reproducibility. *Ann Surg*. 2009;250:772–782.
62. Villani V, Bohnen JD, Torabi R, et al. Idealized" vs. "True" learning curves: the case of laparoscopic liver resection. *HPB (Oxford)*. 2016;18:504–509.
63. Wang X, Li J, Wang H, et al. Validation of the laparoscopically stapled approach as a standard technique for left lateral segment liver resection. *World J Surg*. 2013;37:806–811.
64. Yap PY, Bong JJ. Laparoscopic liver resection in Malaysia—a single surgeon's learning curve. *Annals of Laparoscopic and Endoscopic Surgery*. 3. Epub ahead of print July 10, 2018. doi:10.21037/ales.2018.06.04
65. Yoh T, Seo S, Ogiso S, et al. Learning process of laparoscopic liver resection and postoperative outcomes: chronological analysis of single-center 15-years' experience. *Surg Endosc*. 2022;36:3398–3406.
66. Choi SH, Choi GH, Han DH, et al. Laparoscopic liver resection using a rubber band retraction technique: usefulness and perioperative outcome in 100 consecutive cases. *Surg Endosc*. 2015;29:387–397.
67. Efanov M, Alikhanov R, Tsvirkun V, et al. Comparative analysis of learning curve in complex robot-assisted and laparoscopic liver resection. *HPB (Oxford)*. 2017;19:818–824.
68. Goh BKP, Teo J-Y, Lee S-Y, et al. Critical appraisal of the impact of individual surgeon experience on the outcomes of laparoscopic liver resection in the modern era: collective experience of multiple surgeons at a single institution with 324 consecutive cases. *Surg Endosc*. 2018;32:1802–1811.
69. Goh BKP, Prieto M, Syn N, et al. Critical appraisal of the learning curve of minimally invasive hepatectomy: experience with the first 200 cases of a Southeast Asian early adopter. *ANZ J Surg*. 2020;90:1092–1098.
70. Marino R, Olthof PB, Shi HJ, et al. Minimally invasive liver surgery: a snapshot from a major Dutch HPB and Transplant Center. *World J Surg*. 2022;46:3090–3099.
71. Patriti A, Marano L, Casciola L. MILS in a general surgery unit: learning curve, indications, and limitations. *Updates Surg*. 2015;67:207–213.

72. Swaid F, Sucandy I, Tohme S, et al. Changes in performance of more than 1000 minimally invasive liver resections. *JAMA Surgery*. 2020;155:986–988.
73. Ahmad A, Freeman HD, Corn SD. Robotic major and minor hepatectomy: critical appraisal of learning curve and its impact on outcomes. *Surg Endosc*. 2023;37:2915–2922.
74. Ceccarelli G, Andolfi E, Fontani A, et al. Robot-assisted liver surgery in a general surgery unit with a "Referral Centre Hub&Spoke Learning Program." Early outcomes after our first 70 consecutive patients. *Minerva Chir*. 2018;73: 460–468.
75. Fukumori D, Tschuor C, Penninga L, et al. 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;112:164–172.
76. Gravetz A, Sucandy I, Wilfong C, et al. Single-institution early experience and learning curve with robotic liver resections. *Am Surg*. 2019;85:115–119.
77. Görgec B, Zwart M, Nota CL, et al. Implementation and outcome of robotic liver surgery in the Netherlands: a nationwide analysis. *Ann Surg*. 2023;277:e1269–e1277.
78. Liu Q, Zhang T, Hu M, et al. Comparison of the learning curves for robotic left and right hemihepatectomy: a prospective cohort study. *Int J Surg*. 2020;81:19–25.
79. Magistri P, Guerrini GP, Ballarin R, et al. Improving outcomes defending patient safety: the learning journey in robotic liver resections. *Biomed Res Int*. 2019;2019: 1835085.
80. McCarron F, Cochran A, Ricker A, et al. 10 years, 100 robotic major hepatectomies: a single-center experience. *Surg Endosc*. 2024;38:902–907.
81. O'Connor V, Vuong B, Yang S-T, et al. Robotic minor hepatectomy offers a favorable learning curve and may result in superior perioperative outcomes compared with laparoscopic approach. *Am Surg*. 2017;83:1085–1088.
82. Zhu P, Liao W, Ding Z, et al. Learning curve in robot-assisted laparoscopic liver resection. *J Gastrointest Surg*. 2019;23: 1778–1787.
83. Rössler F, Sapisochin G, Song G, et al. Defining benchmarks for major liver surgery: a multicenter analysis of 5202 living liver donors. *Ann Surg*. 2016;264:492–500.
84. Müller PC, Breuer E, Nickel F, et al. Robotic distal pancreatectomy: a novel standard of care? Benchmark values for surgical outcomes from 16 International Expert Centers. *Ann Surg*. 2023;278:253–259.
85. Ban D, Tanabe M, Ito H, et al. A novel difficulty scoring system for laparoscopic liver resection. *J Hepatobiliary Pancreat Sci*. 2014;21:745–753.
86. Tanaka S, Kawaguchi Y, Kubo S, et al. Validation of index-based IWATE criteria as an improved difficulty scoring system for laparoscopic liver resection. *Surgery*. 2019;165: 731–740.
87. Clavien PA, Barkun J, de Oliveira ML, et al. The Clavien-Dindo classification of surgical complications: five-year experience. *Ann Surg*. 2009;250:187–196.
88. Slankamenac K, Graf R, Barkun J, et al. The comprehensive complication index: a novel continuous scale to measure surgical morbidity. *Ann Surg*. 2013;258:1–7.
89. Görgec B, Benedetti Cacciaguerra A, Lanari J, et al. Assessment of textbook outcome in laparoscopic and open liver surgery. *JAMA Surg*. 2021;156:e212064.
90. Pernar LIM, Robertson FC, Tavakkoli A, et al. An appraisal of the learning curve in robotic general surgery. *Surg Endosc*. 2017;31:4583–4596.
91. Müller PC, Müller-Stich BP, Hackert T, et al. Learning robotic distal pancreatectomy: the force awakens. *Journal of Pancreatology*. 2022;5:132.
92. Marcus HJ, Ramirez PT, Khan DZ, et al. The IDEAL framework for surgical robotics: development, comparative evaluation and long-term monitoring. *Nat Med*. 2024;30: 61–75.
93. McCulloch P, Altman DG, Campbell WB, et al. No surgical innovation without evaluation: the IDEAL recommendations. *Lancet*. 2009;374:1105–1112.
94. Sheetz KH, Claflin J, Dimick JB. Trends in the adoption of robotic surgery for common surgical procedures. *JAMA Network Open*. 2020;3:e1918911.
95. Curtis NJ, Foster JD, Miskovic D, et al. Association of surgical skill assessment with clinical outcomes in cancer surgery. *JAMA Surgery*. 2020;155:590–598.
96. Fecso AB, Szasz P, Kerezov G, et al. The effect of technical performance on patient outcomes in surgery: a systematic review. *Ann Surg*. 2017;265:492–501.
97. van Hilst J, de Rooij T, Bosscha K, et al. Laparoscopic versus open pancreatoduodenectomy for pancreatic or periampullary tumours (LEOPARD-2): a multicentre, patient-blinded, randomised controlled phase 2/3 trial. *Lancet Gastroenterol Hepatol*. 2019;4:199–207.
98. Robinson NB, Fremes S, Hameed I, et al. Characteristics of randomized clinical trials in surgery from 2008 to 2020: a systematic review. *JAMA Network Open*. 2021;4:e2114494.
99. Conroy EJ, Rosala-Hallas A, Blazeby JM, et al. Randomized trials involving surgery did not routinely report considerations of learning and clustering effects. *J Clin Epidemiol*. 2019;107: 27–35.
100. Balvardi S, Kammili A, Hanson M, et al. The association between video-based assessment of intraoperative technical performance and patient outcomes: a systematic review. *Surg Endosc*. 2022;36:7938–7948.
101. van den Broek BLJ, Zwart MJW, Bonsing BA, et al. Video grading of pancreatic anastomoses during robotic pancreatoduodenectomy to assess both learning curve and the risk of pancreatic fistula: a post hoc analysis of the LAELAPS-3 Training Program. *Ann Surg*. 2023;278:e1048–e1054.
102. Ketel MHM, Klarenbeek BR, Eddahchouri Y, et al. A video-based procedure-specific competency assessment tool for minimally invasive esophagectomy. *JAMA Surg*. 2024;159: 297–305.
103. Grüter AAJ, Van Lieshout AS, van Oostendorp SE, et al. Video-based tools for surgical quality assessment of technical skills in laparoscopic procedures: a systematic review. *Surg Endosc*. 2023;37:4279–4297.
104. Hogg ME, Zenati M, Novak S, et al. Grading of surgeon technical performance predicts postoperative pancreatic fistula for pancreaticoduodenectomy independent of patient-related variables. *Ann Surg*. 2016;264:482–491.
105. Fazlollahi AM, Bakhaidar M, Alsayegh A, et al. Effect of artificial intelligence tutoring vs expert instruction on learning simulated surgical skills among medical students: a randomized clinical trial. *JAMA Netw Open*. 2022;5: e2149008.
106. Kiyasseh D, Laca J, Haque TF, et al. A multi-institutional study using artificial intelligence to provide reliable and fair feedback to surgeons. *Commun Med*. 2023;3:1–12.
107. Zwart MJW, Nota CLM, de Rooij T, et al. Outcomes of a Multicenter Training Program in Robotic Pancreatoduodenectomy (LAELAPS-3). *Ann Surg*. 2022;276:e886–e895.
108. Labadie KP, Droullard DJ, Lois AW, et al. IWATE criteria are associated with perioperative outcomes in robotic hepatectomy: a retrospective review of 225 resections. *Surg Endosc*. 2022;36:889–895.
109. Domenghino A, Walbert C, Birrer DL, et al. Consensus recommendations on how to assess the quality of surgical interventions. *Nat Med*. 2023;29:811–822.
110. Dindo D, Demartines N, Clavien P-A. Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. *Ann Surg*. 2004;240:205–213.
111. Rahbari NN, Garden OJ, Padbury R, et al. Post-hepatectomy haemorrhage: a definition and grading by the International Study Group of Liver Surgery (ISGLS). *HPB (Oxford)*. 2011; 13:528–535.

112. Slankamenac K, Nederlof N, Pessaux P, et al. The comprehensive complication index: a novel and more sensitive endpoint for assessing outcome and reducing sample size in randomized controlled trials. *Ann Surg*. 2014;260:757–762; discussion 762-763.
113. Clavien P-A, Vetter D, Staiger RD, et al. The Comprehensive Complication Index (CCI®): added value and clinical perspectives 3 years "down the line." *Ann Surg*. 2017;265:1045–1050.
114. Goh BKP, Han H-S, Chen K-H, et al. Defining global benchmarks for laparoscopic liver resections: an International Multicenter Study. *Ann Surg*. 2023;277:e839–e848.
115. Sousa Da Silva RX, Breuer E, Shankar S, et al. Novel benchmark values for open major anatomic liver resection in non-cirrhotic patients: a multicentric study of 44 International Expert Centers. *Ann Surg*. 2023;278:748–755.
116. Scatton O, Katsanos G, Boillot O, et al. Pure laparoscopic left lateral sectionectomy in living donors: from innovation to development in France. *Ann Surg*. 2015;261:506–512.
117. Broering DC, Berardi G, El Sheikh Y, et al. Learning curve under proctorship of pure laparoscopic living donor left lateral sectionectomy for pediatric transplantation. *Ann Surg*. 2020;271: 542–548.