

research article

The learning curve of laparoscopic liver resection utilising a difficulty score

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Background. This study aimed to quantitatively evaluate the learning curve of laparoscopic liver resection (LLR) of a single surgeon.

Patients and methods. A retrospective review of a prospectively maintained database of liver resections was conducted. 171 patients undergoing pure LLRs between April 2008 and April 2021 were analysed. The Halls difficulty score (HDS) for theoretical predictions of intraoperative complications (IOC) during LLR was applied. IOC was defined as blood loss over 775 mL, unintentional damage to the surrounding structures, and conversion to an open approach. Theoretical association between HDS and the predicted probability of IOC was utilised to objectify the shape of the learning curve.

Results. The obtained learning curve has resulted from thirteen years of surgical effort of a single surgeon. It consists of an absolute and a relative part in the mathematical description of the additive function described by the logarithmic function (absolute complexity) and fifth-degree regression curve (relative complexity). The obtained learning curve determines the functional dependency of the learning outcome versus time and indicates several local extreme values (peaks and valleys) in the learning process until proficiency is achieved.

Conclusions. This learning curve indicates an ongoing learning process for LLR. The proposed mathematical model can be applied for any surgical procedure with an existing difficulty score and a known theoretically predicted association between the difficulty score and given outcome (for example, IOC).

Key words: learning curve; difficulty score; laparoscopy; hepatectomy; intraoperative complication

Introduction

Interest in laparoscopic liver resection (LLR) has grown since the publication of the International Louisville Statement on laparoscopic liver surgery.¹ Since then, the number of LLRs performed worldwide has increased exponentially.²

The laparoscopic approach must not compromise the technical quality of the liver resection. The message from the second Morioka consensus conference in 2014 was the need for a formal structure of education for those interested in performing LLR.³ The need for the organisation of LLR was achieved by the establishment of the

International Laparoscopic Liver Society in 2016.⁴ In Southampton, 2017, the third consensus meeting has produced a set of clinical practice guidelines to direct the speciality's continued safe progression and dissemination.⁵ A few difficulty scoring systems have been proposed to rate the difficulty of LLR, and the need for validating the existing tools before the clinical application has been highlighted.⁶⁻⁹ Halls *et al.*¹⁰ developed and internally validated a difficulty score estimating the risk of intraoperative complications (IOC) during LLR, which was externally validated by the authors of the present study.¹¹

Along with the evolution of LLR, its learning curves (LCs) have received increased attention.¹²⁻¹⁴ The idealised model of the LC has been described, demonstrating continuous result improvement along with experience.¹⁵ Recently, the LC has been reported to resemble a true model, in which alternating periods of progression and regression occurred until mastery was achieved.¹⁶

The present study was based on a thirteen-years single-centre experience and was designed to analyse the real LC of LLR. To the best of our knowledge, it is the only study quantitatively presenting the LC of LLR.

Patients and methods

Patients

Study subjects were identified from a prospectively maintained database of patients who underwent liver resections at the Department of Abdominal and General Surgery, University Medical Centre Maribor, Slovenia. This institution has been a tertiary referral centre specialised in hepato-pancreato-biliary surgery, where the first LLR was performed in April 2008. The study included all the patients in whom a pure laparoscopic liver procedure was performed (intention-to-treat analysis) until 31st March 2021. For the present study, patients who underwent laparoscopic cyst fenestration, liver biopsies, and radiofrequency ablation were excluded.

Only pure LLR were performed; no hand-assisted or hybrid procedures were used. All patients were operated by the same surgeon (AI). He had expertise in open hepato-pancreatico-biliary and laparoscopic surgery but no experience in LLR before this series. Perioperative definitions were provided elsewhere.¹¹ The surgical technique for LLR has been extensively described by others¹⁷ and performed as reported previously.¹⁸⁻²⁰

At the time of the operation all patients had given their written consent that anonymous data can be used for research purposes. Patient records were anonymized and de-identified before analysis. Ethical approval for this study was obtained from the local institutional review board.

Statistical analysis

IBM SPSS for Windows Version 26.0 (IBM Corp., Armonk, NY, USA) and Wolfram Mathematica for Windows Version 10.4 (Wolfram Research, Inc., Champaign, IL, USA) were used for statistical computations.

Categorical variables were reported as frequency (percentages). Continuous variables were reported as mean and standard deviation when data distribution was normal; otherwise, they were reported as median (minimum-maximum, interquartile range). The chi-square and the paired samples t-test were used. Percentages were listed to one decimal place, and a difference in the P-value of <0.05 was considered statistically significant.

Mathematical modelling of the learning curve

The Halls difficulty score (HDS)¹⁰ was applied. Its parameters (neoadjuvant chemotherapy, previous open liver resection, benign or malignant lesion, lesion size, and classification of resection) were captured from the institutional database. Each LLR was retrospectively scored from 0 to 15.

In the proposed model, IOC was used as a sensible measure of the complexity of the resection.¹⁰ IOC's key markers were blood loss over 775 mL, unintentional damage to the surrounding structures and conversion to open approach.¹⁰ The conversion was defined as the requirement for laparotomy at any time of the procedure, except for the extraction of the resected specimen.¹⁰

In¹¹, the authors searched for functorial dependence between IOC and HDS using the first 128 patients of the observed cohort. The best-fit-dependence was found to be the Weibull cumulative distribution function²¹ of the form

$$p_{IOC_{theoretical}}(x) = 1 - e^{-(x/\lambda)^k}$$

with $\lambda = 8.085$ and $k = 2.871$. Here x represents the HDS, and $p_{IOC_{theoretical}}(x)$ represents the predicted probability of IOC occurrence. This functional dependence will be referred as the theoretical probability of IOC¹¹ and is graphically represented in

Figure 1. This figure is rendered here for the self-sufficiency of this article.

The Weibull curve in Figure 1 is monotonically increasing. Regarding the LC, we assume that a procedure with a higher difficulty score must be graded better than a procedure with a lower difficulty score if the resection is done without IOC. Therefore, the difference between the theoretically predicted probability of IOC and obtained IOC is greater if the difficulty score is higher (if IOC = 0). On the other hand, if IOC was detected (if IOC = 1), the difference between the theoretically predicted probability of IOC and obtained IOC is negative (implying a lower grade for a surgeon) if the difficulty score is low. Thus, the learning outcome is proportional to the share of IOC caused by the surgeon obtained in each of the ten classes.

We wanted to test if the time dependency of HDS is (on average) an ascending function. Therefore, resections were divided into three (time) sequential classes (each consisting of 57 patients), and the number of obtained IOC in each class was counted.

HDS¹⁰ was used in the analysis of LC. Its dependency was proven to be (on average) an increasing function (Figure 1).

The proposed mathematical model of a learning curve

The probability (the share of IOC in the time-dependent class) of IOC depends on HDS. The share of IOC in a time-dependent class measures the complexity of resections. Therefore, a novel model for presenting the learning outcome in the case of LLR with existing theoretical dependence between HDS and (the probability of) IOC was introduced.

We assume that the learning outcome consists of two additive components. The first represents the absolute complexity of the resection according to time (which is proportional to effort). The second (additive) component is obtained by comparing the share of IOC to the theoretically predicted (probability of) IOC depending on the HDS of the patient. Components share the same *physical* units; therefore, the addition is justified. The sum of components results in the learning outcome for any patient and finally in the LC. The first component reflects the absolute complexity of the resections within the same class, while the second one reflects the relative complexity (comparing to the theoretically predicted HDS), which can be interpreted as the surgeon's efficiency.

At this point, we mathematically define the objectives determining the learning outcomes, and



FIGURE 1. The continuous mean risk curve of intraoperative complication (IOC) as a function of the Halls difficulty score: the theoretical probability of intraoperative complication.¹¹

consequently, the LC. The cohort of 171 patients is divided into ten sequential classes (the last class contains 17+1 patient). By *n*, we denote the sequential number of the patient. By *N*, we denote the sequential number of the class (for every class, its cardinality #*N* is equal to 17).

Our main assumptions and proposals are the following:

1. Since the resections were listed chronologically, we may assume that the sequential number of the patient corresponds to the effort of the surgeon (the correspondence is monotonically increasing).
2. For every class *N*, the absolute complexity (*ac*) of the tasks in the class is proportional to the ratio of the IOC cases.

$$ac(N) = \sum_{n_i \in N} p_{IOC_{theoretical}}(n_i)$$

The non-smooth dependency (*N_i, ac(N_i)*); *i* = 1,2,...,10 was fitted to smooth logarithmic function *ac(N) = f(N)*. Additionally, it was modified to absolute complexity for each sequential patient (*AC*)

$$AC(n) = f\left(\frac{n + 16}{17}\right).$$

3. For every class *N*, the relative complexity (*rc*) or efficiency of the surgeon is proportional to the sum of differences between the theoretically predicted probabilities of IOC and the obtained probabilities of IOC

$$rc(N) = \sum_{n_i \in N} p_{IOC_{theoretical}}(n_i) - p_{IOC_{obtained}}(n_i)$$

Interpolating the data $(N_i, rc(N_i))$; $i = 1, 2, \dots, 10$ to a polynomial of degree five, one gets a smooth function $rc(N)$ obtained by Mathematica command *SplineFit* using option *Cubic*.

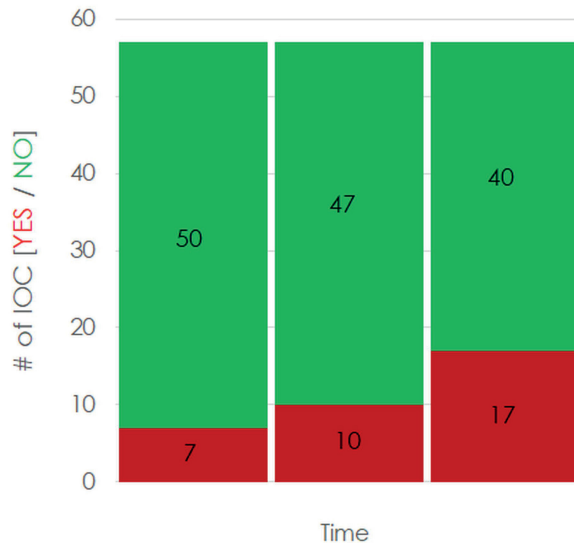


FIGURE 2. Histogrammic time classes dependency of intraoperative complication (IOC) (yes/no) on the observed cohort.

TABLE 1. Baseline characteristics of 171 patients who underwent laparoscopic liver resection

Baseline characteristics	N ^{a,b}
Male sex ^a	104 (60.8%)
Age (years) ^b	64 (20-86, 15)
BMI (kg/m ²) ^b	27 (18-50, 4.8)
ASA score ^a	1 44 (25.7%)
	2 73 (42.7%)
	3 51 (29.8%)
	4 3 (1.8%)
Liver cirrhosis Child-Pugh (22) ^a	A 33 (19.3%)
	B 4 (2.3%)
Previous abdominal surgery ^a	41 (24.0%)
Previous liver resection ^a	8 (4.6%)
Malignant tumour ^a	128 (74.9%)
Neoadjuvant chemotherapy ^a	25 (14.6%)
Max. diameter (mm) ^b	38 (2-160, 33)
Number of tumours ^a	1 (1-10, 0).
Deep location within liver ^a	50 (29.2%)
Posterosuperior liver segments ^a	49 (28.7%)

^a = categorical variables; ^b = continuous variables have been reported as median (minimum-maximum, interquartile range); ASA = American Society of Anaesthesiologists; BMI = body mass index

Additionally, $rc = rc(N)$ was finally modified to relative complexity (RC) for each sequential patient

$$RC(n) = rc\left(\frac{n+16}{17}\right).$$

4. Adding both components, we get the learning curve (LC) of the surgeon: $LC(n) = AC(n) + RC(n)$

Results

The presentation of the cohort

Between April 2008 and April 2021, 171 patients underwent pure LLR. Their baseline characteristics are presented in Table 1.

Perioperative outcomes are given in Table 2.

Two patients (1.2%) suffered from unintentional laceration of the transverse colon, sutured laparoscopically. The procedure was completed laparoscopically in 147 (86.0%) patients. The reasons for conversion to laparotomy in 24 (14.0%) patients were diffuse parenchymal bleeding (N = 3), inability to proceed due to the large liver or dense adhesions (N = 6), and oncological concern (N = 15). The decision to proceed to conversion was not made upon life-threatening bleeding. The indication for liver resection in converted cases was malignant tumours. Three (1.8%) patients died – one bled out from ruptured oesophageal varices, and two died of liver failure; they all had hepatocellular carcinoma and liver cirrhosis Child-Pugh B.

Learning curve analysis results

The analysis of the learning curve was motivated by the increasing time dependency of HDS. Therefore, resections were divided into three sequential classes of 57 resections, and the number of obtained IOC in each class was counted. The results are graphically presented in Figure 2.

On $\alpha = 5\%$ significance level the p -value for Chi Square test is slightly above 5% ($p = 0.055$). However, for linear-by-linear (Mantel Haenszel) test for trend, the p -value is < 0.05 .

HDS¹⁰ was used in the analysis of LC. The risk-of-IOC dependency was proven to be (on average) an increasing function in terms of HDS (Figure 1). A time-dependent and increasing trend can also be seen in Figure 3 (see the red linear trend-line for HDS; the blue chart represents actual data).

The sequential number of the patient corresponds to the effort of the surgeon (the correspondence is monotonically increasing). In the first class,

the average time difference between sequential surgeries was 117 days (with a standard deviation of 132 days), while in the last class, the time difference was 13 days with a standard deviation of 12 days. The paired samples t-test shows that (at the level of confidence of 95%) the two means are not equal ($p < 0.05$).

The final result of our LC data analysis is presented in Figure 4. Ten consecutive classes of 17 patients are given on abscissa. The height of the columns represents the share of the IOC in the time class. Two types of LCs for the observed cohort and the surgeon under consideration are given. The orange line represents the logarithmic regression curve based on absolute complexity for data ($N_i, ac(N_i)$). The green line represents the sum of the orange curve and the quintic regression line of relative complexity for data ($N_i, rc(N_i)$). This green line represents our LC.

Discussion

Like any other human activity, where individuals perform more difficult and intricate tasks over time, surgeons have been interested in their LC when performing LLR.¹⁶ The obtained learning curve has resulted from thirteen years of surgical effort of a single surgeon. It consists of an absolute and a relative part in the mathematical description of the additive function described by the logarithmic function (absolute complexity) and fifth-degree regression curve (relative complexity). The obtained LC determines the functional dependency of the learning outcome versus time and indicates several local extreme values (peaks and valleys) in the learning process until proficiency is achieved.

A typical LC graphically represents the relationship between the learning effort and achievement. LC consists of a measure of learning which usually lies on the ordinate (y-axis), a measure of effort, which usually lies on the abscissa (x-axis) and a mathematical linking function. The shapes of this mathematical (functorial) dependence can vary depending on the nature and difficulty of the learning outcomes and difficulty of the task.^{26,27}

It may be assumed that LC should be increasing in time (*i.e.*, with effort). There are several typical LCs for learning different skills whose shape depends on the complexity of the task. When learning simple skills, S-shaped or logistic curves appear. The logistic curve admits a single inflexion point (indicating the point when half of the knowledge

TABLE 2. Perioperative outcomes of 171 patients who underwent laparoscopic liver resection

Intraoperative details and postoperative course	N ^{a,b}
Anatomic resection (23) ^a	101 (59.1%)
Anatomically major resection (23) ^a	27 (15.8%)
Technically major resection (24) ^a	29 (17.0%)
Operation time (min) ^b	160 (25-450, 90)
Blood loss (mL) ^b	150 (0-2200, 180)
Intraoperative complication (10) ^c	34 (19.9%)
Conversion to open approach ^a	24 (14.0%)
Blood loss > 775 mL ^a	12 (7.0%)
Unintentional damage to the surrounding structures ^a	2 (1.2%)
Hepatic pedicle clamping ^a	45 (26.3%)
Total hepatic pedicle clamping time (min) ^b	8 (0-75, 10)
Transfusion required ^a	20 (11.7%)
Pathohistological diagnosis	
Colorectal liver metastases	53 (31%)
Hepatocellular carcinoma	46 (29.6%)
Intrahepatic cholangiocarcinoma	14 (8.2%)
Other metastases	11 (6.4%)
Hepatic cysts	10 (5.8%)
Hepatic adenoma	6 (4.7%)
Focal nodular hyperplasia	8 (4.7%)
Haemangioma	6 (3.5%)
Other pathology	15 (8.8%)
R0 resection	163 (95.3%)
Major morbidity CD 3a-4b (25) ^a	21 (12.3%)
Hospital stay (days) ^b	6 (2-79, 4)

^a = categorical variables; ^b = continuous variables have been reported as median (minimum-maximum, interquartile range); ^c = intraoperative complication was defined as blood loss over 775 mL, unintentional damage to the surrounding structures and conversion to open approach

was acquired) and a horizontal asymptote (representing the cap to be acquired). In surgical procedures for more complex skills, often a logarithmic LC without a cap appears. However, when interpreting a paediatric ankle radiograph, the LC turns out to be logarithmic.²⁷ The zig-zag shape can appear as well.²⁷ A steep LC is rare in medicine since the skills are associated with difficult and complex procedures.^{26,27}

We have considered the LC of a single surgeon in a technically demanding LLR. When implementing a new surgical procedure, a surgeon already has some fundamental knowledge. The learning outcome is assumed to be proportional to the share of IOC made by the surgeon, *i.e.* we learn from our

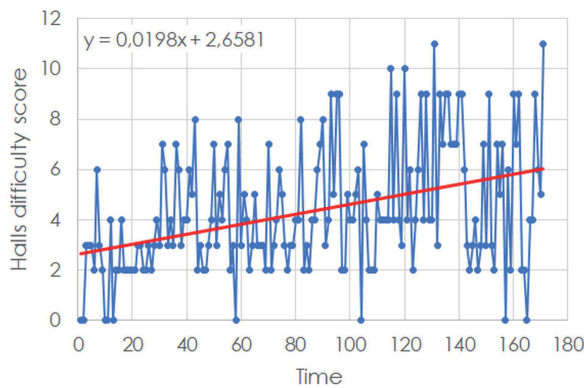


FIGURE 3. Time dependency of the Halls difficulty score on the observed cohort (blue points) and its regression (trend) line (red line).

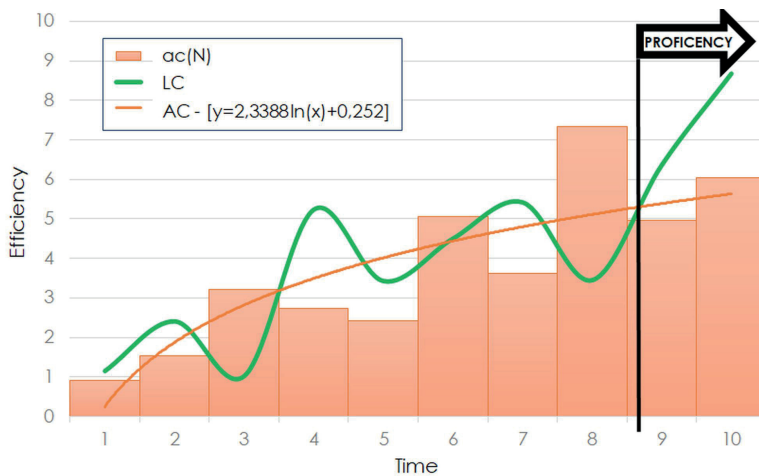


FIGURE 4. Two types of learning curves for observed cohort and the surgeon under consideration. The orange line (AC) represents the logarithmic regression curve based on absolute complexity. The green line (LC) represents the sum of the orange curve and the quintic regression line of relative complexity. This line represents our learning curve.

AC = absolute complexity; ac (N) = absolute complexity expressed by the number of intraoperative complications; LC = learning curve

mistakes (IOC). However, LLR has not been a single procedure, and the complexity of operations varies from wedge resections to extended major hepatectomies. This fact contributes to the difficulties during learning and assessing the LC.¹²⁻¹⁶ In the beginning, solitary and peripherally located symptomatic benign tumours in anterolateral segments were resected.²⁸ With growing experience, the laparoscopic approach was implemented regardless of tumour location and its characteristics.^{1,5} The time difference between sequential surgeries in time classes shortened from 117 days to 13 days. Therefore, one could reasonably assume this was a part of the learning strategy.

It is assumed that a higher level of (the sum of) theoretically predicted probability of IOC (within a particular class) reflects a higher level of gained knowledge (higher grade for the LC). This may be justified because the average HDS is also increasing with time (Figure 4). Therefore, HDS affects the relative complexity of the case. The orange line represents the basic LC. The relative complexity depends on the subjective decision made by the surgeon according to previously successfully finished cases with no IOC. LLR has been encompassing different procedures, each with its own anatomic and procedural considerations. Komatsu *et al.*¹³ demonstrated an ideal learning curve effect for the left lateral sectionectomy and left hepatectomy, but it was not observed for the right hepatectomy. The more successive cases with no IOC encouraged the surgeon to do more cases with increased HDS.

When analysing IOC, the conversion rate of 14% was consistent with the reported ones, counting from 1% to 17%.^{15,29} An increased risk of conversion has been associated with neoadjuvant chemotherapy, previous open liver resection, malignant tumours, their size, anatomically major and technically major resection.³⁰ Patients who had an elective conversion for an unfavourable intraoperative finding had better outcomes than patients who had an emergency conversion secondary to an adverse intraoperative event.³⁰ All our converted cases occurred in malignant tumours. None of the cases was related to life-threatening bleeding. The most common indications for conversion were the inability to proceed and oncological concern, respectively. A chosen method does not change the principle of the surgery. Therefore, an oncologically uncompromised resection has been more crucial than the laparoscopic completion of the procedure. The overall major morbidity and mortality rates of 12.3% and 1.8% followed reports in the literature.^{13,14,16} To sum up, this conversion rate reflected the surgeon's reliance on the open method when dealing with adverse intraoperative findings.²⁰

Although the first anatomical LLR was performed in 1996³¹, the first difficulty score was published not earlier than 2014.³² Our first LLR was performed in 2008, and the surgeon had to lean on his experience from open liver surgery. It would be riveting to study the results of the surgeon's trainees who could benefit from the evolution of techniques, learning modules^{12,16,33}, and difficulty scores.^{6-8,10}

The main shortcoming of the presented research is a relatively low number of patients. Therefore, in future research, a larger number of patients should

be involved to show the robustness of the presented LC. Furthermore, its retrospective manner is another limitation.

The proposed LC and used methodology could guide the trainee surgeons and monitor their performance. In this sense, practitioners should be provided with a statistically independent set of patients with a constant increase (*i.e.*, a constant gradient) of HDS over time. Thus, more difficult cases would be taken over by more qualified surgeons. A newly created application would randomly select patients with the appropriate HDS for each practitioner. It would enable control of the (accidental) variability in HDS and its consequences on IOC, which could not be completely avoided in practice. Under the supervision of a qualified operator, the objective evaluation of the LC would avoid deeper *valleys* in it (higher number of IOCs than theoretically expected) and thus ensure the most optimal learning. Given the basic assumption that we learn from our mistakes (see section *A mathematical modelling of a learning curve*), the maximal acceptable number and type of mistakes in the learning process should be objectively evaluated through further research.

To conclude, our LC is closer to a true model in which alternating periods of progression and regression occurred until mastery was achieved.¹⁶ Furthermore, the method presented in this paper can be applied to any (surgical) procedure with a difficulty score and given outcome (for example IOC), if a theoretically predicted probability dependence for the given outcome is available. From this point of view, the method is novel.

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