Annals of Surgery Publish Ahead of Print
DOI:10.1097/SLA.0000000000006592

OPEN

Competency, Proficiency, and Mastery: Learning Curves for Robotic Distal Pancreatectomy at 16 International Expert Centers

Philip C. Müller, MD[1*], Christoph Kuemmerli, MD, MSc[1*], Adrian T. Billeter, MD, PhD[1], Baiyong Shen, MD[2], Jiabin Jin, MD[2], Felix Nickel, MD, MME[3,4], Cristiano Guidetti, MD[5], Emanuele Kauffmann, MD[6], Julia Purchla, MD[7], Christoph Tschuor, MD, PhD[8], Paul Suno Krohn, MD, PhD[8], Stefan K. Burgdorf, MD, PhD[8], Jan Philipp Jonas, MD, PhD[9], Felix J. Bussmann, MSc[9], Olivier Saint-Marc, MD[10], Abdallah Iben-khayat, MD[10], Paul C.M. Andel MD[11], Izaak Quintus Molenaar, MD[11], Ulrich Wellner, MD[12], Tobias Keck, MD[12], Beat Moeckli, MD, PhD[13], Christian Toso, MD, PhD[13], Fabrizio Di Benedetto, MD[5], Valentina Valle, MD[14], Pier Giulianotti, MD[14], Didier Roulin, MD[15, 16], John B. Martinie, MD[15], Martina Rama, MD[17], Harish Lavu, MD[17], Charles Yeo, MD[17], Parit T. Mavani, MD[18], Mihir M. Shah, MD[18], David A. Kooby, MD[18], Jin He, MD[7], Ugo Boggi, MD[6], Thilo Hackert, MD[3,4], Inne H.M. Borel-Rinkes MD[11], Beat P. Müller, MD[1], Pierre-Alain Clavien, MD, PhD[9]

1 Department of Surgery, Clarunis University Digestive Health Care Center, University Hospital Basel, Basel, Switzerland
2 Department of General Surgery, Pancreatic Disease Center, Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China; Research Institute of Pancreatic Diseases, Shanghai Jiao Tong University School of Medicine, Shanghai, China
3 Department of General, Visceral and Thoracic Surgery, University Medical Center Hamburg-Eppendorf, Hamburg, Germany
4 Department of General, Visceral and Transplantation Surgery, Heidelberg University Hospital, Heidelberg, Germany
5 Hepato-Pancreato-Biliary Surgery and Liver Transplantation Unit, University of Modena and Reggio Emilia, Modena, Italy
6 Division of General and Transplant Surgery, University of Pisa, Pisa, Italy

7 Department of Surgery, Johns Hopkins University School of Medicine, Baltimore, USA
8 Department of Surgery and Transplantation, Rigshospitalet, Copenhagen University Hospital, Copenhagen, Denmark
9 Department of Surgery and Transplantation, University Hospital Zurich, Zurich, Switzerland
10 Service de Chirurgie Digestive, Endocrinienne et Thoracique, Centre Hospitalier Régional, Orleans, France
11 Department of Hepato-Pancreato-Biliary Surgery, Regional Academic Cancer Center Utrecht, St. Antonius Hospital Nieuwegein and University Medical Center Utrecht, the Netherlands
12 Department of Surgery, University Medical Center Schleswig-Holstein, Campus Luebeck, Luebeck, Germany
13 Department of Surgery, University Hospitals of Geneva, Geneva, Switzerland
14 Division of General, Minimally Invasive, and Robotic Surgery, Department of Surgery, University of Illinois at Chicago, Chicago, IL, USA
15 Division of HPB Surgery, Department of Surgery, Carolinas Medical Center, Charlotte, USA
16 Department of Visceral Surgery, Lausanne University Hospital and University of Lausanne, Lausanne, Switzerland
17 Department of Surgery, Thomas Jefferson University Hospital, Philadelphia, USA
18 Department of Surgery, Winship Cancer Institute, Emory University School of Medicine, Atlanta, Georgia, USA

Corresponding Author

Philip C. Müller
Department of Surgery, Clarunis University Digestive Health Care Center, University Hospital Basel
Spitalstrasse 21
4031 Basel
Switzerland
e-mail: philip.mueller@clarunis.ch /phili.mueller@usb.ch

Short running head
Learning Curves in Robotic Distal Pancreatectomy

Author contributions
*PCM and CK contributed equally to this work.
PCM and PAC: conception and design, interpretation of data, figures, drafting the article, final approval. CK: conception and design, acquisition of data, statistical analysis, interpretation of data, figures, drafting the article, final approval. ATB and BPM: conception and design, interpretation of data, drafting the article, critical revision of the article, final approval. BS, JJ, FN, CG, EK, JP, CT, PSK, SKB, JPJ, FJB, OSM, AI, PCMA, IQM, UW, TK, BM, CT, FDB, VV, PG, DR, JM, MR, HL, CY, PTM, MMS, DAK, JH, UB, TH, IHMB, and BPM: conception and design, interpretation of data, critical revision of the article, final

approval. The data underlying the findings of this study are available on request from the corresponding author.

Conflict of interest
The authors declare that no conflict of interest exists. No grants and financial support were received for this study.

Abstract

Objective

The aim of this study was to evaluate the different phases of the learning curve for robotic distal pancreatectomy (RDP) in international expert centers.

Summary Background Data

RDP is an emerging minimally invasive approach; however, only limited, mostly single center data are available on its safe implementation, including the learning curve.

Methods

Consecutive patients undergoing elective RDP from 16 expert centers across three continents were included to assess the learning curve. Based on the first 100 RDPs at each center, three cutoffs were used to define the learning curve: operative time for *competency*, major complications (Clavien–Dindo grade ≥III) for *proficiency*, and textbook outcome for *mastery*. Clinical outcomes before and after the cutoffs were compared.

Results

The learning curve analysis was conducted on 1109 of 2403 RDPs. Competency, proficiency, and mastery, respectively, were reached after 46, 63, and 73 RDP procedures. After competency, operative time decreased from 245 to 235 minutes (p=0.002). Attaining proficiency was reflected by a reduction in the rate of major complications from 20% to 15%

(p=0.012), and mastery was associated with a higher proportion of patients with textbook outcome (71% vs 63%; p=0.028). The postoperative pancreatic fistula rate remained stable along the learning curve, ranging between 18.5% and 21.5%. Previous laparoscopic experience accelerated the learning process by virtue of reduced operative time and an earlier decrease in major complications.

Conclusion

Competency, *proficiency*, and *mastery* for RDP were reached after 46, 63, and 73 procedures, respectively, at international expert centers. The findings highlight that the learning curves for intraoperative parameters are completed earlier; however, extensive experience is needed to master RDP.

Keywords:

Robotic surgery; pancreatic surgery; distal pancreatectomy; outcome research; learning curves

Abbreviations

CD	Clavien–Dindo classification
CCI	Comprehensive complication index
DGE	Delayed gastric emptying
DP	Distal pancreatectomy
ERCP	Endoscopic retrograde cholangiopancreatography
ISGPS	International Study Group of Pancreatic Surgery
IQR	Interquartile range
LOS	Length of hospital stay
LDP	Laparoscopic distal pancreatectomy

MIPS	Minimally invasive pancreatic surgery
PDAC	Pancreatic ductal adenocarcinoma
PPH	Postpancreatectomy hemorrhage
POPF	Postoperative pancreatic fistula
RDP	Robotic distal pancreatectomy
SD	Standard deviation
SP-RDP	Spleen-preserving robotic distal pancreatectomy
VBA	Video-based assessment

Introduction

Distal pancreatectomy (DP) with or without splenectomy is the treatment of choice for benign and malignant tumors confined to the tail or body of the pancreas. Since the first laparoscopic DP (LDP) in 1996, minimally invasive pancreatic surgery (MIPS) has been rapidly adopted worldwide, and 40–50% of all DP are nowadays performed as minimally invasive procedures.[1–3] Compared with the classic open approach, MIPS is associated with improved perioperative outcomes, especially with regard to blood loss and length of hospital stay, while maintaining equal oncologic outcomes.[4,5]

Robotic distal pancreatectomy (RDP) was introduced as an alternative to LDP with the advantages of enhanced versatility of surgical instruments, 3D vision, and magnification of the operative field, resulting in a more precise operative technique with less blood loss and lower conversion rates.[6,7] These beneficial features of the robotic platform compensate for some downsides of LDP, making the transition from open DP to the robotic approach potentially easier than for LDP.[8,9]

International guidelines for minimally invasive and robotic surgery include recommendations for the safe introduction of MIPS formal training .[10–12] Initially, learning curves were assessed mainly on the basis of improvements in intraoperative parameters such as operative time and blood loss.[13–15] However, little is known about the learning curve for RDP, especially with regard to clinically relevant outcomes such as postoperative complications and oncologic results. More recently, three milestones of *competency, proficiency, and mastery* were defined to illustrate a comprehensive process along the learning curve.[16–18] While intraoperative parameters mainly improve during acquisition of *competency*, postoperative complications and oncologic outcomes improve later, in the phases of *proficiency and mastery*.

The aim of this study was to depict the three phases of the RDP learning curve within a consecutive patient series, using data from 16 international expert centers.

Methods

Study Design

The study is reported in accordance with to the STROBE guidelines.[19] High-volume centers performing >50 pancreatic surgeries/year with a minimal experience of 30 RDP were screened. The final *Outcomes4RDP* collaborative consortium included 16 centers: 10 in Europe (Basel, Copenhagen, Geneva, Heidelberg, Orléans, Lübeck, Modena, Pisa, Utrecht, Zürich), 5 in the USA (Atlanta, Baltimore, Chicago, Charlotte, Philadelphia), and 1 in Asia (Shanghai) (**Figure 1**). Consecutive patients were included at each center, starting with the first institutional RDP (May 2007) and continuing up to March 2024. Ethical approval was obtained from the institutional review board at the study center (BASEC ID 2023-01497).

Indication for RPD

Included were patients undergoing RDP with or without splenectomy for benign and malignant pancreatic diseases confined to in the pancreatic corpus or tail, without involvement of the venous or arterial axis (Type 1 DP according to Loos et al.[20]).

Three phases of the learning curve

The *competency* learning curve was based on operative time, the *proficiency* learning curve on major complications (Clavien–Dindo grade IIIa or higher[21]), and the *mastery* learning curve on textbook outcome as previously defined by Müller et al.[16,17]

Data collection and outcomes

Data were retrieved from prospectively maintained institutional databases and stored in an anonymized and secure online data management system.

Intraoperative outcomes included blood loss, operative time, and conversion rate. Postoperatively, complications were assessed using the Clavien–Dindo (CD) classification

and the comprehensive complication index (CCI□) to depict the total number of complications by severity for every patient up to 90 days after surgery.[21–23] Major complications were defined as CD grade IIIa or higher. Pancreas-specific complications were defined according to the International Study Group of Pancreatic Surgery (ISGPS) and included postoperative pancreatic fistula (POPF)[24], delayed gastric emptying (DGE)[25], and postpancreatectomy hemorrhage (PPH)[26]. Reoperation rate, postoperative length of hospital stay (LOS), 90-day readmission rate, and 90-day mortality rate were also evaluated. Textbook outcome was defined by the absence of POPF, bile leak, PPH (each ISGPS grade B/C), major complications, readmission, and in-hospital mortality.[27] For the subgroup of patients with pancreatic ductal adenocarcinoma (PDAC), short-term oncological quality indicators included the number of lymph nodes resected.

Institutional characteristics included annual caseload of open, laparoscopic, and robotic pancreatic surgery; furthermore, preferred transection technique and coverage of the pancreatic remnant were assessed. Surgeon-specific characteristics included overall surgical experience (years), minimally invasive experience (years), and minimally invasive DP experience (cases).

Statistical analysis

Descriptive statistics were used to express the perioperative cohort characteristics. Qualitative variables were expressed as frequencies and percentages, and quantitative variables as means and standard deviation (SD) if normally distributed and otherwise as medians and interquartile range (IQR). Comparison of means between groups was done using Student's t-test (pooled t-test) or the nonparametric Mann–Whitney test. To compare percentages between groups, a contingency table analysis was used with the chi-square test or, if the frequency of events was low, Fisher's exact test. All analyses were performed using R version 4.2.3, R Core Team (2023) (R: A language and environment for statistical

computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/).

Learning curve analysis

For the learning curve analysis, the first 100 procedures were considered. Locally weighted smoothing functions were fitted to all pooled outcome parameters because they capture nonlinear data distributions and show trends and associations of the outcome variable with the number of procedures. These trends were graphically assessed. Due to the inherent selection of the patients in this cohort (i.e., only low-risk cases), no risk adjustment was made but the nadir of each analysis was marked as the first turning point and any change in complexity between the patients treated before and after was assessed by group comparison. Regression analyses were used to assess the relationship of parameters that impact the learning curve and the outcome per center.

Results

Patient Demographics

Sixteen centers from eight countries contributed 2403 patients. For the learning curve analysis, 1109 patients were included. The median age of these patients was 63 (51-71) years and their median body mass index was 25(23-30) kg/m^2. The most frequently occurring indications for RDP were cystic lesions (43.0%), neuroendocrine tumors (26.9%), and PDAC (21.0%). The characteristics of the entire population and the learning curve cohort are listed in **Table 1**.

Institution- and surgeon-specific characteristics

The institutional overall annual pancreatic surgery caseload was 137 (78-229) cases, divided into 80 (35-148) open, 0 (0-20) laparoscopic, and 36 (21-69) robotic cases. The

annual DP caseload was 34 (28-82), divided into 17 (3-29) open, 0 (0-14) laparoscopic and 20 (13-35) robotic cases. The preferred transection techniques were stapling (13 centers) and ultrasonic transection (3 centers). Six centers did not routinely cover the pancreas stump, while six centers covered the pancreas remnant with autologous and four with artificial material. The number of surgeons performing RDP per center ranged from one to eight: Their overall surgical experience was 20 (14-24) years, with 10 (6-15) years' experience of complex minimally invasive surgery.

Intraoperative Outcomes

The median operative time was 240 (185-310) minutes and the median blood loss was 100 (50-200) mL. A spleen-preserving approach was performed in 50.2% of cases. Conversion to an open approach was necessary in 57 patients (5.2%). Median tumor size was 28 (19-45) mm.

Postoperative Outcomes

The overall complication rate was 48.2%, with 18.5% of the patients experiencing major complications, leading to a reoperation rate of 3.5%. The rate of POPF was 22.0%. An additional postoperative percutaneous drain was placed in 8.4% of patients, and endoscopic retrograde cholangiopancreatography (ERCP) was performed in 4.6% of cases. The 90-day mortality rate was 1.5%. The median length of hospital stay was 7 (5-10) days and the readmission rate 16.2%. A textbook outcome was achieved in 64.5% of patients.

Learning curve

Competency

Analysis of operative time revealed a cutoff for competency at 46 RDP procedures (**Figure 2A**). Operative time decreased from 245 minutes (IQR 190-320) before this point to 235 minutes (IQR 180-293) thereafter (p=0.002). The rates of conversion (5.3% vs. 5.1%; p=1.000), POPF (20.9% vs. 21.4%; p=0.914), readmission (17.4% vs. 14.3%; p=0.201), and

textbook outcome (62.7% vs. 67.1%; p=0.154) did not differ significantly before and after reaching competency. The rate of major complications (19.3% vs. 17.2%; p=0.439) and LOS was similar (7 days (5-10) vs. 7 days (5-12); p=0.209) after reaching competency (**Table 2**).

Proficiency

Evaluation of major morbidity revealed a cutoff for proficiency at 63 RDP procedures, and such complications occurred less frequently after proficiency was attained (19.6% vs 14.6%; p=0.012) (**Figure 2B**). Operative time (242 (IQR 187 - 312) vs 231 (IQR 178 - 290) minutes, p=0.081), conversion rate (5.2% vs. 5.1%; p=1.000), POPF (21.5% vs. 18.5%; p=0.444), and textbook outcome (63.4% vs 70.7%; p=0.095) did not differ before and after achieving proficiency. However, the rate of readmissions decreased (17.6% vs. 11.5%; p=0.028) (**Table 2**).

Mastery

Analysis of textbook outcome revealed a cutoff for mastery at 73 RDP procedures, with the rate of such outcomes increasing thereafter (63.4% vs 70.7%; p=0.028) (**Figure 2C**). Operative time (242 (187-312) vs. 231 (178-290) minutes; p=0.081) and the rates of conversion (5.4 vs 3.8%; p=0.532), major complications (16.9% vs. 11.0%; p=0.100), and POPF (21.5% vs 18.5%; p=0.444) did not differ significantly between before and after attaining mastery. Again, the readmission rate was lower after reaching mastery (19.2 % vs. 14.0%; p=0.148) (**Table 2**).

Comparison with international benchmark values

Intraoperative outcomes such as operative time and blood loss were well within the established benchmark cutoffs throughout the learning curve. However, the conversion rate was almost double the benchmark cutoff during competency (5.2%), and although it decreased with the attainment of mastery (3.8%) it never reached the benchmark cutoff of 3%. Postoperative outcomes such as rates of overall complications (≤58.3%), major complications

(≤26.7%), POPF (≤31.8%), DGE (≤5.0%), PPH (≤6.6%), and readmission (≤24%) were below the benchmark cutoffs throughout the learning curve, demonstrating a safe introduction of RDP along the learning curve (**Figure 3 and Table 2**).

Impact of Previous Laparoscopic Experience and Volume

Previous laparoscopic experience led to a faster decrease in operative time ($p<0.001$) and to an earlier decrease in the rate of major complications ($p<0.001$) (**Figure 4 A/B**). An RDP volume of >15 procedures per year was likewise associated with an earlier decrease in operative time ($p<0.001$). The rate of patients achieving textbook outcome was affected neither by previous laparoscopic experience nor by annual RDP case load (**Figure 4 C/D**).

Overall pancreatic center volume did not affect the learning curve. High-volume centers (<100 cases annually) and super high-volume centers (>100 cases annually) exhibited similar learning curves for major complications ($p=0.956$) and textbook outcome ($p=0.494$) (**Figure 4 E/F**).

Impact of Spleen-Preserving RDP

Patients undergoing spleen-preserving RDP (SP-RDP) were healthier, as reflected by the higher rate of benchmark patients (57% vs. 40%). SP-RDP was associated with shorter operation times (230 (175-295) vs. 256 (198-329) minutes) and a similar conversion rate (5.7% vs. 4.7%). Postoperatively, SP-RDP had a higher POPF rate (25% vs. 19%), resulting in a higher major complication rate (22% vs. 16%), mainly due to a higher rate of patients undergoing ERCP (7% vs. 3%). However, the proportion of patients reaching textbook outcomes was comparable (64% vs. 65%) (Supplementary Table 1, Supplemental Digital Content 1, http://links.lww.com/SLA/F350).

Comparing the learning phases of SP-RDP and RDP with splenectomy, reaching competency took longer for SP-RDP (n=34 vs. n=17), while the proficiency and mastery

learning phases remained unchanged and were equal for both procedures (n=63 and n=73 respectively) (Supplementary Figure 1, Supplemental Digital Content 1, http://links.lww.com/SLA/F350).

Discussion

In this large international multicenter cohort of 2403 patients, competency, proficiency, and mastery were reached after 46, 63, and 73 RDP procedures, respectively. Operative time decreased from 245 minutes before reaching competency to 235 minutes thereafter, while the other outcome parameters remained mostly unchanged. Reaching proficiency was reflected by a near halving of major complications, from 20% to 15%, and a lower readmission rate. Finally, mastery was associated with an increased rate of patients reaching textbook outcome, namely 71% vs 63%.

Importantly, the changes along the learning curve have to be interpreted with regard to clinical relevance and not solely statistical significance.[28,29] A decrease in operative time of 10 minutes over time is certainly not clinically relevant. Interestingly, most clinically relevant outcomes after RDP were already within international benchmark cutoffs during the early learning curve, with the exception of the conversion rate, demonstrating the safe implementation of this novel surgical approach in international high-volume centers.[7] In particular, overall complications, 90-day mortality, and pancreas-specific complications such as DGE, POPF, and need for percutaneous drainage were well within benchmarks from the beginning of the learning curve and showed minimal changes thereafter.

Novel surgical techniques are generally introduced in a selected, low-risk patient cohort; therefore, centers reported that vascular involvement (n=15, 94%), previous extensive upper gastrointestinal surgery (n=10, 63%) and the need for additional organ resections (n=10, 63%) were initial contraindications for the robotic approach. At the end of the reported

series, only vascular involvement (n=7, 44%) and the need for additional organ resections (n=7, 44%) remained contraindications to RDP at some centers. Interestingly, the proportion of low-risk, benchmark patients remained largely unchanged throughout the learning curve; however, the proportion of patients with PDAC increased from 19% to 27%, demonstrating the wider indication for the robotic approach. Adequate oncologic outcomes are one of the key quality measures of pancreatic cancer surgery, and a lymph node yield of 17 nodes was achieved from the beginning, significantly higher than the benchmark cutoff of ≥9 lymph nodes.

Another important factor affecting the learning curve was previous experience in LDP. Those centers with previous LDP experience had earlier decreases in operative time and rate of major complications. Interestingly, centers with more than 15 annual RDP had an earlier decrease in operative time, while the major complication rate was unaffected by RDP caseload.

Similar to our reported international evaluation of learning curves of RDP, the European Consortium on Minimally Invasive Pancreatic Surgery (E-MIPS) performed an analysis of LDP in a multicenter cohort.[30] In that study, conversion rate, operative time, and blood loss decreased after 40, 56, and 71 procedures, respectively, while the rate of textbook outcomes increased after 85 procedures. While the patient characteristics of the two cohorts are comparable and both operative time (LDP 243, RDP 240 minutes) and POPF rate (LDP 22.9%, RDP 21.1%) were similar, RDP showed a much lower conversion rate (LDP 12.9%, RDP 5.2%). This finding is in line with the international literature, and the lower conversion rate seems to be one of the main advantages of the robotic approach.[31–33] The composite endpoint textbook outcome showed an almost identical increase with LDP (from 63% to 70%) and RDP (from 63% to 71%). The changes along the learning curves of RDP and LDP are therefore very similar, although no direct comparison of the two minimally invasive approaches has been carried out in a multicenter study setting. However, such an analysis will

probably never be performed, as a huge shift towards robotic surgery is currently taking place, with projected elimination of laparoscopic surgery within the next 15 years.[34]

Previously, learning curves in pancreatic surgery were almost exclusively defined in small single-center patient cohorts on the basis of changes in intraoperative parameters such as operative time and blood loss.[13,35,36] As a result, the number of cases to complete the first phase (competency) of the learning curve was given as 15 for RDP and 16 for LDP in a recent systematic review, considerably lower than found in our study.[16] This demonstrates the importance of adequate study sample size, as a strong correlation between sample size and number of procedures needed to surpass the learning curve has been described.[16] This factor has to be taken into account, because improvements in patient-centered, clinically relevant outcomes such as complications and oncologic parameters are generally observed at a much later stage.

Assessment of the learning curve of a procedure is highly relevant not only for its safe implementation, but also for the proper scientific evaluation of a novel surgical technique along the different IDEAL stages.[37,38] For example, the recently published randomized multicenter DIPLOMA trial evaluated the oncology efficacy of LDP versus ODP and required surgical teams to perform at least 15 DP per year with previous experience of at least 50 MIDPs prior to the start of trial enrolment.[5] While a predefined previous case load was shown to be insufficient to ascertain a required quality in both the LEOPARD-2 and EUROPA trials[39,40], video-based assessment (VBA) might be a modern, more individual way to evaluate the surgical quality of minimally invasive procedures. In pancreatic surgery VBA was shown to be a valid method for both surgical quality control and to highlight areas for further improvement.[41–43] As even randomized controlled trials in high-impact journals do not control for surgical quality in 80% of studies, the findings of this trial should be considered in the planning phase of future high quality prospective trials, especially to exclude bias through learning curve effects.[44]

We strongly recommend standardized, statistical assessment and reporting of learning curves in pancreatic surgery in the three-phase model of *competency, proficiency, and mastery* as proposed by Müller et al.[16] Within the learning curve, we furthermore advocate reporting the quality of surgical outcomes in accordance with the Outcome4medicine consensus recommendations[45] including intraoperative and technical parameters as well as postoperative overall complications. Postoperative complications should be graded according to the Clavien–Dindo system[21,46] or the CCI[22,23] and procedure-specific complications according to the International Study Group of Pancreatic Surgery.[24–26,47]

Together with standardized reporting, structured training programs such as that from the University of Pittsburgh or the nationwide implementation program ("LEARNBOT") from the Netherlands, which is endorsed by the European–African Hepato-Pancreato-Biliary Association (E-AHPBA) should be followed for safe implementation of RDP.[48,49] These programs include an extensive preparatory program with virtual simulation[50], biotissue training[51], and video library studies and have been shown to drastically decrease the learning curve for second- and third-generation surgeons. In line with these recommendations, center volume strongly affects outcomes of MIDP, and both the Miami and Brescia guidelines recommend a minimal center volume of at least 20 MIDP per year, which seems adequate and permits attainment of competency within 2 years.[10,11]

The results of this study should be interpreted in the light of some limitations. While the study describes the learning curves at international high-volume institutions, individual, surgeon-specific learning curves were not analyzed. Secondly, the learning process is depicted in relation to the first 100 procedures and did not include type II-IV DP with venous, multivisceral, or arterial resections[20]. Therefore, changes in indications, surgical complexity, and outcomes will be observed even at later stages. A third important confounding factor remains the variation in center-specific perioperative management of patients, including

coverage of the pancreatic remnant[52], drainage[53], and discharge management[54,55]. All of these factors lead to heterogeneity of the assessed outcomes.

In conclusion, this international, multicenter cohort study evaluated the length of the institutional learning curve based on intraoperative and postoperative outcomes. Competency, proficiency, and mastery were reached after 46, 63, and 73 RDP procedures, respectively. While previous studies have suggested rapid learning of RDP, our findings suggest that a longer, more complex process is required to master the robotic approach.

Compliance with Ethical Standards

Conflict of interest:	The authors declare that they have no conflict of interest.
Source of Funding:	The study was funded by institutional means.
Ethical approval:	All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Ethical approval from the institutional review board of the University of Basel was obtained (BASEC ID 2023-01497)
Informed consent:	Not applicable due to the nature of the study design

References

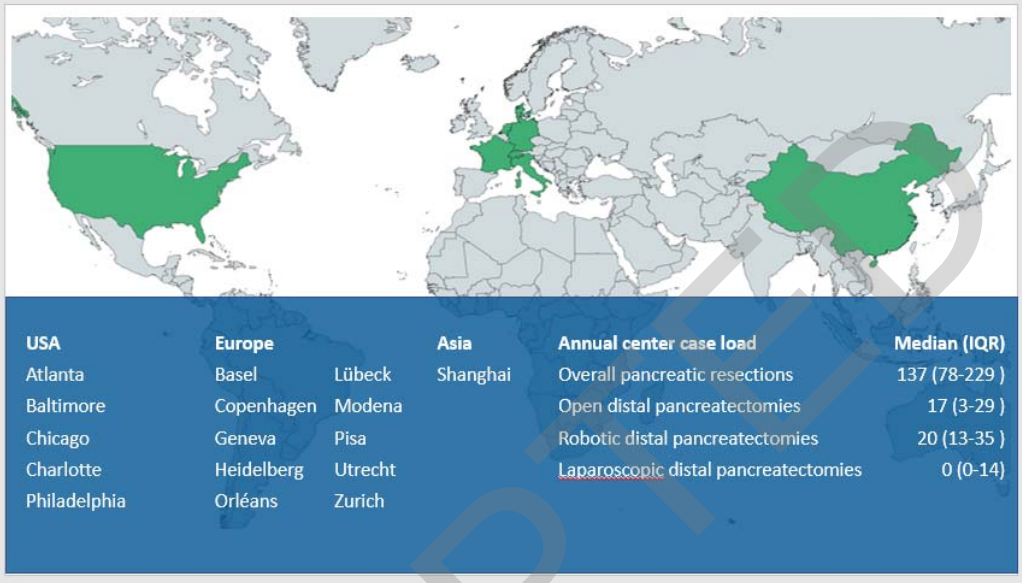
1. Cuschieri A, Jakimowicz JJ, van Spreeuwel J. Laparoscopic distal 70% pancreatectomy and splenectomy for chronic pancreatitis. *Ann Surg*. 1996;223:280–285.
2. Jehan FS, Khreiss M, Seth A, et al. Trends and disparities in access to minimally invasive distal pancreatectomy (midp): an eight-year analysis from the national cancer database. *J Robotic Surg*. 2024;18:52.
3. van Bodegraven EA, van Ramshorst TME, Bratlie SO, et al. Minimally invasive robot-assisted and laparoscopic distal pancreatectomy in a pan-European registry a retrospective cohort study. *Int J Surg*. . Epub ahead of print March 18, 2024. DOI: 10.1097/JS9.0000000000001315.
4. Pfister M, Probst P, Müller PC, et al. Minimally invasive versus open pancreatic surgery: meta-analysis of randomized clinical trials. *BJS Open*. 2023;7:zrad007.
5. Korrel M, Jones LR, van Hilst J, et al. Minimally invasive versus open distal pancreatectomy for resectable pancreatic cancer (DIPLOMA): an international randomised non-inferiority trial. *Lancet Reg Health Eur*. 2023;31:100673.
6. Giulianotti PC, Coratti A, Angelini M, et al. Robotics in General Surgery: Personal Experience in a Large Community Hospital. *Archives of Surgery*. 2003;138:777–784.
7. Müller PC, Breuer E, Nickel F, et al. Robotic Distal Pancreatectomy: A Novel Standard of Care? Benchmark Values for Surgical Outcomes From 16 International Expert Centers. *Ann Surg*. 2023;278:253–259.
8. Haney C, Karadza E, Limen E, et al. Training and learning curves in minimally invasive pancreatic surgery: from simulation to mastery. *Journal of Pancreatology*. 2020;3:101–110.
9. Müller PC, Müller-Stich BP, Hackert T, et al. Robotic pancreaticoduodenectomy after the learning curve-a new hope. *Hepatobiliary Surg Nutr*. 2022;11:489–491.
10. Asbun HJ, Moekotte AL, Vissers FL, et al. The Miami International Evidence-based Guidelines on Minimally Invasive Pancreas Resection. *Ann Surg*. 2020;271:1–14.
11. Abu Hilal M, van Ramshorst TME, Boggi U, et al. The Brescia Internationally Validated European Guidelines on Minimally Invasive Pancreatic Surgery (EGUMIPS). *Ann Surg*. 2024;279:45–57.
12. Hobeika C, Pfister M, Geller D, et al. Recommendations on Robotic Hepato-Pancreato-Biliary Surgery. The Paris Jury-Based Consensus Conference. *Ann Surg*. . Epub ahead of print May 24, 2024. DOI: 10.1097/SLA.0000000000006365.
13. Napoli N, Kauffmann EF, Perrone VG, et al. The learning curve in robotic distal pancreatectomy. *Updates Surg*. 2015;67:257–264.
14. Klompmaker S, van der Vliet WJ, Thoolen SJ, et al. Procedure-specific Training for Robot-assisted Distal Pancreatectomy. *Ann Surg*. 2021;274:e18–e27.
15. Shyr B-U, Chen S-C, Shyr Y-M, et al. Learning curves for robotic pancreatic surgery-from distal pancreatectomy to pancreaticoduodenectomy. *Medicine (Baltimore)*. 2018;97:e13000.
16. Müller PC, Kuemmerli C, Cizmic A, et al. Learning Curves in Open, Laparoscopic, and Robotic Pancreatic Surgery: A Systematic Review and Proposal of a Standardization. *Annals of Surgery Open*. 2022;3:e111.
17. Zwart MJW, van den Broek B, de Graaf N, et al. The Feasibility, Proficiency, and Mastery Learning Curves in 635 Robotic Pancreatoduodenectomies Following a Multicenter Training Program: "Standing on the Shoulders of Giants." *Ann Surg*. 2023;278:e1232–e1241.
18. Kuemmerli C, Toti JMA, Haak F, et al. Towards a Standardization of Learning Curve Assessment in Minimally Invasive Liver Surgery. *Ann Surg*. . Epub ahead of print

June 26, 2024. DOI: 10.1097/SLA.0000000000006417.
19. von Elm E, Altman DG, Egger M, et al. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *BMJ*. 2007;335:806–808.
20. Loos M, Mack CE, Xu ATL, et al. Distal Pancreatectomy: Extent of Resection Determines Surgical Risk Categories. *Ann Surg*. 2024;279:479–485.
21. Clavien PA, Barkun J, de Oliveira ML, et al. The Clavien-Dindo classification of surgical complications: five-year experience. *Ann Surg*. 2009;250:187–196.
22. Clavien P-A, Vetter D, Staiger RD, et al. The Comprehensive Complication Index (CCI®): Added Value and Clinical Perspectives 3 Years "Down the Line." *Ann Surg*. 2017;265:1045–1050.
23. Slankamenac K, Graf R, Barkun J, et al. The comprehensive complication index: a novel continuous scale to measure surgical morbidity. *Ann Surg*. 2013;258:1–7.
24. Bassi C, Marchegiani G, Dervenis C, et al. The 2016 update of the International Study Group (ISGPS) definition and grading of postoperative pancreatic fistula: 11 Years After. *Surgery*. 2017;161:584–591.
25. Wente MN, Bassi C, Dervenis C, et al. Delayed gastric emptying (DGE) after pancreatic surgery: a suggested definition by the International Study Group of Pancreatic Surgery (ISGPS). *Surgery*. 2007;142:761–768.
26. Wente MN, Veit JA, Bassi C, et al. Postpancreatectomy hemorrhage (PPH): an International Study Group of Pancreatic Surgery (ISGPS) definition. *Surgery*. 2007;142:20–25.
27. van Roessel S, Mackay TM, van Dieren S, et al. Textbook Outcome: Nationwide Analysis of a Novel Quality Measure in Pancreatic Surgery. *Ann Surg*. 2020;271:155–162.
28. Gikandi A, Hallet J, Koerkamp BG, et al. Distinguishing Clinical From Statistical Significances in Contemporary Comparative Effectiveness Research. *Ann Surg*. 2024;279:907–912.
29. Puhan MA, Clavien P-A. Is Statistical Significance Alone Obsolete?: Let's Turn to Meaningful Interpretation of Scientific and Real-world Evidence on Surgical Care. *Ann Surg*. 2024;279:913–914.
30. Lof S, Claassen L, Hannink G, et al. Learning Curves of Minimally Invasive Distal Pancreatectomy in Experienced Pancreatic Centers. *JAMA Surg*. 2023;158:927–933.
31. Nassour I, Wang SC, Christie A, et al. Minimally Invasive Versus Open Pancreaticoduodenectomy: A Propensity-matched Study From a National Cohort of Patients. *Ann Surg*. 2018;268:151–157.
32. Ausania F, Landi F, Martinie JB, et al. Robotic versus laparoscopic distal pancreatectomy in obese patients. *Surg Endosc*. 2023;37:8384–8393.
33. Müller PC, Toti JMA, Guidetti C, et al. Benchmarking outcomes for distal pancreatectomy: critical evaluation of four multicenter studies. *Langenbecks Arch Surg*. 2023;408:253.
34. Ferrari D, Violante T, Novelli M, et al. The death of laparoscopy. *Surg Endosc*. 2024;38:2677–2688.
35. Shakir M, Boone BA, Polanco PM, et al. The learning curve for robotic distal pancreatectomy: an analysis of outcomes of the first 100 consecutive cases at a high-volume pancreatic centre. *HPB (Oxford)*. 2015;17:580–586.
36. Nickel F, Distler M, Limen EF, et al. Initial learning curves of laparoscopic and robotic distal pancreatectomy compared with open distal pancreatectomy: multicentre analysis. *British Journal of Surgery*. 2023;110:1063–1067.
37. McCulloch P, Altman DG, Campbell WB, et al. No surgical innovation without evaluation: the IDEAL recommendations. *Lancet*. 2009;374:1105–1112.

38. Marcus HJ, Ramirez PT, Khan DZ, et al. The IDEAL framework for surgical robotics: development, comparative evaluation and long-term monitoring. *Nat Med*. 2024;30:61–75.
39. van Hilst J, de Rooij T, Bosscha K, et al. Laparoscopic versus open pancreatoduodenectomy for pancreatic or periampullary tumours (LEOPARD-2): a multicentre, patient-blinded, randomised controlled phase 2/3 trial. *Lancet Gastroenterol Hepatol*. 2019;4:199–207.
40. Klotz R, Mihaljevic AL, Kulu Y, et al. Robotic versus open partial pancreatoduodenectomy (EUROPA): a randomised controlled stage 2b trial. *The Lancet Regional Health – Europe*.;39 . Epub ahead of print April 1, 2024. DOI: 10.1016/j.lanepe.2024.100864.
41. van den Broek BLJ, Zwart MJW, Bonsing BA, et al. Video Grading of Pancreatic Anastomoses During Robotic Pancreatoduodenectomy to Assess Both Learning Curve and the Risk of Pancreatic Fistula: A Post Hoc Analysis of the LAELAPS-3 Training Program. *Ann Surg*. 2023;278:e1048–e1054.
42. Hogg ME, Zenati M, Novak S, et al. Grading of Surgeon Technical Performance Predicts Postoperative Pancreatic Fistula for Pancreaticoduodenectomy Independent of Patient-related Variables. *Ann Surg*. 2016;264:482–491.
43. Zimmitti G, La Mendola R, Manzoni A, et al. Investigation of intraoperative factors associated with postoperative pancreatic fistula following laparoscopic left pancreatectomy with stapled closure: a video review-based analysis : Video-review for predictors of pancreatic leak. *Surg Endosc*. 2021;35:941–954.
44. Robinson NB, Fremes S, Hameed I, et al. Characteristics of Randomized Clinical Trials in Surgery From 2008 to 2020: A Systematic Review. *JAMA Network Open*. 2021;4:e2114494.
45. Domenghino A, Walbert C, Birrer DL, et al. Consensus recommendations on how to assess the quality of surgical interventions. *Nat Med*. 2023;29:811–822.
46. Dindo D, Demartines N, Clavien P-A. Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. *Ann Surg*. 2004;240:205–213.
47. Schuh F, Mihaljevic AL, Probst P, et al. A Simple Classification of Pancreatic Duct Size and Texture Predicts Postoperative Pancreatic Fistula: A classification of the International Study Group of Pancreatic Surgery. *Ann Surg*. 2023;277:e597–e608.
48. Al Abbas AI, Wang C, Hamad AB, et al. Mentorship and formal robotic proficiency skills curriculum improve subsequent generations' learning curve for the robotic distal pancreatectomy. *HPB (Oxford)*. 2021;23:1849–1855.
49. Korrel M, van Hilst J, Bosscha K, et al. Nationwide use and Outcome of Minimally Invasive Distal Pancreatectomy in IDEAL Stage IV following a Training Program and Randomized Trial. *Annals of Surgery*. 2024;279:323.
50. Hogg ME, Tam V, Zenati M, et al. Mastery-Based Virtual Reality Robotic Simulation Curriculum: The First Step Toward Operative Robotic Proficiency. *Journal of Surgical Education*. 2017;74:477–485.
51. Karadza E, Haney CM, Limen EF, et al. Development of biotissue training models for anastomotic suturing in pancreatic surgery. *HPB (Oxford)*. 2023;S1365-182X(23)00041–2.
52. Walber JK, Antony P, Strothmann H, et al. Effect of artificial or autologous coverage of the pancreatic remnant or anastomosis on postoperative pancreatic fistulas after partial pancreatectomy: meta-analysis of randomized clinical trials. *BJS Open*. 2024;8:zrae059.
53. He S, Xia J, Zhang W, et al. Prophylactic abdominal drainage for pancreatic surgery. *Cochrane Database Syst Rev*. 2021;2021:CD010583.

54. Ahmad SA, Edwards MJ, Sutton JM, et al. Factors Influencing Readmission After Pancreaticoduodenectomy: A Multi-Institutional Study of 1302 Patients. *Annals of Surgery*. 2012;256:529.
55. Fisher AV, Fernandes-Taylor S, Campbell-Flohr SA, et al. 30-day Readmission After Pancreatic Resection: A Systematic Review of the Literature and Meta-analysis. *Annals of Surgery*. 2017;266:242.

Figure 1: Participating centers and annual center-specific case volumes.



USA	Europe		Asia
Atlanta	Basel	Lübeck	Shanghai
Baltimore	Copenhagen	Modena	
Chicago	Geneva	Pisa	
Charlotte	Heidelberg	Utrecht	
Philadelphia	Orléans	Zurich	

Annual center case load	Median (IQR)
Overall pancreatic resections	137 (78-229)
Open distal pancreatectomies	17 (3-29)
Robotic distal pancreatectomies	20 (13-35)
Laparoscopic distal pancreatectomies	0 (0-14)

Figure 2: Learning curve analysis for operative time (A), major complications (B), and textbook outcome (C). The *red dashed line* marks the first turning point.

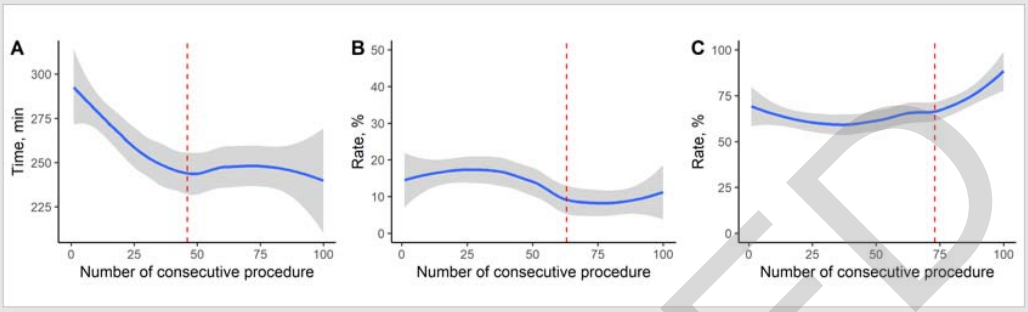


Figure 3. Evolution of overall complications (A), 90-day comprehensive complication index (B), and postoperative pancreatic fistula (C) along the learning curve.

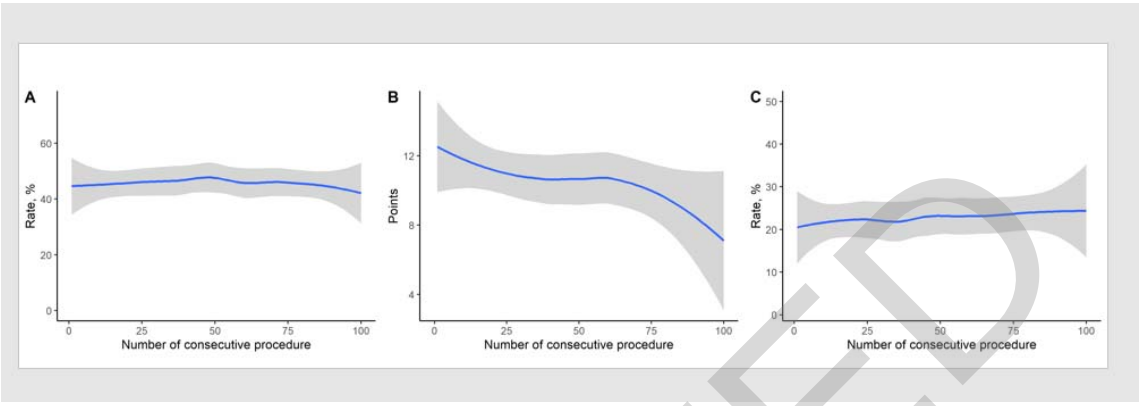


Figure 4. Effect of previous experience in laparoscopic distal pancreatectomy on operative time (A), major complications (B), and textbook outcome (C); influence of annual robotic distal pancreatectomy case volume on operative time (D); impact of overall case volume on major complications (E) and textbook outcome (F).

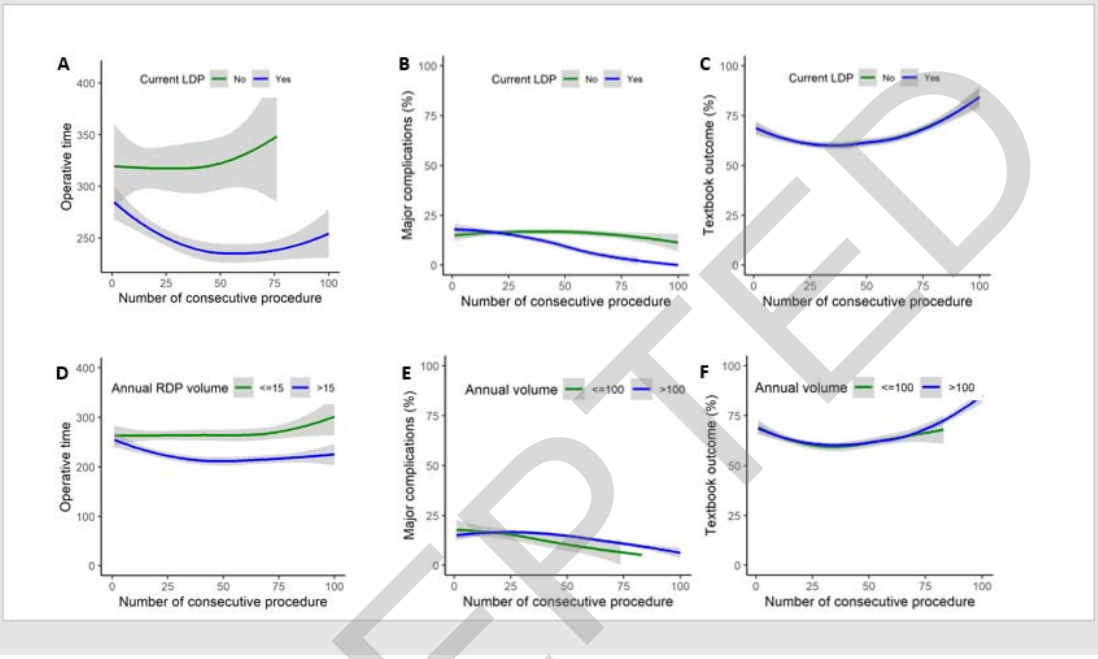


Table 1: Baseline characteristics of the entire cohort and all patients included in the learning curve analysis.

	Total cohort (n=2'403)	**Learning curve analysis** (n=1'109)
Age, years	59 (46-68)	63 (51-71)
Male	988 (41.2)	460 (41.7)
BMI, kg/m^2	24 (22-27)	25 (23-90)
Comorbidities		
Diabetes	450 (18.8)	252 (22.8)
COPD	64 (2.7)	52 (4.7)
CRF	37 (1.6)	35 (3.2)
Cardiac disease	236 (9.8)	151 (13.7)
Histological diagnosis		
PDAC	600 (25.2)	231 (21.0)
NET	512 (21.5)	296 (26.9)
IPMN	268 (11.3)	166 (15.1)
MCN	185 (7.8)	55 (5.0)
Other benign lesions	640 (28.8)	251 (24.5)
Chronic pancreatitis	70 (2.9)	42 (3.8)
Other malignant	52 (2.2)	37 (3.3)
Size of lesion, mm	30 (20-45)	28 (19-45)
Operative time, min	180 (120-245)	240 (185-310)
Blood loss, ml	100 (50-200)	100 (50-200)
Spleen-preservation	979 (43.0)	494 (50.2)
Conversion rate	63 (2.6)	57 (5.2)
Overall complication rate	923 (38.9)	520 (48.2)
Major complication rate	239 (10.0)	204 (18.5)
Highest CD complication		
3a	111 (11.9)	105 (19.9)
3b	82 (8.8)	73 (13.8)
4a	12 (1.3)	12 (2.3)
4b	6 (0.6)	6 (1.1)
5	28 (3.0)	8 (1.5)
POPF		
B	442 (18.4)	226 (20.4)
C	13 (0.5)	8 (0.7)
DGE		
B	29 (1.2)	18 (1.6)
C	7 (0.3)	7 (0.6)
PPH		
B	13 (0.5)	11 (1.0)
C	41 (1.7)	19 (1.7)
CCI at 90 days	0 (0-8.7)	0 (0-20.9)
Reoperation rate	68 (2.8)	39 (3.5)
LOS	14 (7-20)	7 (5-10)
Readmission rate	188 (7.9)	178 (16.2)

Textbook outcome	1763 (73.5)	713 (64.5)

Note: Data are given as n (%) and median (IQR).
BMI, body mass index; CCI, Comprehensive Complication Index; COPD, chronic obstructive pulmonary disease; CRF, chronic renal failure; DGE, delayed gastric emptying; ERCP, endoscopic retrograde cholangiopancreatography; LOS, length of stay; MPD, main pancreatic duct; POPF, postoperative pancreatic fistula; PPH, postpancreatectomy hemorrhage; PDAC, pancreatic ductal adenocarcinoma; NET, neuroendocrine tumor; IPMN, intraductal papillary mucinous neoplasia; MCN, mucinous cystic neoplasm; SCN, serous cystic neoplasm; SPN, solid pseudopapillary neoplasm

Table 2:

	Before Competency (n=674)	**After competency** (n=435)	***P***	**Before Proficiency** (n=855)	**After Proficiency** (n=254)	***P***	**Before Mastery** (n=952)	**After Mastery** (n=157)	***P***	***International Benchmarks***[7]
Benchmark patients	306 (47.8)	203 (46.8)	0.786	394 (48.0)	115 (45.3)	0.483	430 (46.9)	79 (50.3)	0.479	
Operative time, min	245 (190-320)	235 (180-293)	**0.002**	243 (190-311)	231 (180-298)	**0.040**	242 (187-312)	231 (178-290)	0.081	≤300
Blood loss, ml	100 (50-200)	100 (50-200)	**0.004**	100 (50-200)	100 (50-200)	**0.009**	100 (50-200)	100 (50-188)	**0.025**	≤150
Conversion rate	35 (5.2)	22 (5.1)	1.000	44 (5.2)	13 (5.1)	1.0000	51 (5.4)	6 (3.8)	0.532	≤3
Overall complications	317 (47.7)	210 (48.4)	0.985	409 (48.3)	118 (46.6)	0.611	446 (47.3)	81 (51.6)	0.410	≤58.3
Major complications	111 (19.3)	44 (17.2)	0.439	167 (19.6)	37 (14.6)	**0.012**	182 (19.2)	22 (14.0)	0.148	≤26.7
Highest CD complication			0.285			0.259			0.089	
1	108 (33.8)	81 (38.9)		139 (33.7)	50 (43.1)		149 (33.2)	40 50.6)		
2	83 (25.9)	52 (25.0)		106 (25.7)	29 (25.0)		118 (26.3)	17 21.5)		
3a	73 (22.8)	32 (15.4)		90 (21.8)	15 (12.9)		94 (20.9)	11 13.9)		
3b	39 (12.2)	34 (16.3)		56 (13.6)	17 (14.7)		65 (14.5)	8 10.1)		
4a	7 (2.2)	5 (2.4)		9 (2.2)	3 (2.6)		11 (2.4)	1 (1.3)		
4b	5 (1.6)	1 (0.5)		6 (1.5)	0 (0.0)		6 (1.3)	0 (0.0)		
5	5 (1.6)	3 (1.4)		6 (1.5)	2 (1.7)		6 (1.3)	2 (2.5)		
CR POPF	141 (20.9)	93 (21.4)	0.914	184 (21.5)	50 (19.7)	0.588	205 (21.5)	29 (18.5)	0.444	≤31.8
ERCP	33 (5.0)	17 (3.9)	0.508	42 (5.0)	8 (3.1)	0.291	46 (4.9)	4 (2.5)	0.272	
Percutaneous drain	56 (8.4)	36 (8.3)	1.000	74 (8.8)	18 (7.1)	0.469	82 (8.7)	10 (6.4)	0.407	
DGE			**0.023**			**0.039**			0.647	≤5
A	26 (3.9)	7 (1.6)		28 (3.3)	5 (2.0)		30 (3.2)	3 (1.9)		

B	8 (1.2)	10 (2.3)		11 (1.3)	7 (2.8)		14 (1.5)	4 (2.5)	
C	2 (0.3)	5 (1.1)		3 (0.4)	4 (1.6)		6 (0.6)	1 (0.6)	
						0.003			**<.001**	≤6.6
PPH			0.148						
A	2 (0.3)	4 (0.9)		2 (0.2)	4 (1.6)		2 (0.2)	4 (2.5)	
B	9 (1.3)	2 (0.5)		11 (1.3)	0 (0.0)		11 (1.2)	0 (0.0)	
C	9 (1.3)	10 (2.3)		11 (1.3)	8 (3.1)		13 (1.4)	6 (3.8)	
						0.732			0.272	≤8.7
CCI at discharge	0 (0-8.7)	0 (0-8.7)	0.303	0 (0-12.2)	0 (0-8.7)		0 (0-10.5)	0 (0-8.7)	
						0.124			0.359	≤8.7
CCI at 90 days	0 (0-20.9)	0 (0-20.9)	0.333	0 (0-20.9)	0 (0-8.7)		0 (0-20.9)	0 (0-8.7)	
						1.000			0.362	
Reoperation rate	22 (3.3)	17 (3.9)	0.705	30 (3.5)	9 (3.5)		31 (3.3)	8 (5.1)	
						0.015			**0.002**	≤7
LOS	7 (5-10)	7 (5-12)	0.209	7 (5-10)	7 [5-14]		7 (5-10)	7 (5-14)	
						0.028			**0.043**	≤24
Readmission rate	116 (17.4)	62 (14.3)	0.201	149 (17.6)	29 (11.5)		162 (17.2)	16 (10.3)	
						0.095			**0.028**	
Textbook outcome	421 (62.7)	292 (67.1)	0.154	534 (62.7)	179 (70.5)		602 (63.4)	111 (70.7)	
			0.029			**0.012**			0.049	
PDAC	126 (18.9)	105 (24.3)		162 (19.1)	69 (27.5)		189 (20.0)	42 (27.3)	
						0.907			0.705	≥9
Lymph node harvest	17 (13-27)	17 (10-26)	0.734	17 (13-26)	18 (9-29)		17 (12-26)	18 (11-31)	

Note: Data are given as n (%) and median (IQR).

BMI, body mass index; CCI, Comprehensive Complication Index; COPD, chronic obstructive pulmonary disease; CR, clinically relevant; CRF, chronic renal failure; DGE, delayed gastric emptying; ERCP, endoscopic retrograde cholangiopancreatography; MPD, main pancreatic duct; POPF, postoperative pancreatic fistula; PPH, postpancreatectomy hemorrhage;