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ORIGINAL ARTICLE

Learning curve in robotic liver surgery: easily achievable, evolving from laparoscopic background and team-based

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Abstract

Background: Limited and heterogeneous literature data necessitate a focused examination of the learning curve in robotic liver resections. This study aims to assess the learning curve of two surgeons from the same team with differing laparoscopic backgrounds.

Methods: Since February 2021, San Raffaele Hospital in Milan has implemented a robotic liver surgery program, performing 250 resections by three trained console surgeons. Using cumulative sum (CUSUM) analysis, the learning curve was evaluated for a Pioneer Surgeon (PS) with around 1200 laparoscopic cases and a New Generation Surgeon (NGS) with approximately 100 laparoscopic cases. Cases were stratified by complexity (38 low, 74 intermediate, 85 high).

Results: Both PS and NGS demonstrated a learning curve for operative time after 15 low-complexity and 10 intermediate-complexity cases, with high-complexity learning curves apparent after 10 cases for PS and 18 cases for NGS. Conversion rates remained unaffected, and neither surgeon experienced increased blood loss or postoperative complications. A "team learning curve" effect in terms of operative time emerged after 12 cases, suggesting the importance of a cohesive surgical team.

Conclusion: The robotic platform facilitated a relatively brief learning curve for low and intermediate complexity cases, irrespective of laparoscopic background, underscoring the benefits of team collaboration.

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Introduction

The robotic-assisted technique has gained widespread acceptance as an innovative approach in hepatobiliary surgery.[1] Similarly to laparoscopy, robotic liver surgery provides superior peri-operative outcomes in comparison to the open approach, including lower blood loss, decreased morbidity, shortened length of hospitalization and earlier return to daily activities.[2] Additionally, the robotic approach has shown adequacy for the treatment of malignant disease, even providing advantages to achieve the oncological radicality while preserving the benefits of minimally invasive procedures.[3] Since its inception, the robotic technology has been designed and has progressively evolved to overcome the limitations imposed by the laparoscopic approach.[4] One of the major drawbacks of laparoscopic surgery is reduced dexterity, along with limited range of motion, and difficulty in performing complex tasks.[5] The robotic platform has provided instruments with high degrees of freedom in wrist articulation, a stable three-dimensional stereoscopic vision, tremor suppression algorithms, and superior ergonomics for the surgeon.[6–8]

Although the robotic approach is emerging as an important contribution to the minimally invasive liver surgery and is expected to progressively enter daily clinical practice in most of the centers performing hepatobiliary surgery, the implementation of robotic programs arises several questions concerning the learning curve particularly in the context of surgeons with

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varying background in laparoscopy.[9] The learning curve in surgery refers to the period during which a surgeon acquires the necessary skills and proficiency to perform procedures independently, consistently, and with minimal complications.[10] The complexity of liver surgery, coupled with the intricacies of robotic technology necessitates a comprehensive understanding of the acquisitions of skills and expertise over time. Currently available literature concerning the learning curve in robotic liver resections remains limited. Several study reported a lower number of cases needed to surpass the learning curve for the robotic approach compared to laparoscopy.[11,12] However, one pressing question that remains unanswered is the role of previous extensive laparoscopic expertise in facilitating the transition to robotic liver resections.[13,14] Interestingly, in a systematic review on learning curves in robotic surgery in general, Kassite *et al.* likewise found that previous surgical experience and training were underreported and only described in 20 % of the studies.[15] Beside surgeon related factors, the effect of an institutional learning curve should not be underestimated.[16,17] The institutional competency depend on the frequency of a specific surgery, team familiarity, and training of surgical assistants, operating room nurses, and technical staff.[18] Additionally, different liver resections may require varying levels of technical skills and expertise in robotic surgery. Thus, several limitations to the robotic approach exist resulting in a distinct learning curve associated with procedures of various degrees of complexities.[19,20]

The primary objective of this study is to investigate the learning curve of two surgeons within the same surgical team, each with significantly different volumes of laparoscopic cases in their surgical portfolios. By comparing the two learning curves we aim to provide valuable insights into the relationship between laparoscopic expertise and the mastery of robotic liver resections stratifying the cases per complexity according to Iwate score.

The secondary endpoint is to analyze the effect of learning curve on short term surgical outcomes and evaluate the learning curve for docking phase.

Methods

Study design

Between February 2021 and March 2023, a robotic surgery program was implemented at the Hepatobiliary Surgery Division of San Raffaele Hospital, Milano. During this period 250 robotic liver resections have been performed by three surgeons who received specific training as console surgeons and constituted the object of the present study. Data from these procedures were prospectively collected and are now retrospectively reviewed.

To fulfill the primary endpoint procedures were stratified per complexity according to Iwate criteria score. It is based on six preoperative factors - tumor location (scored according to the different segments), tumor size (<30 or ≥30), extent of liver resection (partial resection, left lateral resection, segmentectomy, or more), liver function (Child-Pugh score A/B), proximity to major vessels (to the major hepatic veins, inferior vena cava, or main branches of Glisson's tree), and use of the hybrid approach/HALS[21] – allowing to define a final score by the scores for the six factors. Basing on the final result, each case has been classified into three different categories: low-complexity (LC) cases.

- Iwate score 1–3; intermediate complexity (IC) cases – Iwate score 4–6; high complexity (HC) cases.
- Iwate score ≥7. After stratification of procedures according to their difficult score, three groups were obtained: the LC cases group – including 38 resections; the IC cases group – including 74 resections; the HC cases group including 85 resections.

The learning curve effect – defined as the improvement in surgical performance over time[22]– was analyzed in the three groups using the cumulative sum (CUSUM) method focusing on two surgeons with different levels of laparoscopic expertise: a Pioneer Surgeon -PS (background about 1200 laparoscopic liver resections) and a the New Generation Surgeon -NGS (background 100 laparoscopic liver resections).

For the analysis of the learning curve, only cases performed by the pioneer surgeon (PS) and the new generation surgeon (NGS) were included, excluding the third surgeon due to their intermediate experience, which was not the focus of the comparison.

The evaluation of the learning curve, for both the primary and secondary endpoints, has been systematically performed across various parameters, which will be explicated in subsequent sections.

The Groups were assessed in terms of surgical indications (patients and disease characteristics). Short term outcome were compared, within each group and for each surgeon, before and after the acquisition of the learning curve. Stratification by complexity using the Iwate score allowed for a homogeneous comparison between the Pioneer Surgeon (PS) and the New Generation Surgeon (NGS), while reflecting the real distribution of cases between the two operators.

A 'step-wise guided' approach were adopted, where less experienced surgeons were mentored and gradually advanced to more complex robotic procedures only after demonstrating full autonomy in lower complexity cases.

Finally, the learning curve for the docking phase, calculated as the operative time from skin incision to preparation of Pringle maneuver, was evaluated in order to fulfill the secondary endpoint.

Approval to perform this study was obtained from the Institutional Review Board of institutions and written consent from subjects was waived.

Preoperative assessment

A standard staging before surgery was performed including routine blood tests, computed tomography of the abdomen with triphasic liver contrast enhancement, and/or liver specific contrast magnetic resonance imaging scanning. All cases underwent a comprehensive evaluation in formal weekly institutional multidisciplinary meetings, involving the surgical team, pathologist, radiologist, oncologist, anaesthetists, and navigator nurse. These meetings facilitated the development of an overall operative plan, considering patient characteristics, comorbidities, and the pathological, anatomical, and radiological features of the disease, guiding the selection of the surgical approach. Indication for robotic approach was evaluated on a case-by-case basis, with evolving recruitment criteria.

The criteria to exclude patients from the robotic approach during the whole period were the followings:

i. Lesions strictly adjacent or infiltrating the hepatocaval confluence or inferior vena cava;
ii. Lesions with presumed infiltration of the hepatic vein of the future liver remnant;
iii. Patients with portal vein thrombosis requiring portal vein thrombectomy;
iv. Patients with more than 10 liver lesions and/or requiring more than 10 resection areas;
v. Anaesthesiologic contraindications to pneumoperitoneum (e.g., severe cardio-pulmonary disease).

Surgical technique

Robotic resections

All procedures were attempted with the robotic technique utilizing the *Da Vinci* ® Xi robotic platform (Intuitive Surgical, USA). After receiving general anaesthesia, 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 surgeon operated at the console while the assistant was standing between the patient's legs. A laparoscopic 10 mm trocar was positioned in an infraumbilical right position, and pneumoperitoneum was induced. Four robotic trocars were placed following a standardized configuration based on the planned resection. A second laparoscopic access was positioned in right hypochondrium (between robotic arms 1 and 2 or between 2 and 3) only after docking of robotic arms, to exclude conflicts among laparoscopic and robotic instruments and to improve ergonomics. Robotic liver ultrasonography 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. Primary extraparenchymal vascular control was achieved before transection (Pringle maneuver). The standard robotic instrumentation for liver resections included: prograsp forceps, Maryland bipolar forceps, and monopolar scissors. Robo-Lap approach was used in selected cases to address the task of parenchymal transection.[23] 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.

Outcome evaluation

Intra- and post-operative outcomes were analysed for the purpose of the present study.

- Intraoperative outcomes included: operative time (OT), blood loss, use of Pringle maneuver, blood transfusion rate, surgical radicality rate (R0), intraoperative complications.
- Postoperative outcomes included: morbidity and mortality rate, postoperative hospitalization (length of stay before discharge).

More specifically, OT was defined as time between skin incision and accesses closure. Any intraoperative accident was recorded according to Satava classification of intraoperative events.[24] The severity of postoperative morbidity was classified according to the Clavien–Dindo Classification of postoperative complications.[25] Minor complications were defined as grade 1 or 2 complications, while major complications as Clavien–Dindo grade of 3 or more. Mortality was defined as any death during intraoperative or postoperative hospitalization or within 90 days after resection.

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

Statistical analysis

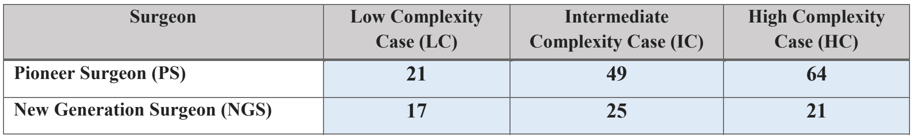
All variables were compared using the Chi-square or Fisher's exact test for categorical data, the Mann–Whitney U test for non-normally distributed continuous data, and Student's t test for normally distributed continuous variables. The analysis of the learning curve for the PS and NGS was performed using the cumulative sum (CUSUM) method. The CUSUM allows the detection of changes in a parameter of the probability distribution. Specifically, length of surgery was identified as the outcome value for learning curve evaluation. Significance was defined as $p < 0.05$. All analyses were performed using the statistical package SPSS 18.0 (SPSS, Chicago, IL, USA).

Results

Characteristics of the robotic series over time

Within the study period (2021–2023), the number of candidates of robotic approach progressively increased, as did the ratio of robotic to total liver resections. In particular, the annual ratio of robotic to total procedures increased from 21 % to 31 % and the annual ratio of robotic to minimally invasive procedures increased from 32 % to 47 % between 2021 and 2022. However, the introduction of the robotic approach did not affect the annual ratio of minimally invasive to total procedures, which remained approximatively about 66 % over the two years (Fig. 1).

Pre- and intraoperative variables that could affect the learning curve were assessed through univariate analysis across the entire patient cohort, comparing the procedures of the NGS and the PS



Surgeon	Low Complexity Case (LC)	Intermediate Complexity Case (IC)	High Complexity Case (HC)
Pioneer Surgeon (PS)	**21**	**49**	**64**
New Generation Surgeon (NGS)	**17**	**25**	**21**

Figure 1 Stratification of cases by complexity for the NGS and the PS

(Table 1). Among these factors, previous interventional procedures, tumor size, type of hepatectomy, the inclusion of lymphadenectomy, and associated biliary anastomosis displayed significant disparities between the case series of the two surgeons contributing to variations in the difficulty score of the resections they performed. As expected in clinical practice, while the number of intermediate complexity robotic cases was similar between the two surgeons, the NGS performed significantly more low-complexity cases compared to the PS. Conversely, the NGS handled significantly fewer high-complexity cases than the PS (Fig. 2). However, the distribution of benign/malignant diseases did not showed statistically significant differences among the two case series. The most common indication for robotic liver resections was cholangiocarcinoma (81 patients, 32.4 % in the whole series; 48 patients, 35.8 % in the PS series; 22 patients, 34.9 % in the NGS series). PS series included 16 patients who underwent robotic liver resections for benign disease (12 %) and 118 patients for malignant disease (88 %). Similarly, the NGS series included 6 patients for benign disease (9.5 %) and 57 patients for malignant disease (90.5 %).

Learning curve according to previous laparoscopic portfolio – primary endpoint

No learning curve effect was detectable in terms of conversion for either the PS and the NGS surgeon.

A learning curve effect, however, was observed when analyzing Operative time (OT) as the outcome.

Evolution of OT along with case progression was analyzed comparing the PS and the NGS series. In the PS series, there was a statistically significant logarithmic correlation between the operative time and the cumulative sum of the procedures (Fig. 3). Conversely, in the NGS series, operative time did not decrease as the number of case progressed.

After stratifying procedures by difficulty score, a ROC curve analysis was performed to identify the cutoff for completion of the learning curve for each surgeon.

The learning curve effect on operative time was achieved after the 10th case for both PS and NGS in the LC group and at the 15th case in the IC group (Figs. 4,5). For HC procedures, the learning curve was achieved after the 10th case for PS and after the 18th case for NGS (Fig. 6).

Safety of learning curve – primary endpoint

Upon comparison the PS and NGS series, no significant differences were observed across all the three groups (LC IC, and HC) in terms of conversion rate, blood loss, morbidity rate and length of stay before and after the acquisition of the learning curve. This implies that the short-term surgical outcomes remained consistent across the specified case complexities, indicating stable outcomes regardless of the complexity of the procedures.

The learning curve for the docking phase – secondary endpoint

Fig. 7 depicts the analysis of the learning curve for the docking phase - calculated as the operative time from skin incision to preparation of Pringle maneuver - across the whole series. A “team learning curve” effect was detectable after completing 12 cases.

Discussion

The study aimed to analyze the learning curve associated with robotic liver resections performed by two surgeons within the same team, each with varying levels of laparoscopic experience. Our findings provide valuable insights into the relationship between laparoscopic expertise and the mastery of robotic liver resection, particularly when cases were stratified for complexity. The robotic platform allowed for a relatively short learning curve in low and intermediate complexity procedures, irrespectively of the extent of laparoscopic experience.

Addressing the secondary endpoints, no significant difference were observed in terms of conversion rate, blood loss, postoperative complications and length of stay for both surgeons, regardless of the level of complexity of the procedures. Finally, the analysis of the learning curve for the docking phase revealed that a “team learning curve effect” was detectable after 12 cases, underscoring the importance of collaboration within the surgical team Fig. 8.

Remarkably, there is a growing awareness in scientific literature that the robotically assisted technique may facilitate a steeper learning curve compared to laparoscopic liver surgery. The results of a meta-analysis revealed that the learning curve for robotic liver resections was shorter (30 patients) than that for laparoscopic liver resections (60 patients).[26] Zhao *et al.* suggest that the learning curve of robotic resections in postero-superior segments of the liver might be shorter, based on their experience and previous publications. They found that after 30 robotic liver procedures, operative time decrease but then plateaued, while C conversion rate to open surgery dropped by 4.5 % after 70 operations.[27] Similarly, Zwart *et al.* reported a reduction in operative time and conversion rates after 55 operations, with a second drop after 145 cases for conversion rate improvement.[28] Tsung

Table 1 Patients and disease characteristics of robotic liver resections

		Whole series (n = 250)	PS (n = 134)	NGS (n = 63)	*p*
Age (years)	Mean ± SD	66 ± 5	68 ± 4	65 ± 5	ns
Male sex, n (%)		155 (61.9)	71 (53.0)	37 (57.1)	ns
ASA score, n (%)	1	24 (9.5)	11 (8.29	4 (6.3)	
	2	155 (62)	82 (61.2)	33 (52.4)	
	3	71 (28.4)	41 (30.7)	26 (41.3)	
BMI	Mean ± SD	23.5 ± 2.3	24.1 ± 2.2	23 ± 2.6	ns
Underlying liver disease, n (%)	None	48 (19.2)	23 (17.2)	16 (25.4)	ns
	Steatosis/mild impairment	155 (62.0)	72 (53.7)	36 (57.1)	ns
	Cirrhosis	47 (18.8)	39 (29.1)	11 (17.5)	ns
Previous abdominal surgery, n (%)		60 (23.8)	30 (22.4)	14 (22.2)	ns
Previous liver surgery, n (%)		12 (4.8)	7 (5.5)	3 (4.8)	0.041
Previous interventional procedures, n (%)	Portal vein embolization	4 (1.6)	3 (2.2)	1 (1.6)	
	Hepatic deprivation	23 (9.2)	18 (13.4)	2 (3.2)	
	Biliary drainage	22 (8.8)	17 (12.7)	1 (1.6)	
Indication, n (%)					
Malignant		226 (90.5)	118 (89)	57 (90.5)	
	Colorectal cancer metastases	72 (28.6)	27 (20.1)	19 (30.2)	
	Non colorectal cancer metastases	8 (3.2)	5 (3.7)	2 (3.2)	
	Hepatocellular carcinoma	65 (26.0)	38 (28.4)	14 (22.2)	
	Cholangiocarcinoma	81 (32.4)	48 (35.8)	22 (34.9)	
Benign		24 (9.5)	16 (12.0)	6 (9.5)	
	Adenoma	10 (4)	6 (4.5)	2 (3.2)	
	Hemangioma	10 (4)	8 (6.0)	4 86.3)	
	Hepatolitiasis	4 (1.6)	2 (1.5)	0	
Size (cm)	Mean ± SD	3.9 ± 2.6	3.2 ± 2.8	4.3 ± 3.1	0.05
Tumor number, n (%)	Single	155 (61.9)	86 (64.2)	37 (58.7)	
	Multiple	95 (38.1)	48 (35.8)	26 (41.3)	
Type of hepatectomy, n (%)					0.039
	Wedge resection	41 (16.4)	20 (1.5)	20 (31.7)	
	Anatomical segmentectomy	89 (35.6)	44 (32.8)	22 (34.9)	
	Anatomical bisegmentectomy	38 (15.2)	19 (14.2)	12 (19.0)	
	Right hepatectomy	41 (16.4)	30 (22.4)	3 (4.8)	
	Left hepatectomy	36 (14.4)	16 (12.0)	6 (9.5)	
	Central hepatectomy	2 (0.8)	2 (1.5)	0	
	Right extended hepatectomy	3 (1.2)	3 (2.2)	0	
Associated procedures, n (%)	Colorectal resection	4 (1.6)	2 (1.5)	1 (1.6)	ns
	Lymphadenectomy	83 (33.2)	51 (38.0)	19 (30.2)	0.032
	Biliary anastomosis	19 (7.6)	15 (11.2)	1 (1.6)	0.027
	Other	12 (4.8)			
Difficulty according to iwate score	Median	7 (2–10)	8 (2–10)	6 (2–9)	0.044
	Low	59 (23.5)	21 (15.7)	17 (27)	0.029
	Intermediate	93 (37.3)	49 (36.6)	26 (39.7)	ns
	High	98 (39.2)	64 (47.7)	21 (33.3)	0.017

*The distribution of dichotomous categorical variables is expressed by percentages (absolute frequency). Continuous variables are expressed as median (interquartile range).

Legend: BMI, body max index; ASA score, American Society of Anaesthesiologist score.

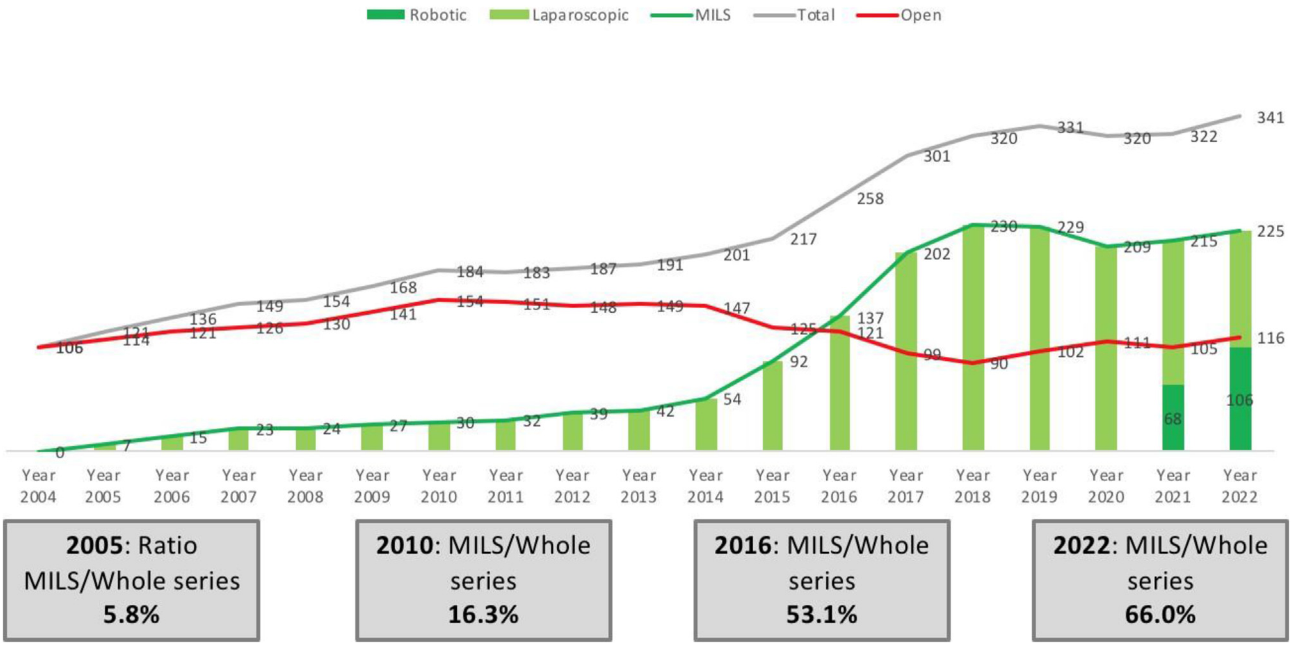


Figure 2 Time course of liver resection activity per year. MILS minimally invasive liver surgery

et al. showed significant improvement in surgical parameters after 57 consecutive robotic hepatectomies during the late phase of the learning curve.[29] A single-center study (140 cases) looked at the conversion to open surgery during the learning phase and found improvement in the conversion rate after 30 cases compared to 60 cases for laparoscopic hepatectomy. This confirms the Morioka consensus statement in which learning minimally invasive surgery (MIS) is easier with the robotic system.[30] Efanov *et al.* compared the learning curves of robotic and laparoscopic hepatectomies in a series including 131 MIS hepatectomies performed by 2 MIS inexperienced surgeons. They stated that the learning curve of posterosuperior segment resection in robotic liver resections takes only 16 procedures and 29 for laparoscopic liver resections. The overall difficulty index significantly increased in the robotic group, in contrast to the laparoscopic group. Advanced robotic surgical procedures could be done during the intermediate phase of the learning curve. The level of difficulty increased in robotic resections during the learning curve (after 16 cases) and the closeness to major vascular structures and the size of the tumor were higher in the robotic group. In contrast, the level of difficulty did not change in the laparoscopic group. Zhu *et al.* concluded that more challenging procedures were performed with robotic liver surgery over time, while there was no increase in complexity over time in laparoscopic resections.[31] A study found a significant reduction in operative time in the last 18 robotic hemi-hepatectomies compared to the first 18 robotic cases (467.9 ± 108.0 min vs. 331.9 ± 129.1 min, p = 0.002). Furthermore, they stated that hilar dissection, hemostasis, and vascular control are easier in robotic approach, while the instruments are not adequate for parenchymal dissection.[32] O'Connor *et al.* showed superior outcomes with robotic-assisted minor hepatectomy compared with laparoscopic surgery after 25 cases.[33] Magistri *et al.* found that operative time reduced significantly after 30 cases of robotic hepatectomy.[34] The technological innovations provided by the robotic platform seem to significantly enhance the potential of the minimally invasive approach, preserving the R0 resection rate, reducing the risks of injuries, and minimizing the risk of conversion and conversion-related morbidity and mortality, particularly in complex liver resections and time-consuming interventions requiring extensive dissection or reconstruction.[35–38] Additionally, it has been shown that surgeons with

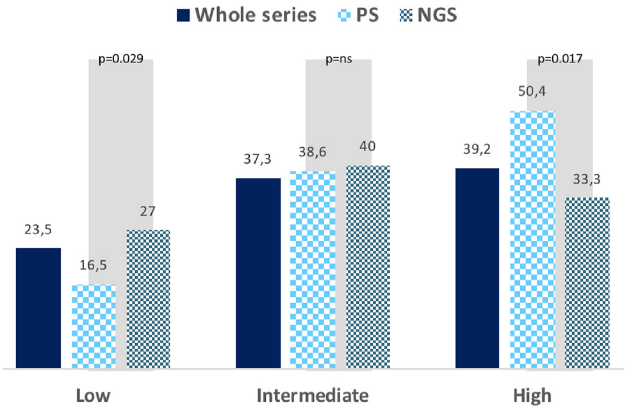


Figure 3 Different distribution of liver resections according to difficulty score among case series. * Values on the top of the bars: percentages of liver resections performed in the whole series, PS, and NGS, stratified by complexity level

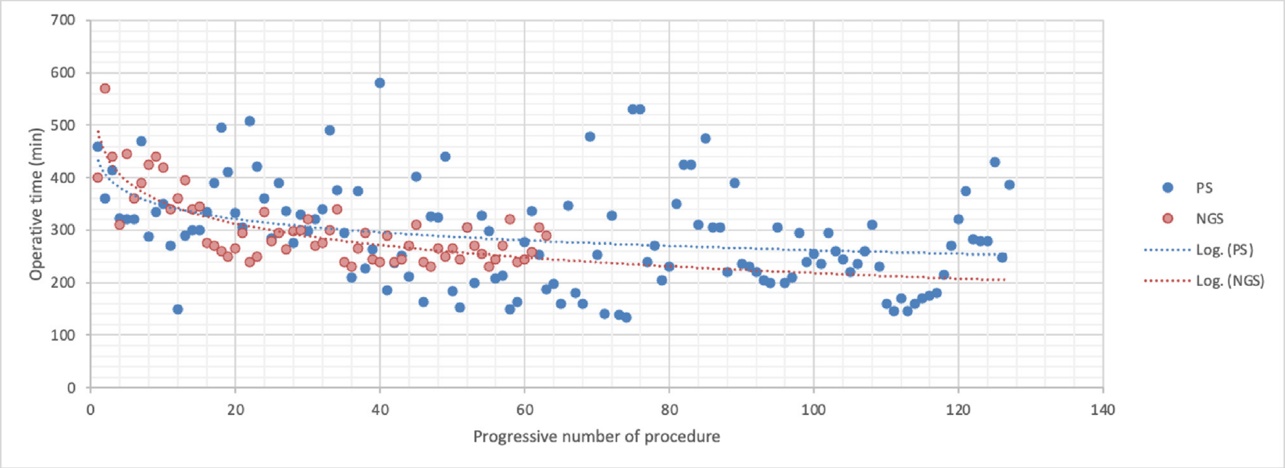


Figure 4 Operative time in the whole series

prior laparoscopic experience can transition more quickly to robotic procedures, further supporting the benefits of robotic technology in modern surgical practices.[39,40]

Despite these benefits, a standardized educational process for robotic liver surgery has not yet been fully established. Current literature stress the need for a more structured training curriculum to optimize surgical proficiency, with specific recommendations for overcoming the learning curve.[41]

In the present study, the o relatively short learning curves for low and intermediate complexity procedures highlight the adaptability of surgeons to the robotic platform. These findings suggest that, regardless of their individual laparoscopic experience, surgeons can swiftly acquire proficiency in robotic liver resections. This adaptability can be attributed to the enhanced capabilities of the robotic platform, including improved dexterity, three-dimensional visualization, and advanced instruments.

Stratification by complexity served as the foundation for the adoption of a step-wise guided approach allowing surgeons to gradually acquire robotic surgical skills. The presence of a mentor helped accelerate the learning curve by providing real-time feedback and by allowing the less experienced surgeon to focus on specific surgical skills at each stage of their development.[42] This step-wise approach not only benefited the individual surgeon but also fostered an environment of continuous learning within the team. As team members became familiar with the nuance of robotic liver surgery, their roles and responsibility evolved, leading to more efficient coordination in complex procedures.

The establishment of a dedicated robotic team fostered a team learning curve, where surgeons collectively refined their performance through shared experience. This effect is not solely attributable to the surgeon's experience but involves the entire surgical team, including anesthesiologists, operating room nurses, technicians, and surgical assistants. Throughout the study period, team dynamics evolved as coordination improved, and communication between team members became more seamless, contributing significantly to the reduction in docking time and smoother surgical operations.

The traditional concept of an individual liver surgeon has evolved into a collaborative liver team, characterized by experienced and specialized personnel. The learning curve of a single surgeon cannot be considered separately from technological advancements and the experience of the center.[43] Fast-track protocols, hypovolemia management during transection phases, and minimally invasive intraoperative monitoring have become key elements that contribute to success and accelerate the acquisition of the learning curve.[44,45]

However, technical advantages should not lead surgeons to jeopardize the delicate balance between expertise and the integration of robotic techniques. In fact, the learning curve for liver surgery is also influenced by the complexity of the procedures, which can differs significantly from case to cases.[46,47]

Notably, the learning curves for PS and NGS differed for HC procedures, suggesting that the inherent heterogeneity in complex procedures can influence the learning curve trajectories of surgeons differently. This finding enhance the importance of addressing complex robotic procedures only when both technical and technological conditions are proportional to the difficulty of liver resection within a dedicated robotic team, irrespectively of surgical expertise. Variability observed in the learning curve for IC cases can be attributed to the diverse demands these procedures imposed. This results emphasizes that surgical learning curves are shaped not only by the surgeon's experience but also by the complexity of the cases and the coordination and efficiency of the overall team.

Despite the differences in case portfolios between PS and NGS, no significant differences were observed in terms of conversion rate, blood loss, short-term postoperative complications and length of stay across procedures with different complexity. This consistency suggests that, once the learning curve is overcome,

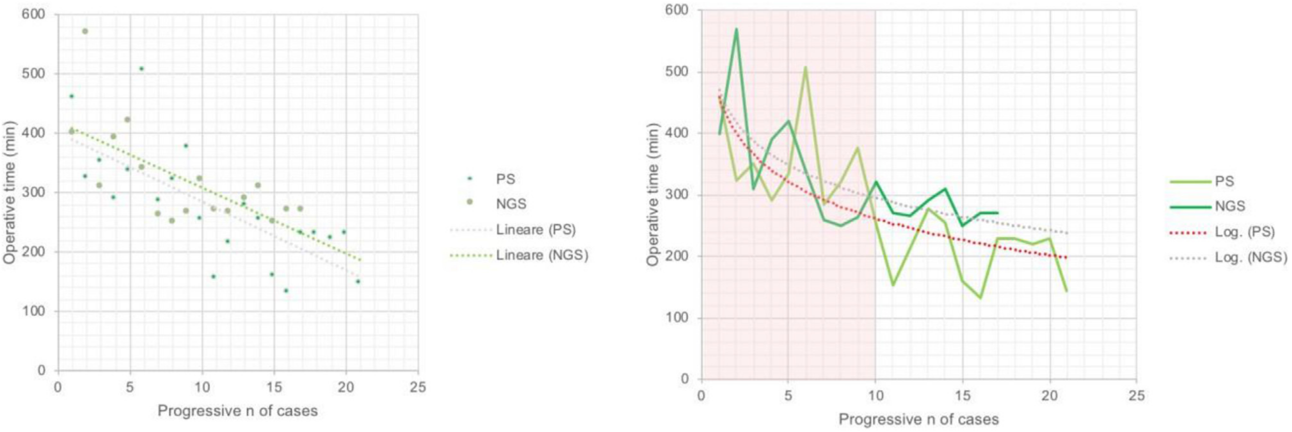


Figure 5 Learning curve for low complexity procedures

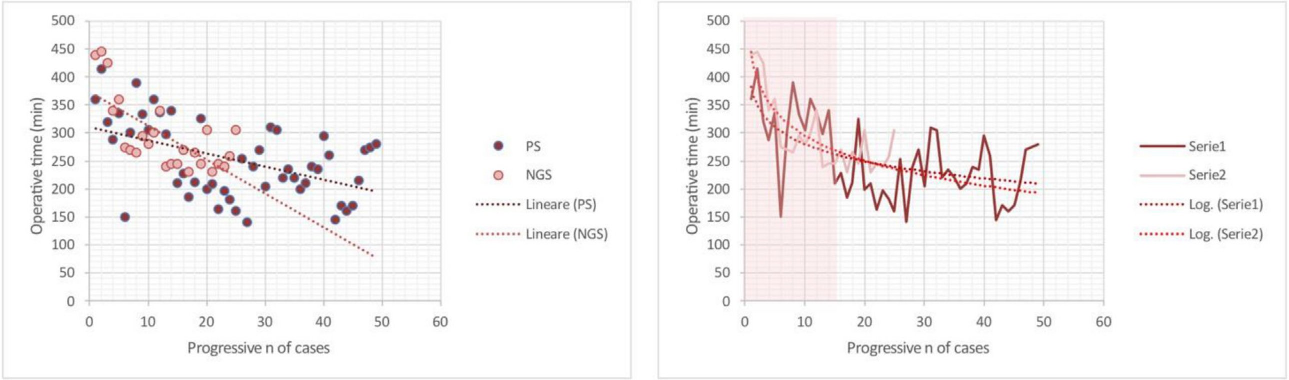


Figure 6 Learning curve for intermediate complexity procedures

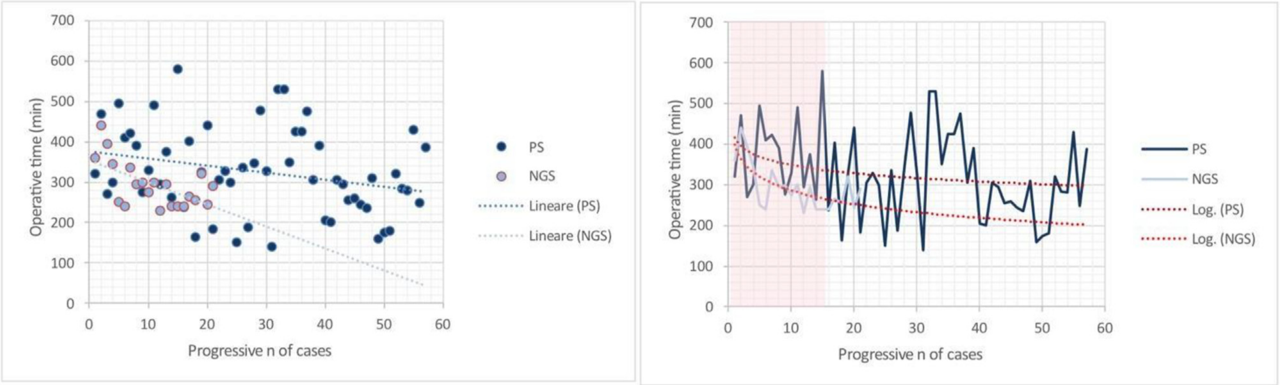


Figure 7 Learning curve for high complexity procedures

the robotic approach provides reliable outcomes regardless of the surgeon's prior laparoscopic expertise. As patient safety is the primary endpoint of surgery, the learning curve period should not increase peri-operative risk. Surgeons may face higher risks and complications during the initial phases of robotic liver resections. Analyzing this effect on short term outcome can contribute to identify areas for improvement in surgical training and patient management.

The team learning curve effect, evident after 12 cases, underscores the collaborative nature of the surgical team in optimizing the operative time for the docking phase. This collective improvement may result from shared experiences, refined

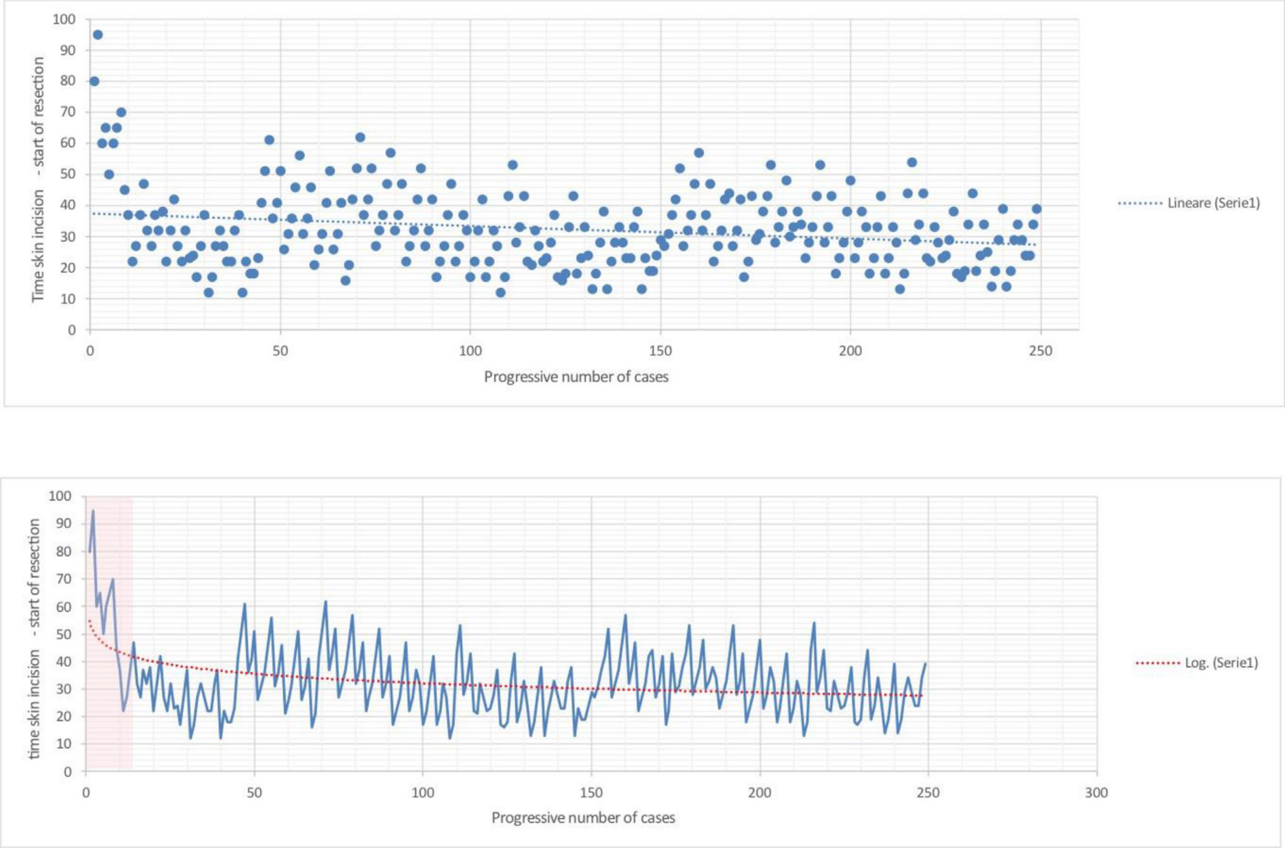


Figure 8 Learning curve for docking procedure

coordination among team members, and the establishment of standardized protocols within the robotic team. The concept of a team learning curve emphasizes the importance of cohesive teamwork in the successful implementation of robotic liver surgery. Assessing the learning curve for the docking phase can help measure the proficiency of surgeons in setting up the robotic system, with the ultimate goal of optimizing workflow efficiency.

Among tools to implement the diffusion of robotic liver programs events of training are advisable. Specifically, robotic surgery training programs should adopt a step-wise approach where surgeons progressively learn to manage increasingly complex procedures. This ensures that each level of complexity is mastered before advancing to more challenging cases, thereby enhancing safety and efficiency. Additionally, these programs should not only focus on the technical skills of the surgeon but must also engage the entire operating room team, including anesthesiologists, nurses, and technicians. All team members play a crucial role in optimizing workflow and reducing operative times. Training programs should, therefore, promote coordinated teamwork alongside individual skill acquisition to reflect the collaborative nature of robotic liver surgery and ensure the cohesive functioning of the entire surgical unit. The inclusion of mentoring can provide valuable real-time feedback, further supporting this progressive learning model.

However, our study is not exempt from limitations. Firstly, a potential limitation of the present study is the specific setting in which it was carried out. Being conducted in a single institution, the study's findings may be influenced by biases related to the specific patient population, surgical practices, and team dynamics. In centers with varying levels of experience in laparoscopy or those transitioning from open to robotic surgery may experience a longer learning curve do to the need for additional training and adaptation to robotic platform. Additionally, the version of the Da Vinci robotic surgical system used may also influence the learning curve, with older systems being more challenging to handle, especially for tasks such as docking and port placement.[48] Furthermore, the classification of surgeons into PS and NGS may have inherent subjectivity. Other centers might categorize surgeons differently. Lastly, the limited number of high complexity cases after learning curve in the NGS group reduces the statistical power for meaningful comparisons of intra- and post-operative outcomes in this subgroup. Broader studies across multiple centers could help assess the transferability of these findings and enhance their generalizability to other surgical teams and institutions.

Conclusions

The robotic platform allows a relatively short learning curve for procedures of low and intermediate complexity, irrespective of the extent of laparoscopic experience, which is still considered mandatory.

The evaluation of learning curve for high complexity procedures is influenced by the heterogeneity within this group of cases.

The creation of a dedicated and stable robotic team contributes to the development of a "team learning curve", where surgeons improve their performance through the collective experience of the group.

The findings of this study provide valuable insights into the adaptability of surgeons to robotic liver surgery, emphasizing the collaborative nature of team learning within a dedicated robotic team. These insights can inform future surgical training programs and guide the implementation of robotic liver surgery into clinical practice.

Data availability statement

The data that support the findings of this study are available from the corresponding author, FR, upon reasonable request.

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