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ORIGINAL ARTICLE

A stepwise learning curve to define the standard for technical improvement in laparoscopic liver resections: complexity-based analysis in 1032 procedures

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Abstract

The objective of this study is to define the learning curve in a series of procedures grouped according to their complexity calculated by difficulty index to define a standard for technical improvement. 1032 laparoscopic liver resections performed in a single tertiary referral center were stratified by difficulty scores: low difficulty (LD, $n=362$); intermediate difficulty (ID, $n=332$), and high difficulty (HD, $n=338$). The learning curve effect was analyzed using the cumulative sum (CUSUM) method taking into consideration the expected risk of conversion. The ratio of laparoscopic/total liver resections increased from 5.8% (2005) to 71.1% (2018). The CUSUM analysis per group showed that the average value of the conversion rate was reached at the 60th case in the LD Group and at the 15th in the ID and HD groups. The evolution from LD to ID and HD procedures occurred only when learning curve in LD resections was concluded. Reflecting different degree of complexity, procedures showed significantly different blood loss, morbidity, and conversions among groups. A standard educational model—stepwise and progressive—is mandatory to allow surgeons to define the technical and technological backgrounds to deal with a specific degree of difficulty, providing a help in the definition of indications to laparoscopic approach in each phase of training.

Keywords Laparoscopy · Learning curve · Training · Difficulty · Expertise

Abbreviations

MILS	Minimally invasive liver surgery
DI	Difficulty index
LD	Low difficulty
ID	Intermediate difficulty
HD	High difficulty

Introduction

Benefits of laparoscopic approach for liver resections are supported by strong scientific evidence, documenting better short-term outcomes and adequate oncological results when compared with open approach [1–7]. In this scenario, improvements in peri-operative protocols [8, 9], technological advances, and standardization of technique [10] contributed to strengthen the establishment of minimally invasiveness; presently, minimally invasive liver surgery (MILS) programs are mandatory in centers regularly performing hepatobiliary surgery [11, 12] and the need for a specific expertise is encouraged by the scientific community [13, 14]. Since the term "liver resection" includes a wide spectrum of procedures and the range of technical difficulty among them is even more consistent, a stepwise broadening of procedures to be performed laparoscopically, deemed by increasing technical challenges, is strongly recommended [14].

Indeed, a strong commitment towards surgical training in MILS was high lightened in recent years. Furthermore, as patient safety must be persecuted as the main endpoint of surgery, surgical training should be scheduled as a progressive and stepwise process [15, 16].

The issue of learning curve in laparoscopic liver resection has been extensively debated, with the aim of clarifying which is the number of procedures required to gain an adequate expertise [17–22]: Viganò et al. [17] in 2009 established a cut-off number of 60 procedures that was widely used as a valid threshold, despite some reports

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from the literature argued that the learning curve can be shorter when a single procedure (e.g., left lateral sectionectomy) is taken into account [23].

Anyway, the balance between learning curve and complexity has never been specifically deepened until now: this topic is a crucial issue to allow a surgeon to define the criteria of recruitment to laparoscopic approach in each phase of technical improvement. The primary endpoint of this study is, therefore, to define a standard educational path to face the learning curve in each degree of complexity, maintaining an adequate profile of safety until its completion. The study analyzes the learning curve in a progressive and consecutive series of procedures—performed in a tertiary referral center for hepatobiliary surgery—grouped according to their complexity calculated by the means of the difficulty index (DI). The secondary endpoint was to evaluate if and how learning curve affects the short-term outcome and how indications to laparoscopic approach have been modified from surgeons and center experience.

Methods

Study design

Between January 2004 and March 2019, 2971 liver resections were performed at the Hepatobiliary Surgery Division of San Raffaele Hospital, Milano. Data from these procedures were prospectively collected and are now retrospectively reviewed. During this period, 1032 laparoscopic resections (34.7% of the whole institutional series) were performed and constituted the object of the present study. After stratification of procedures according to their difficulty score [15, 16] (see later for details), three groups were obtained: the low-difficulty (LD) group—including 362 resections; the intermediate-difficulty (ID) group—including 332 resections; and the high-difficulty (HD) group—including 338 resections.

The learning curve effect—defined as the improvement in surgical performance over time [24]—was analyzed in the three groups using the cumulative sum (CUSUM) method taking into consideration the expected risk of conversion associated with each procedure—primary endpoint.

The Groups were compared in terms of surgical indications (patients and disease characteristics) and outcome and the indication to laparoscopic approach was divided per year and per complexity to analyze the trend of minimally invasiveness in the whole series over center experience. Short-term outcome was compared, in each group, before and after learning curve acquisition—secondary endpoint.

Preoperative assessment

Routine blood tests (including serum concentrations of tumor markers—carcinoembryonic antigen, Ca 19.9, and alpha-fetoprotein) and computed tomography of the abdomen with triphasic liver contrast enhancement or liver-specific double-contrast magnetic resonance imaging scanning were obtained for all patients.

Treatment strategies were systematically evaluated during formal weekly multidisciplinary meetings, where liver surgeons, radiologists, medical oncologists, and pathologists identified the indications for surgery and the appropriate type of resection. Indication for laparoscopic approach was evaluated on a case-by-case basis, with evolving recruitment criteria. The criteria to exclude patients from laparoscopic approach during the whole period were the followings: peri-hilar tumors requiring biliary resections; lesions adjacent or infiltrating hepatocaval confluence; lesions infiltrating inferior vena cava; parenchymal sparing resection with need for vascular detachment; lesions with suspected infiltration of hepatic vein in future liver remnant; patients requiring portal vein resection; patients with portal vein thrombosis requiring portal thrombectomy.

Surgical technique

Laparoscopic resections

Only pure laparoscopic procedures were attempted and no hybrid techniques were used. The patient was placed in a supine 30° anti-Trendelenburg position with open legs (French position), with both right and left arms at a 90° angle. The first operator stood between the patient's legs, the first assistant on the left and the second assistant on the right side of the patient. Two different patterns of trocar configurations were used (as shown in Fig. 1a, b), according to the planned procedure. Laparoscopic liver ultrasonography (ProSound Alpha6, Hitachi Aloka Medical America, Willington, USA) was carried out routinely to complete intraoperative staging by assessing nodule number, location, and extension, relationships with the main vascular or biliary structures of the area, and to exclude the presence of unknown lesions. Whenever possible, primary extraparenchymal vascular control was achieved before transection (hilar approach to inflow). For major liver resections, the hepatic hilum was dissected with a non-traumatic grasper to identify the right or left hepatic artery. Superficial parenchymal transection was performed with Thunderbeat (Olympus, Tokyo, Japan), which integrates ultrasonic and bipolar energies

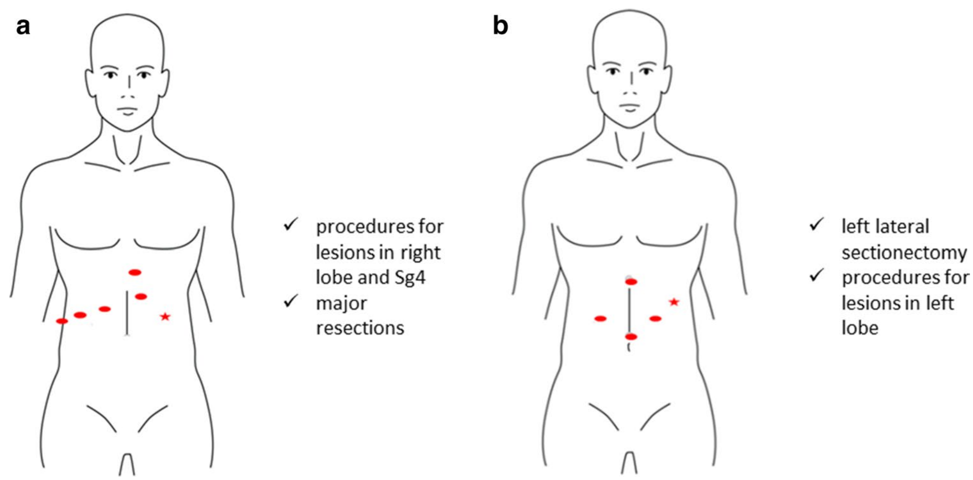

Fig. 1 **a** Standard trocar configuration. **b** Trocar configuration for lesions located in the left lobe of the liver

to simultaneously seal and cut vessels. When moving to deeper planes, this was followed by the alternating use of SonoSurg ultrasonic dissector (Olympus, Tokyo, Japan), bipolar forceps, and Thunderbeat itself, until resection was complete [25]. The extraction of the specimen was performed through a Pfannestiel incision or the enlargement of a port site or the partial incision of a previous abdominal scar.

Definition of difficulty

A preoperative index of difficulty for each operation was assessed using two different Difficulty Scores developed in the setting of laparoscopic resections. The first—by Ban-Wakabayashi [15]—is based on five preoperative factors (tumor location, extent of liver resection, tumor size, proximity to major vessels, and liver function), allowing to define a final score by the scores for the five factors [15]. Basing on the final result, each operation is then classified into three different categories: low (1–3), intermediate (4–6), and high difficulty (>7). The second—by Kawaguchi-Gayet et al. [16]—takes into account the type of procedure and categorizes it into three levels with progressive difficulty: the stratification was built based on intraoperative outcomes including operative time, blood loss, and conversion rate [16]. The level of concordance between the two difficulty scoring systems was high (96.6%). Thirty-five patients (3.4% of the series) obtained a different degree of difficulty when the two scoring systems were applied: these patients were classified and analyzed according to the higher level of difficulty (in particular, 25 patients with a low difficulty and 10 patients with an intermediate difficulty—by Kamaguchi–Gayet score [16]—were considered in the ID and HD Groups respectively).

Outcome evaluation

Intra- and peri-operative outcomes were analyzed for the assessment of feasibility and efficacy of the procedures. Intraoperative outcomes included: operative time, blood loss, use of Pringle maneuver, and blood transfusions rate. Postoperative outcomes included: total postoperative stay (days), reoperation rates, mortality, morbidity rates, and readmission rates and reason for readmission evaluated within 90 days after resection, transfusions rates.

Mortality was defined as any death occurred during the postoperative hospitalization or within 90 days after resection. The severity of postoperative morbidity was classified according to the Clavien–Dindo Classification of postoperative complications [26]. Minor complications were defined as grade 1 or 2 complications, while major complications as Clavien–Dindo grade of 3 or more [26].

The conversion rate was also evaluated, along with the analysis of the reasons for conversion. Converted cases were analyzed within the laparoscopic cohort on an intention-to-treat basis.

Statistical analysis

All variables were compared using the Chi-square or Fisher's exact test for categorical data, the Mann–Whitney *U* test for non-normally distributed continuous data, and Student's *t* test for normally distributed continuous variables. The ANOVA analysis of variance has been used when three categories to be compared were present. All data are expressed as mean plus or minus the standard deviation or median and range. Cox regression was used to determine independent predictors of outcome, using conversion as the dependent variable and factors found to be significant ($p < 0.05$) in univariate analysis as covariates. The learning curve in each difficulty group was performed using the cumulative sum (CUSUM) method for conversion rate (CR) and after adjustment for factors potentially influencing the risk of conversion at the multivariate analysis. The CUSUM allows the detection of changes in a parameter of the probability distribution. Specifically, every decrease in the curve represents a conversion, with a depth influenced by factors affecting the risk of conversion. Significance was defined as $p < 0.05$. All analyses were performed using the statistical package SPSS 18.0 (SPSS, Chicago, IL, USA).

Results

Within the study period (2005–2019), the number of candidates to laparoscopic approach progressively increased as well as the ratio laparoscopic/whole number of liver resections. In particular, in the last 3 years of recruitment, the annual ratio of laparoscopic/total procedures was above 50% (Fig. 2). Along with an increasing number of total laparoscopic procedures per year (7 in 2005 and 230 in 2018), the complexity of cases changed within the study period (Fig. 3a, b) due to widening of indications to laparoscopy to encompass procedures with an increasing profile of technical difficulty (i.e., major resections and complex minor resections).

Sixteen pre- and intraoperative factors potentially affecting the risk of conversion were evaluated at univariate analysis in the whole series of patients (120/1032 conversions, 11.6%): among these, anthropometric data (ABSI index) [27], difficulty of resection, previous liver resection, indication, extent of hepatectomy, lesion location, lesion diameter, preoperative portal vein embolization [28], underlying liver

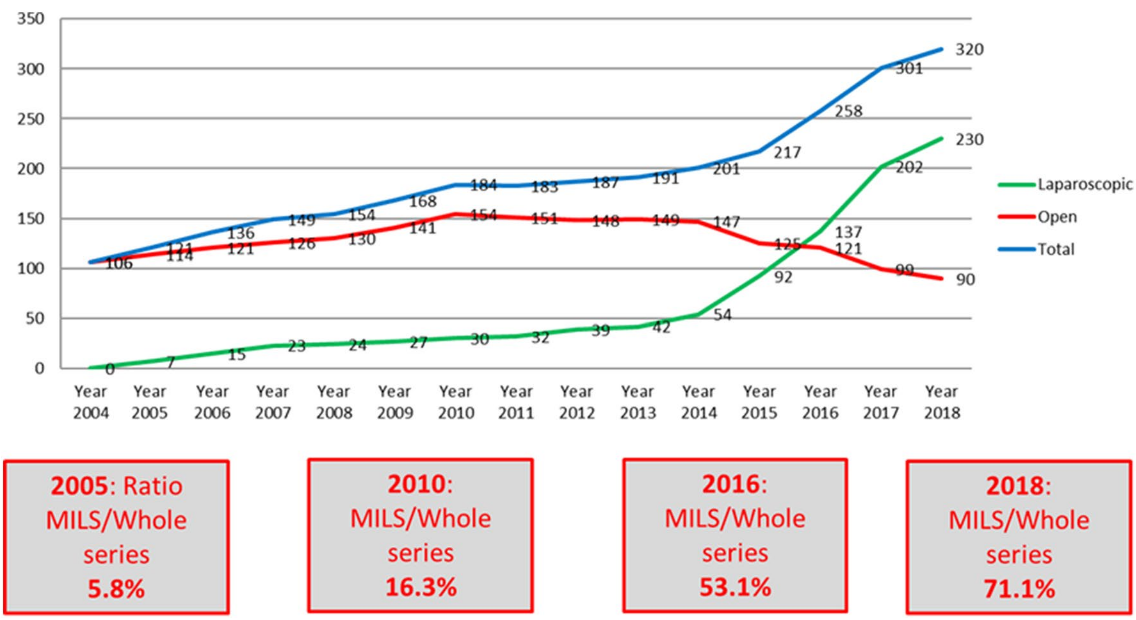

Fig. 2 Time course of liver resection activity per year. *MILS* minimally invasive liver surgery

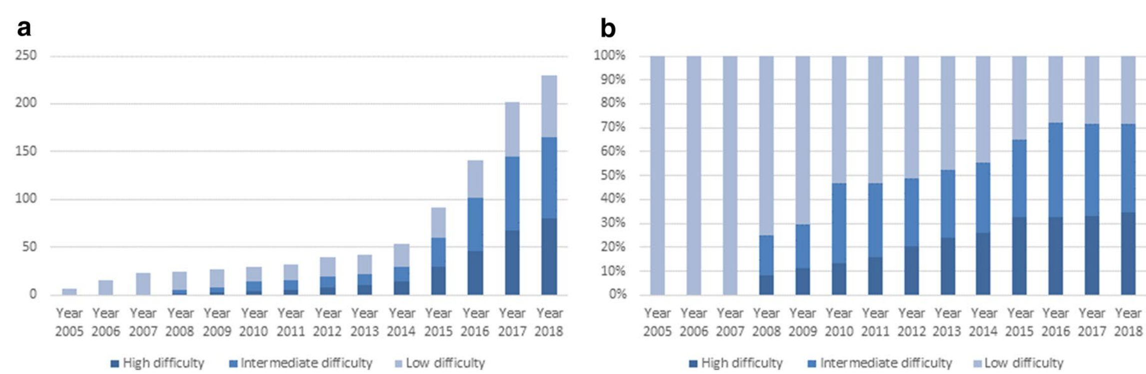

Fig. 3 Stratification of procedures per year according to difficulty

disease, and length of surgery resulted significant. Extent of hepatectomy, lesion diameter, and liver impairment were excluded from subsequent multivariate analysis, since they are already included in the algorithm for difficulty index. Difficulty of resection, ABSI index, indication, and previous liver surgery confirmed their association with conversion at multivariate analysis. See Table 1 for details.

Learning curve—primary endpoint

The CUSUM chart is used to monitor the mean risk of conversion based on samples taken from the process of learning curve at given times: the measurements of the samples at a given time constitute a subgroup. Rather than examining the mean of each subgroup independently,

Table 1 Patients and disease characteristics according to difficulty of laparoscopic liver resection

	Total (*n* = 1032)		Low difficulty (*n* = 362)		Intermediate difficulty (*n* = 332)		High difficulty (*n* = 338)	
	n	%	*n*	%	*n*	%	*n*	%
Age (years), mean ± SD	66.4 ± 5.2		65.2 ± 6.5		63.6 ± 7.4		64.8 ± 6.7	
Sex								
Male	551	53.4	187	51.5	167	50.4	197	58.3
Female	481	46.6	175	48.5	165	49.6	141	41.7
BMI, mean ± SD	24.2 ± 2.8		25.2 ± 4.5		24.2 ± 4.1		24.5 ± 3.8	
Hypertension	315	30.5	84	23.3	120	36.2	110	32.6
Diabetes mellitus	171	16.6	37	10.3	70	21.1	64	18.8
Heart disease	178	17.2	54	14.9	59	17.7	65	19.3
Pulmonary disease	48	4.7	10	2.7	21	6.5	17	5.0
ASA score								
1	110	10.7	37	10.3	37	11.2	36	10.6
2	514	49.8	163	45.0	159	47.8	192	56.9
3	408	39.5	162	44.7	136	40.9	110	32.6
Underlying liver disease								
None	273	26.4	111	30.5	82	24.6	81	23.9
Steatosis	335	32.5	123	34.0	112	33.6	101	29.8
Chronic liver disease	254	24.6	88	24.4	79	23.7	87	25.7
Cirrhosis	170	16.5	40	11.1	60	18.1	70	20.6
Previous abdominal surgery	460	44.6	82	22.5	145	43.5	234	69.3
Indication								
Benign disease	220	21.4	83	22.9	80	24.1	57	17.0
Hemangioma	79	7.7	30	8.4	29	8.6	20	6.0
Focal nodular hyperplasia	35	3.4	22	6.1	11	3.4	2	0.5
Adenoma	50	4.8	23	6.5	20	6.0	6	1.8
Hepatolithiasis	49	4.8	4	1.1	17	5.2	28	8.3
Other benign	7	0.7	3	0.8	3	0.9	2	0.5
Malignant disease	812	78.6	279	77.1	252	75.9	281	83.0
HCC	362	35.1	93	25.6	137	41.4	132	39.0
Cholangiocarcinoma	119	11.5	14	3.8	44	13.4	60	17.9
Metastases	300	29.1	152	42.0	64	19.4	84	24.8
Other malignant	31	3.0	21	5.7	6	1.7	5	1.4
Lobe								
Right	404.7	39.2	112	30.9	114	34.5	178	52.8
Left	524.0	50.8	246	67.9	160	48.3	118	34.9
Bilobar	103.2	10.0	4	1.1	57	17.2	42	12.4
Type of resection								
Minor resection	780	75.6	362	100.0	238	68.7	180	50.6
Major resection	252	24.4	0	0.0	94	31.3	158	49.4
Tumor number, mean ± SD	1 ± 2		1 ± 1		2 ± 2		1 ± 2	
Tumor size (cm) mean ± SD	4.3 ± 2.9		2.8 ± 1.9		3.7 ± 1.1		4.9 ± 1.4	

the CUSUM chart shows the accumulation of information of current and previous samples by multivariate logistic analysis and provides the expected risk of conversion for each case. The risk-adjusted CUSUM analysis of procedures stratified according to their difficulty score showed that the average value of the conversion rate is reached at

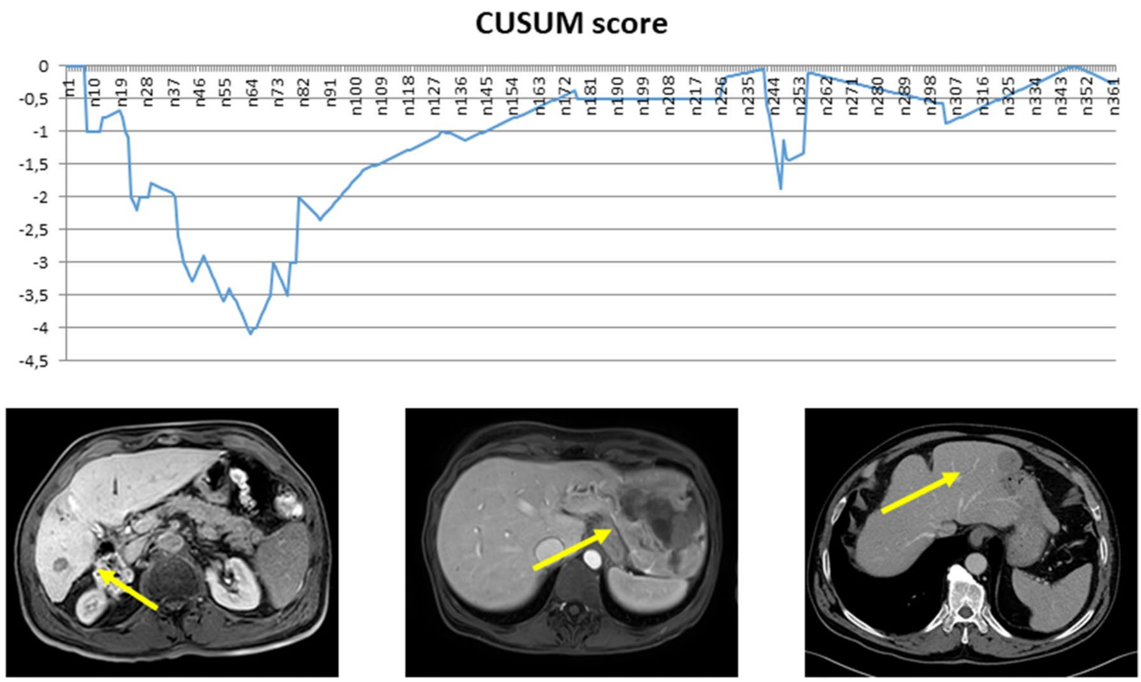

Fig. 4 Cusum analysis of the learning curve in low-difficulty procedures (above) and CT scans of cases graded as low difficulty based on preoperative characteristics (below). The average value of the conversion rate is reached at the 60th case

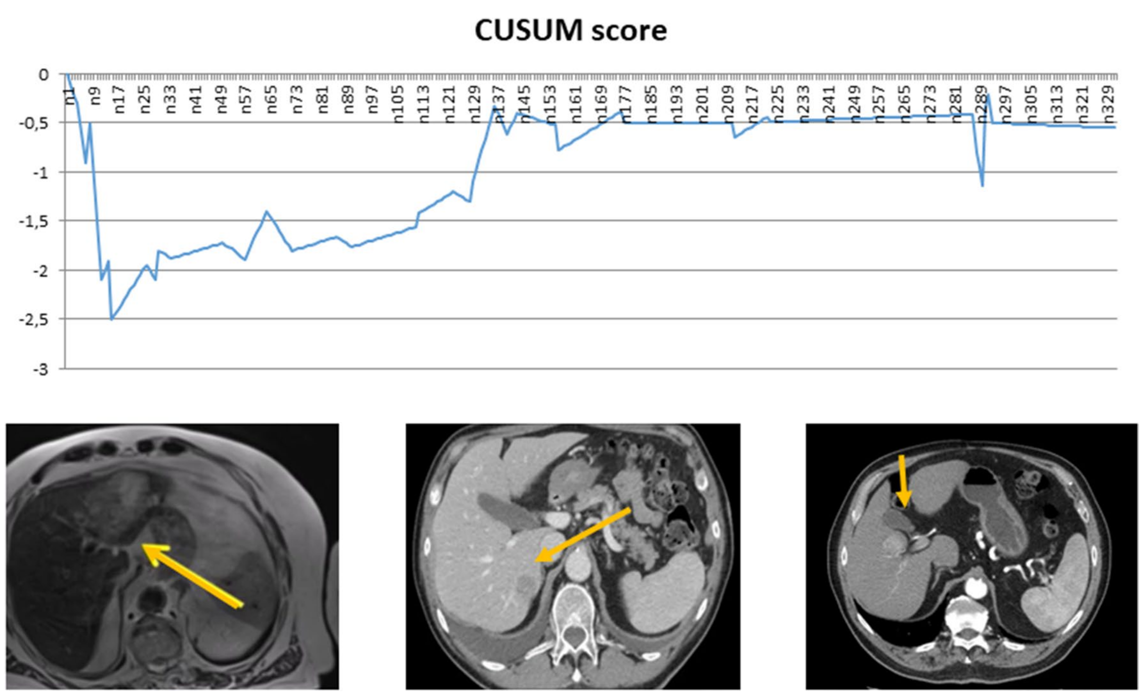

Fig. 5 Cusum analysis of the learning curve in intermediate-difficulty procedures (above) and CT scans of cases graded as low difficulty based on preoperative characteristics (below). The average value of the conversion rate is reached at the 15th case

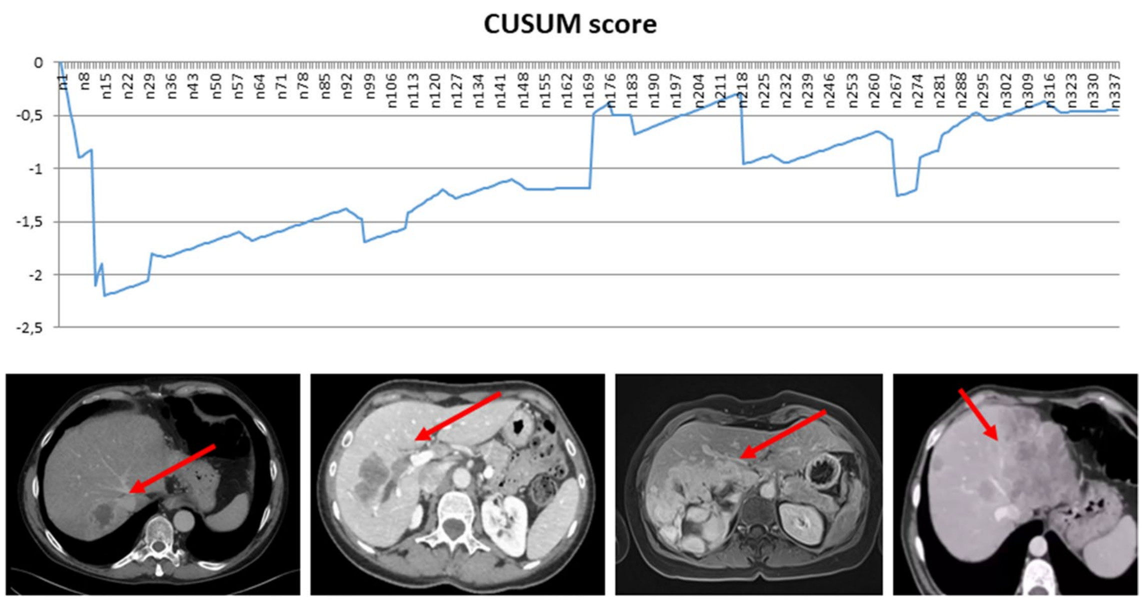

Fig. 6 Cusum analysis of the learning curve in high-difficulty procedures (above) and CT scans of cases graded as low difficulty based on preoperative characteristics (below). The average value of the conversion rate is reached at the 15th case

the 60th case in the LD Group (Fig. 4) and at the 15th in the ID and HD groups (respectively, Figs. 5, 6).

Procedures with ID and HD resulted to be present in the series after the 60th procedure belonging to LD Group.

Indications and outcome data—secondary endpoints

Table 2 reports patients and disease characteristics in the whole series and grouped according to their difficulty score. Distribution of diagnosis, lesion side and type of resection, as well as tumor dimensions was different among groups:

Table 2 Intra- and postoperative outcome of procedures according to difficulty of laparoscopic liver resection

	Total ($n=1032$)		Low difficulty ($n=362$)		Intermediate difficulty ($n=332$)		High difficulty ($n=338$)		*p*
	n	%	*n*	%	*n*	%	*n*	%	
Pringle maneuver [*n* (%)]	946	91.7	295	81.5	317	95.5	334	98.8	<0.05
Length of surgery (min), mean ± SD	175 ± 64		149 ± 64		187 ± 71		235 ± 91		NS
Blood loss (mL), mean ± SD	210 ± 115		150 ± 150		200 ± 50		350 ± 200		<0.05
Associated procedures [*n* (%)]	302	29.3	25	6.9	106	31.9	171	50.6	<0.05
Surgical margin [*n* (%)]									NS
*R*0	997	96.6	357	98.6	320	96.4	320	94.7	
*R*1	35	3.4	5	1.4	12	3.6	18	5.3	
Surgical margin (mm), mean ± SD	8 ± 4		10 ± 2		8 ± 5		5 ± 5		NS
Intraoperative blood transfusions [*n* (%)]	114	11.0	14	3.9	33	9.9	67	19.8	<0.05
Postoperative blood transfusions [*n* (%)]	160	15.5	31	8.6	51	15.4	78	23.1	<0.05
Conversion [*n* (%)]	120	11.6	24	6.6	38	11.4	58	17.2	<0.01
Morbidity [*n* (%)]	184	17.8	31	8.6	59	17.8	94	27.8	<0.05
Grade of complications [*n* (%)]		0.0							
Minor	120	11.6	22	6.1	34	10.2	64	18.9	<0.05
Major	64	6.2	9	2.5	25	7.5	30	8.9	NS
Mortality [*n* (%)]	4	0.4	1	0.3	1	0.3	2	0.6	NS
Length of stay (days), mean ± SD	4 ± 1		3 ± 1		4 ± 1		5 ± 1		NS

these differences were the basis for differences in DI and consequent stratification in groups.

Details regarding the procedures are reported in Table 3. Mean intraoperative blood loss was higher in the HD—compared with the ID and LD groups (respectively, 350 ± 200 mL, 200 ± 50 mL and 150 ± 150 mL), with a statistically significant difference. Mean operative time was generally longer in the HD compared with other groups, even without reaching a significant difference. Conversion was necessary in 17.2, 11.4, and 6.6% of the HD, ID, and LD groups, respectively ($p < 0.05$), with an overall conversion rate of 11.6%.

Mortality was comparable between groups, while a significantly lower morbidity was recorded in the LD (8.6%) compared with the ID and HD groups (17.8% and 27.8%, respectively).

Overall, mean length of postoperative stay was increasingly longer according to increased difficulty of the procedure, even without significant differences among groups.

No differences in terms of blood loss, transfusion requirements, and morbidity were recorded when a comparison of procedures performed before and after learning curve completion was performed. Indeed, blood loss before and after learning curve completion was, respectively, 130 ± 100 mL versus 90 ± 140 mL in the LD group (*p* ns), 220 ± 90 mL versus 210 ± 100 mL in the ID group (*p* ns), and 400 ± 140 mL versus 350 ± 170 mL in the HD group (*p* ns). Total transfusion requirement before and after learning curve was, respectively, 10% and 9.7% in the LD group (*p* ns), 18% and 17.4% in the ID group (*p* ns), and 26.3% versus 26.9% in the HD group (*p* ns), and finally, morbidity before and after learning curve was, respectively, 10% and 9.4% in the LD group (*p* ns), 20.4% and 18.8% in the ID group (*p* ns), and 29.5% versus 31.5% in the HD group (*p* ns).

Discussion

The definition of the standard educational process to be covered by a surgeon during the training period is still lacking in the field of laparoscopic liver surgery, while this need was acknowledged both during the 2nd International Consensus Conference on Laparoscopic Liver Surgery (Morioka, 2014) [14] and during the 1st International Guidelines Meeting on Laparoscopic Liver surgery [29].

As patient safety must be persecuted as the primary endpoint of surgery, the learning curve period should not affect peri-operative risk and the need for technical improvement should not push the surgeon to compromise the balance between expertise and recruitment to laparoscopy: in this view, a procedure should not be only "attempted", but, instead, faced when the technical and technological background is adequate. Hence, the need to use the difficulty index [15, 16] in an educational perspective: the present study is the first to report the path to be run during the process of training and provides indications regarding procedures to be performed, skills to be owned, and instrumentations to be present in the operating room per each degree of complexity.

Indeed, since centers regularly performing liver surgery carry out liver procedures with a wide range of difficulty [6], a surgeon should know which resections he should perform laparoscopically in each phase of training and how many of them are required to further expand the pool of candidates to laparoscopy.

Interestingly, Villani et al. [21], focusing on the topic of learning curve within the overall series of MILS performed in a single institution without stratifying them per complexity, described a shift in real learning curve compared with an ideal one, with the initial period of improvement followed by periods of regression in which length of stay and complication rates increased before improving again (therefore without really reaching a plateau as expected). We can speculate that these deviations from the ideal slope of the learning curve are not only related to surgeon confidence or over-confidence with the technique (as reported by authors) [21], but instead with the enrolment of progressively more complex cases to laparoscopy along with the implementation of an MILS program. In this perspective, the need to define the learning curve according to complexity is again enhanced.

The present study confirms that expertise acquisition in the field of MILS is a stepwise process: to maintain an adequate profile of safety, the conclusion of the learning curve in low-difficulty procedures is mandatory before widening indications to laparoscopy to encompass even more complex procedures. Viganò et al. [17] reported a plateau of the learning curve at 60 cases in minor resections, meaning that the conversion rate reached at that point the mean value of the entire series: despite this cut-off value was widely used and reported, it was developed out of a complexity-based perspective, so that some issues of "complexity" are not taken into account when considering minor resections. Komatsu et al. [19] described the stepwise evolution of laparoscopic resections from the left side to the right side, therefore, suggesting that the indications to MILS have to be adjusted in accordance with procedural evolution (left lateral sectionectomy, then left hepatectomy, and then right hepatectomy); furthermore, a careful patients' selection is mandatory to avoid compromising peri-operative and oncological outcomes, especially for beginners: authors, therefore, suggested to initially perform procedures in normal liver background and then to implemented MILS to operate on compromised livers [19]. Tomassini et al. [20] described a learning curve effect after 160 cases, considering a gradual increase (from 1 to 10) in technical complexity defined according to the type of resection (e.g., wedge resection of Sg3 and 4b is graded 1, left hepatectomy is graded 5, and right hepatectomy is graded 9). Anyway, this analysis does not take into account many factors potentially influencing technical complexity (i.e., proximity to vessels, lesion dimension, and liver background) and does not allow defining how many "easy" procedures are required to implement MILS in more challenging procedures.

In the present study, factors indicating technical challenges are represented by the difficulty score [15, 16]: this stratification allows analyzing educational process within the same class of difficulty. Indeed, the completion of the learning curve within the same difficulty class is recommended before passing to the subsequent one. In the LD Group, the CUSUM analysis documented a learning curve effect at 60 cases, while the same effect was reached after 15 cases both in the ID and HD Groups. Interestingly, even though, at the time of series development, difficulty scores had not been described yet, the increase in difficulty was attempted only after the learning curve in the step before was completed, witnessing that the surgeon has a perception of his degree of training and of his possibility to proceed safely with more complex procedures. This self-awareness is now confirmed by statistical analysis.

The choice of conversion rate as a landmark of learning curve was made, since passage to open approach is the maneuver used by a surgeon perceiving a situation which cannot be handled safely by laparoscopic technique [30, 31]. In this view, experienced surgeons have a lower conversion rate (although different from "zero") as a consequence of their technical expertise and their skill to deal with challenging situations by laparoscopy. On the contrary, in the same situation, a beginner surgeon converts to guarantee patients safety and to avoid surgical outcomes being jeopardized by surgical technique. Operative time and morbidity were not considered adequate markers of the learning curve effect in this setting: indeed, the wide range of procedures and of patients characteristics could have an influence on them, without really affecting technical difficulties. In particular, operative time can decrease along with the learning curve when a single procedure is considered (e.g., left lateral sectionectomy), but could underestimate the learning curve effect when a class of difficulty is taken into account.

To our knowledge, the definition of the learning curve according to technical difficulty is an innovative concept: the scoring system described by Ban-Wakabayashi [15] and by Kawaguchi-Gayet [16], indeed, overcomes the use of minor/major resections [32] as synonyms of easy/complex resections, respectively [15, 16]. It is well known, indeed, that a wedge resection in a posterior segment of a cirrhotic liver can definitively be more challenging compared with a left hepatectomy in a normal liver (and, by the way, laparoscopic left hepatectomy can be considered a standard, while resections in postero-superior segments are still far from this concept).

Some issues regarding the apparently shorter learning curve in the ID and HD Groups compared with the LD group have to be deepen: first of all, apart from specific technical characteristics, most of liver procedures have common features like technique for parenchymal transection and liver mobilization which enter the surgeon's portfolio during the first phase and are then maintained during the subsequent steps of the career. Second, single surgeon's learning curve cannot be considered separately from technological improvement and center expertise (both surgical and anaesthesiological) [9, 10].

After the first pioneering work in MILS, adopting and testing techniques and tools from open liver surgery and from laparoscopic general surgery, many advanced technologies specifically designed for laparoscopic liver resections have been developed [25], in the attempt to reduce limits of hepatic minimally invasiveness. Furthermore, the idea of the laparoscopic liver surgeon was overcome by the laparoscopic liver team, with dedicated and experienced personnel and with some flagship concepts like the advantages of the adoption of fast-track protocols, the need for maintenance of hypovolemia during transection phases, and the need for minimally invasive intraoperative monitoring [9, 10, 33]. All these factors contributed to success and acquisition of the learning curve. It is remarkable that the reduction of conversion rate substantially corresponded to minimization of conversion for bleeding: indeed, while oncological concerns and adhesions from the previous surgery cannot be abolished and cannot be completely controlled and reduced, on the contrary management of hemorrhage is a key point in a liver surgery program, influenced by many peri-operative factors.

Results from the present study describe how learning curve in laparoscopic liver resections is a progressive (i.e., expertise is gained along with increasing number of cases), but even a step-by-step process (i.e., a surgeon should complete his learning curve in low-difficulty procedures before facing intermediate and then complex resections). The same idea was reported by Nomi et al. [34] in the analysis of the LC for major hepatectomies: interestingly, three characteristics phases were identified by the CUSUM in this setting too and a minimum number of 45–60 cases were required to complete the training process. The same numerosity of cases in major resections was confirmed by Brown et al. [35].

This perspective acquires a concrete dimension when considering that procedures with different degree of difficulty require even specific instrumentation and skills: indeed, irrespectively of surgical expertise, it is strongly recommended to face a laparoscopic procedure only when both technical and technological conditions are proportional to the level of difficulty of the procedure itself. Furthermore, the hepatic hilum should be systematically prepared for

Pringle maneuver to control intraoperative bleeding, especially in the early phases of training and even in low difficulty procedures (the lower application of the Pringle in the LD group of the present study was related to left lateral sectionectomy procedures): indeed, it allows to limit blood loss without any detrimental effect on outcome [36].

Among tools to implement the diffusion of laparoscopic liver programs, events of training and surgical proctoring are advisable. Even if, to our knowledge, scientific data regarding the effect of these initiatives are still lacking, we can speculate that, for beginners, operating under the technical supervision of a master surgeon and after the acquisition of a theory background should be the standard practice to obtain safe and cost-effective procedures [37].

A potential limitation of the present study is the high-volume setting in which it was carried out: indeed, it is possible that a different proportion of procedures per unit of time could have an influence on the learning curve. It is, indeed, presumable that the lower is the number of procedures per month, the slower is the learning curve. Future studies should focus on the topic of center volume and relationship with the open/laparoscopic ratio.

Conclusion

The present study reports a progressive and stepwise learning curve in MILS which is nowadays a mandatory prerequisite in a program of liver resections. A standard educational model is proposed to allow surgeons to be aware of the technical and technological background to deal with a specific degree of difficulty, providing a help even in the definition of indications to laparoscopic approach in each phase of training. Furthermore, the standardization of learning curve allows both to check the adequacy of a single center conversion rate and to improve and implement MILS programs without negatively affecting the postoperative course or even the oncological result.

Author contributions Study design: LA. Acquisition of data: FC. Analysis and interpretation: RF and AL. Manuscript drafted by: RF. Revision: CF, FG, CM, and PM. Statistical advice: RF.

Compliance with ethical standards

Conflict of interest Dr Luca Aldrighetti, Federica Cipriani, Guido Fiorentini, Marco Catena, Michele Paganelli, and Francesca Ratti have no conflicts of interest to disclose concerning any commercial interest that they may have in the subject of study and the source of any financial or material support.

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Research involving human participants and/or animals All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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