Surgery 166 (2019) 8–14

Contents lists available at ScienceDirect

Surgery

journal homepage: www.elsevier.com/locate/surg

Pancreas

Robotic pancreatoduodenectomy with vascular resection: Outcomes and learning curve

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ARTICLE INFO

Article history:
Accepted 10 January 2019
Available online 21 March 2019

ABSTRACT

Introduction: The safety, efficacy, and learning curve for robotic pancreatoduodenectomy has been reported; however, the outcomes and learning curve of robotic pancreatoduodenectomy with vascular resections remain unknown. Our aim was to evaluate the outcomes of robotic pancreatoduodenectomy with vascular resections compared with robotic pancreatoduodenectomy without vascular resection and to identify the learning curve and benchmarks for improved performance during robotic pancreatoduodenectomy with vascular resections.

Methods: A retrospective review of consecutive patients who underwent robotic pancreatoduodenectomy with vascular resections and robotic pancreatoduodenectomy between 2011 and 2017. Patients were analyzed consecutively, and a cumulative sum analysis was performed to detect improvements in performance over time.

Results: Of 380 consecutive robotic pancreatoduodenectomy patients, 50 (13%) underwent robotic pancreatoduodenectomy with vascular resections. Compared with robotic pancreatoduodenectomy, robotic pancreatoduodenectomy with vascular resections were more likely to have had pancreatic adenocarcinoma (84% vs 42%) and had received neoadjuvant therapy (35% vs 65%, $P < .01$). Robotic pancreatoduodenectomy with vascular resections operative time revealed a steady, significant decrease (Rho = −0.38, p = .006) with marked initial improvement after the first 8 cases and maturation of the learning curve after 35 cases. A significant decrease in duration of the hospital stay was observed throughout the experience (Rho = −0.528, $P < .0001$), whereas margin status, pancreatic fistula, major morbidity, and mortality remained constant and comparable to robotic pancreatoduodenectomy alone.

Conclusion: Robotic pancreatoduodenectomy with vascular resections is safe and feasible. For surgeons who have surpassed the learning curve of robotic pancreatoduodenectomy, it appears that improvements in performance of robotic pancreatoduodenectomy with vascular resections can be observed after 35 cases.

Introduction

Vascular involvement at the time of pancreatoduodenectomy (PD) poses a substantial technical challenge to the surgeon. Data indicate that open PD with vein resection for borderline resectable pancreatic cancer (PDA) is associated with comparable oncologic outcomes to resectable tumors, particularly when neoadjuvant therapy is used to maximize the probability of a margin negative resection.[1–6] Data on the safety of PD with vascular resection, however, are more discordant. Studies emanating from high-volume centers report comparable morbidity and mortality between pancreatoduodenectomy with vascular resections (PD-VR) and PD alone[3,4,7,8]; however, when applied nationally, PD-VR appears to be associated with greater morbidity, with some studies reporting a mortality rate of up to 12% when outcomes are followed to 90 days.[9–11]

Surgeons began pioneering minimally invasive approaches to PD more than 2 decades ago with the hope of improving postoperative outcomes.[12] Early studies established the safety and efficacy of laparoscopic PD (LPD).[13–15] With advances in technology,

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https://doi.org/10.1016/j.surg.2019.01.037
0039-6060/

robotic pancreatoduodenectomy (RPD) has emerged as a safe and feasible alternative to open PD and LPD when performed at high-volume centers.[16–20] Similarly, the learning curve for RPD has been identified and, although long, is comparable with its open counterpart.[21–24] Given the advanced ergonomics, improved visualization, and potential to improve patient outcomes, adopters of robotic pancreatectomy are expanding their selection criteria to include pancreatic adenocarcinoma and borderline resectable tumors.[22,25,26] Although LPD with vascular resections (LPD-VR) has been reported, the safety, feasibility, and learning curve of a robotic approach to PD-VR (RPD-VR) remains unknown.[26–28] Our aim, therefore, was to report our institutional outcomes of RPD-VR compared with RPD alone and to identify the learning curve and benchmarks for improved performance during RPD-VR. We hypothesized that RPD-VR would be associated with comparable morbidity and mortality compared with RPD alone and that improvements in performance metrics would be observed over time as the experience matured.

Methods

Study design, case selection, and population

This report is a retrospective review of a prospectively maintained database of consecutive patients who underwent RPD and RPD-VR (venous) at the University of Pittsburgh Medical Center (Pittsburgh, PA) between October 2011 and May 2017. RPD-VR was performed by 3 surgeons (H.Z., M.H., and A.Z.) and was attempted after the learning curve for RPD was surmounted (80 patients between September 2008 and August 2011). This study was approved by the Institutional Review Board at the University of Pittsburgh Medical Center (PRO14120203).

The approach to managing borderline resectable tumors is similar among the 3 surgeons performing RPD. Patients with any vascular abutment are evaluated in our multidisciplinary clinic and considered for neoadjuvant therapy. The type of regimen is dependent on patient factors and inclusion and exclusion criteria of available neoadjuvant trials. The use of radiation in the setting of neoadjuvant therapy does not preclude RPD or RPD-VR. Patients who receive neoadjuvant therapy are re-evaluated typically every 2 months and, in the presence of stable or partial radiographic response, good performance status, and a decrease in CA19-9, are eligible for RPD-VR.[29]

Case selection for RPD-VR is dependent largely on anatomic considerations identified on preoperative, high-resolution, pancreas-protocol computed topography (CT) and has evolved as our experience has matured. Initially, vascular resections (VR) were limited to short-segment abutments (<90-degree abutment over a 1–2 cm segment) of the superior mesenteric vein and portal vein that were predictably amenable to side-bite VR (via a stapler or clamping and oversewing). As the experience matured, surgeons used the robotic approach on patients with more extensive involvement in imaging, including those requiring a bovine pericardial patch (when 90- to 180-degree venous involvement was encountered), and—more recently—lesions that necessitated a short segmental venous resection with end-to-end venous anastomosis (<2-cm segment with ≥180-degree abutment or encasement). Patients with longer-segment involvement (>2 cm) are reserved for an open approach because maximizing the length of venous segmental resections can be challenging using the robotic platform in which patients are typically placed in steep reverse Trendelenberg position making mobilization of the SMV difficult, particularly in patients with a heavy or fatty mesentery. Although the liver can be mobilized robotically to facilitate primary repair when a small amount of added length is needed, longer venous segments are more challenging to perform. Using these careful selection criteria, cases that necessitated larger segmental resections, venous interposition grafts, or arterial reconstructions, were not performed using the robotic approach.

Operative technique

The approach to RPD for resectable tumors has been described elsewhere.[30] For RPD-VR, after generous right colon mobilization, a superior mesenteric artery (SMA) first approach is employed. In general, the dissection begins at the inferior border of the uncinate on the left side of the superior mesenteric vein (SMV) and portal vein, proceeding cephalad until the origin of the SMA is reached. In the process, the splenic vein is dissected at its confluence with the SMV, vessel looped, and retracted anteriorly using the third robotic arm; however, on occasion, the vein is transected to provide further length, especially if an end-to-end anastomosis is anticipated. Often, the middle colic vein or inferior mesenteric vein is ligated to facilitate exposure. On the right side of the vessels, the uncinate is dissected off the SMA along the uninvolved areas of the SMV and portal vein. The superior pancreatoduodenal vein (of Belcher) is ligated, as are small venous tributaries emanating from the first jejunal vein inferiorly. The first jejunal vein itself is preserved when possible. The decision to perform a vascular resection is guided by preoperative imaging but ultimately is dependent on intraoperative findings. If the tumor cannot be dissected off the vessel safely, then we proceed with a vascular resection—the extent of which is determined by the length and degree of vascular involvement. After complete mobilization of the tumor and uncincate process, ultimately leaving the specimen only attached to the involved venous segment, vascular isolation with proximal and distal control is achieved by applying laparoscopic bulldog clamps on the SMV below, portal vein above, and splenic vein to the left of the involved segment. The venous attachment is then resected in one of three methods: (1) side-bite or tangential resection using a linear stapler (Fig 1, *A*), (2) venorrhaphy using 5-0 polypropylene suture or placement of a bovine pericardial patch (Fig 1, *B*), or (3) segmental resection and primary veno-venous anastomosis (Fig 1, *C*). Patients are heparinized if prolonged vascular cross-clamping is anticipated, particularly for venorraphy, placement of a bovine pericardial patch, or segmental resection and primary veno-venous anastomosis, but not for stapled, side-bite resections. In addition, for bovine pericardial patches or segmental resections, full-dose aspirin is started on the night of the operation in the form of a suppository. When tolerating oral intake, those patients are transitioned to oral aspirin, which is continued at discharge.

Surgical outcomes and definitions

Patient demographics and clinicopathologic variables were collected. Operative time was defined as duration of time from skin incision to closure, including the time required to dock the robot. All pancreaticojejunal anastomoses were constructed with a duct-to-mucosa technique. Postoperative pancreatic fistula (POPF) and delayed gastric emptying (DGE) were classified in accordance with the definitions of the International Study Group for Pancreatic Fistula.[31,32] Complications were graded according to the Clavien-Dindo classification system.[33] Cancer staging and resection margins were classified according to American Joint Committee on Cancer 8th edition.[34] A negative margin was defined as 0 mm (no tumor on ink). All outcomes were followed to 90 days.

Statistical analysis

Continuous data were summarized as mean and standard deviation or median and interquartile range where appropriate.

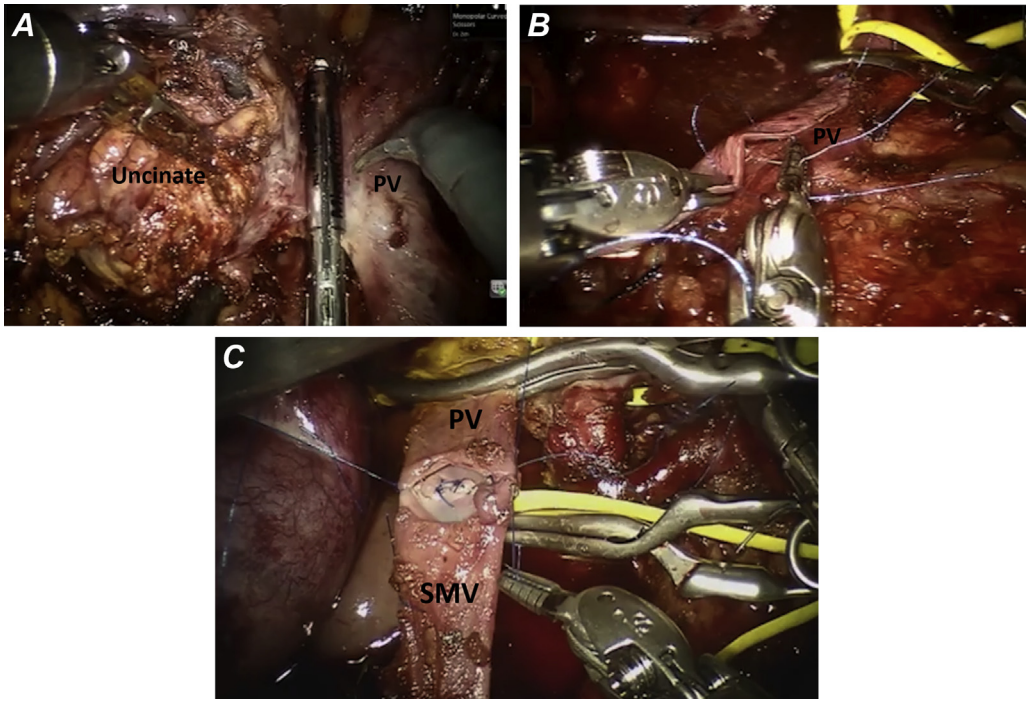

Fig 1. After vascular isolation with proximal and distal control, the venous attachment is resected and repaired in one of three of the following methods: (*A*) a side bite or tangential resection using a 5-mm linear vascular stapler, (*B*) a tangential resection and placement of a bovine pericardial patch, or (*C*) segmental resection and primary repair.

Discrete data were summarized as frequency and percentage. In analyzing continuous variables, differences between groups were tested using an independent, two-sample *t* test for normally distributed data or by the nonparametric Wilcoxon rank-sum test when not normally distributed. The χ^2 test or the Fisher exact test were used in the analysis of categorical variables. Correlation and linear regression were used to analyze relationships and test trends in continuous data. Measures of operative performance were analyzed consecutively to detect improvements across time in patients who underwent RPD-VR. The learning curve for RPD-VR was evaluated using cumulative sum (CUSUM). All tests were two-tailed. Statistical analyses were conducted using the Intercooled Stata 13.0 statistical software package (StataCorp, College Station, TX).

Results

Demographics and outcomes of the entire cohort

Of 380 total patients, 330 underwent RPD and 50 (13%) underwent RPD-VR. Demographics and outcomes of the entire cohort are presented in Table I. Mean age was 66.3 years, and 45.5% were female. Most patients (92.1%, $n = 349$) had a classic PD. The conversion rate was 4.0%, mean operative time was 383 minutes, and estimated blood loss was 200 mL (range 150–400). The 30-day and 90-day mortality for the entire cohort was 1.6% ($n = 13$) and 3.5% ($n = 13$), and the 90-day major (Clavien > 2) morbidity was 23.4%. Pancreas-specific complications of a clinically relevant, postoperative pancreatic fistula (CR-POPF) and DGE occurred in 7.4% and 22.4% respectively, and median length of stay was 7 days (range 6–11). Regarding the method of vascular resection and reconstruction, 27 patients (54.%) had a side-bite resection, using an endovascular stapler, 16 (32%) had a tangential resection and venorraphy with suture repair, 6 (12%) had a tangential resection that required bovine pericardial patch placement, and 1 (2%) had a segmental resection with end-to-end anastomosis.

Table I
Patient characteristics

Variable	All patients n = 380	RPD n = 330	RPD-VR n = 50	P
Age, years	66.3 ± 11.1	65.0 ± 11.3	68.5 ± 9.3	.139
Sex, female, *n* (%)	173 (45.5)	152 (46.1)	21 (42.0)	.649
BMI, kg/m^2	27.8 ± 5.7	28.0 ±5.9	26.5 ± 4.4	.098
CCI	4.72 ± 2.0	4.67 ± 2.0	5.0 ± 2.0	.213
Prior abdominal surgery, *n* (%)	202 (53.6)	177 (54.1)	25 (50)	.586
Preoperative albumin, g/dL	3.66 ± 0.58	3.66 ± 0.58	3.7 ± 0.6	.502
Pancreatic duct size, mm	4.89 ± 4.8	4.79 ± 4.36	5.7 ± 7.1	.276
Gland texture	226 (64.2)	213 (69.4)	13 (29)	< .001
Pathology, *n* (%)				
PDAC	180 (47.4%)	138 (41.8%)	42 (8%)	< .001
Ampullary adenoca	51 (13.4%)	50 (15.2%)	1	
Distal cholangioca	31 (8.2%)	28 (8.5%)	3 (6%)	
Duodenal adenoca	19 (5.0%)	19 (5.8%)	0	
Other malignancy	10 (2.6%)	6 (1.8%)	4 (8%)	
CA 19-9* U/mL	59 (20-279)	49 (17-219)	110 (46-626)	.011
Neoadjuvant therapy, *n* (%)	128 (39.8)	96 (35.2)	32 (65)	< .001
Chemotherapy	127 (39.4)	95 (34.8)	32 (65)	< .001
EBRT	9 (2.8)	5 (1.8)	4 (8)	.013

CCI, Charlson comorbidity index; *PDAC*, pancreatic ductal adenocarcinoma; *EBRT*, external beam radiation therapy.
* CA19-9 within 1 month of surgery.

Baseline demographics for RPD and RPD-VR are also presented in Table I. RPD-VR patients had a greater mean preoperative CA19-9 ($P < .01$), more PDA (84.0% vs 42%, $P < .001$), a greater proportion of patients treated with neoadjuvant therapy (chemotherapy or radiation therapy, 65.3% vs 35, $P < .001$), and more patients with firm gland texture (69.4% vs 29%, $P < .001$). All patients who underwent a vascular resection carried a diagnosis of cancer. A total of 42 patients (84%) had PDA, 1 had an ampullary cancer, 3 had a distal cholangiocarcinoma, and 4 had rare variants of PDA, including 3 with pancreatic adenosquamous carcinoma and 1 with a pancreatic signet-ring–cell carcinoma.

Table II
Postoperative outcomes

Outcomes, n (%)	All patients n = 380	RPD n = 330	RPD-VR n = 50	P
CR-POPF	28 (7.4)	26 (7.9)	2 (4)	.559
DGE	85 (22.4)	74 (22.5)	11 (22)	.938
Pseudoaneurysm	13 (3.4)	12 (3.6)	1	1.000
Wound infection	52 (13.7)	42 (12.7)	10 (20)	.163
Reoperation	14 (3.7)	13 (3.9)	1	.704
Major morbidity*	89 (23.4)	75 (22.7)	14 (28)	.412
Duration of stay, days (median; IQR)	7 (6–11)	7 (6–11)	7 (6–9)	.414
90-day readmission	138 (37.1)	117 (36.2)	21 (43)	.370
Adjuvant therapy	192 (68.3)	162 (68.4)	30 (68)	.982
30-day mortality	6 (1.6)	4 (1.2)	2 (4)	.180
90-day mortality	13 (3.5)	9 (2.8)	4 (8)	.080

* Major morbidity: Clavien-Dindo greater than grade 2.

Table III
Subgroup analyses of patients with pancreatic ductal adenocarcinoma

Variable	All PDAC n = 180	PDAC RPD n = 138	PDAC RPD-VR n = 42	P
Neoadjuvant therapy* (%)	111 (61.7)	83 (60.1)	28 (66.7)	.371
Preoperative CA19-9 U/mL (range)	118 (30-562)	125 (27-562)	89 (46-615)	.751
Tumor size (cm)†	2.6 ± 1.1	2.6 ± 1.1	2.8 ± 1.1	.234
Lymph node yield†	32.0 ± 12.1	32.0 ± 11.9	31.7 ± 13.1	.861
Positive lymph nodes, *n* (%)	125 (69.4)	97 (70.3)	28 (66.7)	.655
Lymphovascular invasion, *n* (%)	129 (71.7)	98 (71.0)	31 (73.8)	.580
Perineural invasion, *n* (%)	149 (82.8)	112 (81.2)	37 (88.1)	.336
R0 sesection, *n* (%)	150 (83.3)	116 (84.1)	34 (81.0)	.860
AJCC stage *n* (%)				
I	9 (5.0)	7 (5.1)	2	.952
II	1 (0.6)	1 (0.7)	0	
III	40 (22.2)	29 (21.0)	11 (26)	
IV	124 (68.9)	96 (69.6)	28 (67)	

PDAC, pancreatic ductal adenocarcinoma; *AJCC*, American Joint Commission on Cancer Staging 8th ed.
* Includes chemotherapy and/or external beam radiation therapy.
† Mean ± SD.

Perioperative outcomes of RPD and RPD-VR

Perioperative outcomes are presented in Table II. RPD-VR was associated with a greater conversion rate (10% vs 3%, $P = .035$) and mean operative time (419 vs 377 minutes, $P = .004$) compared with RPD. Conversions for RPD-VR included intraoperative bleeding ($n = 1$) and failure to progress ($n = 4$). Mean estimated blood loss was also greater for RPD-VR (275 vs 200 minutes, $P = .006$) but did not result in a statistically significant increase in blood transfusion in the overall RPD-VR group (22.0% vs 14.2%, $P = .155$).

Regarding postoperative outcomes, no differences in CR-POPF, DGE, and postpancreatectomy hemorrhage were noted between RPD-VR and RPD. Major (Clavien > 2) morbidity was 28% vs 22.7% ($P = .412$). We observed no statistically significant difference in 30-day mortality after RPD-VR (2 of 50; 4.0%) compared with PD (4 of 330; 1.2%, $P = .180$). Sources of 30-day mortality in RPD-VR were respiratory failure secondary to postoperative aspiration in 1 patient and a massive pulmonary embolus complicated by cardiac arrest in the other. There was a trend toward greater 90-day mortality in the RPD-VR cohort (4 of 50, 8.0%, vs 9 of 330, 2.8%, $P = .08$). One death between postoperative days 30 and 90 was attributed to decompensated congestive heart failure, and the other to withdrawal of care in a patient who was readmitted with respiratory failure, malignant ascites, and widespread intra-abdominal recurrence.

Operative and postoperative outcomes of patients who underwent tangential resection using a vascular stapler ($n = 43$) were compared with the lesser number of patients ($n = 7$) undergoing a more complex venous reconstruction, including primary anastomosis or bovine pericardial patch. Operative time was 412 ± 82 minutes in patients who underwent a stapled tangential resection compared with 463 ± 109 minutes in those who required a more complex repair ($P = .274$). Mean (range) estimated blood loss for patients who underwent a stapled tangential resection was 250 mL (200–500 mL) and was 400 mL (200-1,500 mL) in those who underwent a more complex repair ($P = .169$). In addition, the conversion rate was 4 of 43 and 1 of 7, and the need for blood transfusion was 8 of 43 and 3 of 7, respectively. We observed one 30-day mortality in each cohort. Major morbidity occurred in 13 of 43 patients who underwent a stapled resection and 1 of 7 after a complex reconstruction. We observed no differences in the number of patients admitted to the intensive care unit, duration of stay, readmission, or failure to receive adjuvant therapy.

Postoperative CTs in patients who underwent RPD-VR were reviewed to determine patency rates after vascular resection. A total of 45 of the 50 patients (90%) had a postoperative CT, with a median follow-up of 14.8 months with a patency rate of 91%. The 4 patients with a thrombosed portomesenteric vein had a side-bite or tangential resection, with 1 of those patients developing an early local recurrence that likely led to the thrombosed vein. We observed no 30-day mortalities in these 4 patients who developed a portomesenteric venous thrombosis after RPD-VR.

Oncologic outcomes of RPD and RPD-VR

In the subset of patients with pancreatic ductal adenocarcinoma (PDA = 180), tumor size (2.8 cm vs 2.6 cm), ratio of positive lymph nodes (0.07 vs 0.06), and patients with perineural (88% vs 81.2 %) and lymphovascular invasion (74% vs 71.0%) were similar in the RPD-VR cohort ($n = 42$) compared with RPD alone ($n = 138$), as were the mean number of lymph nodes resected (32 vs 32.0) and R0 resection rates (81 vs 80.6; Table III).

Learning curve of RPD-VR

Operative time, estimated blood loss, and duration of stay were analyzed consecutively to detect improvements in performance over time in patients who underwent RPD-VR. As presented in Fig 2 (*A*), there was a steady decrease in operative time during the course of the experience ($R = -0.38$, $P = .006$). Estimated blood loss, margin status, pancreatic fistula, maximum Clavien grade complication, and mortality did not change significantly during the course of the experience. In contrast, postoperative duration of stay did decrease progressively as our experience matured ($R = -0.528$, $P \leq .001$, Fig 2, *B*).

Cumulative sum analysis was performed to determine inflexion points for decreases in operative time for the RPD-VR (Fig 3). The learning curve for RPD-VR appeared to be about 35 cases. Operative times were consistently greater than the cohort mean during the first 8 cases (sharp incline = positive slope), representing steep maturation of the learning curve, followed by a plateau phase between cases 8 to 35, and finally a downward (negative) slope representing improved operative times after surmounting the learning curve of 35 cases. The mean operative time for the first 35 cases was greater compared with the 15 postlearning curve cases (444 minutes vs 362 minutes). An increase in blood loss appeared during the first 35 cases (350 mL vs 200 mL). A comparison of postoperative outcomes of the first 35 patients and the 15 postlearning curve patients did not reveal any obvious differences in morbidity or mortality.

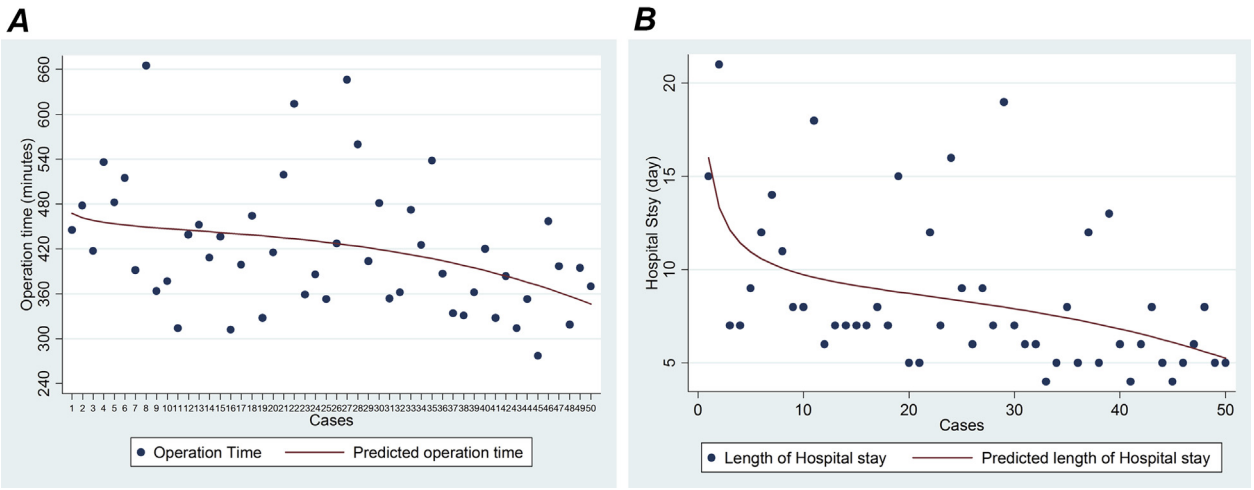

Fig 2. (*A*) Operative time for PD-VR improved as the experience matured (Rho = −0.38; $P = .006$). (*B*) Postoperative duration of hospital stay for patients undergoing PD-VR decreased as the experience matured (Rho = −0.528; $P < .001$).

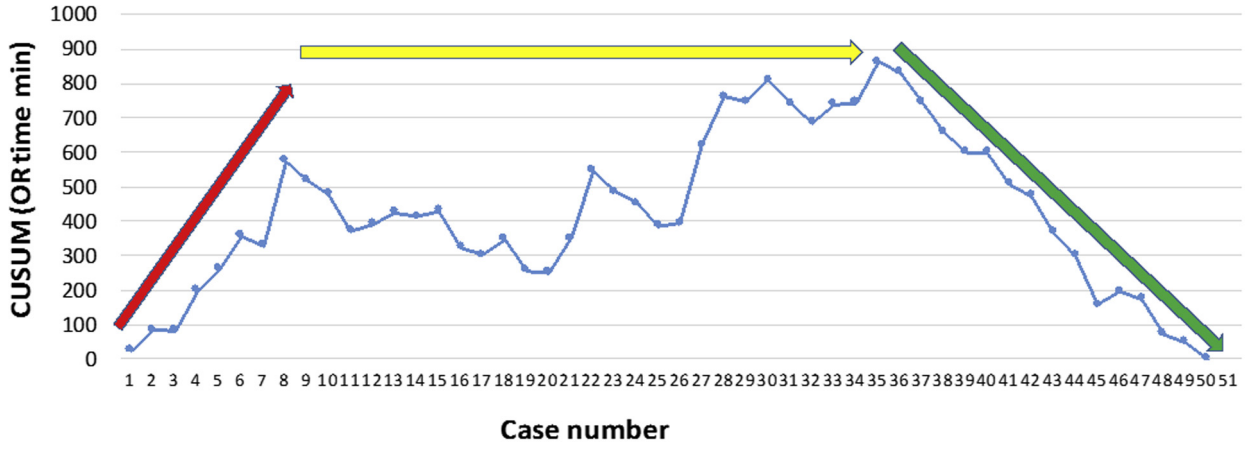

Fig 3. CUSUM analysis of operative time for PD-VR revealed an initial improvement after the first 8 cases and with maturation of the learning curve and a decrease in operative time after 35 cases.

Discussion

Herein, we report the outcomes and learning curve of RPD-VR. To date, this represents the largest series of minimally invasive PDs with vascular resection. Our results indicate that careful expansion of selection criteria for RPD to include major vascular resection can be implemented safely by pancreatic surgeons who have already surmounted their learning curves for both open PD and RPD. Furthermore, CUSUM analysis of operative time suggests that the learning curve for RPD-VR in such experienced pancreatic surgeons is approximately 35 cases.

A minimally invasive approach to PD was developed to curtail surgical morbidity.[12] Early studies established the safety and efficacy of LPD, and a select group of surgeons have also established the feasibility of LPD with vascular resection.[13–15,35] More recently, various groups have reported on the safety, feasibility, and learning curve of RPD.[20,26] Expanding selection criteria to include patients with venous involvement represents the next frontier in applying this platform to complex abdominal surgery, provided it is introduced in a thoughtful and structured manner. Our group embarked on RPD-VR only after surmounting the initial RPD learning curve of 80 cases. We involved 2 attending surgeons for the critical portions (head, uncinate, and vascular resection) of these operations and performed a disproportionate number of tangential and side-bite resections, emphasizing careful selection criteria and the need for a team approach in the safe development of complex, robotic, surgical programs.

Data on open PD at high-volume centers suggests that borderline resectable pancreatic cancer patients undergoing PD with vascular resection can achieve survival outcomes comparable with their resectable counterparts, particularly when negative margins are achieved[1,2]; however, the risks and benefits of such an aggressive approach must be weighed carefully against the potential for increased morbidity. Reported outcomes of PD-VR at high-volume centers are acceptable; however, when applied nationally, PD-VR appears to be associated with greater morbidity and mortality compared with PDs without vascular resection.[10,11,36]

Reports on vascular resections during minimally invasive PD are scant. A minimally invasive approach to PD-VR was first described using laparoscopy, when Kendrick and Sclabas[35] at the Mayo Clinic reported on total laparoscopic PD with vascular resection. Of 11 patients, 10 underwent a tangential resection and 1required a segmental resection. Similar to our study, median operative time was 413 minutes, blood loss was 500 mL, and the conversion rate to open occurred in 1 of the 11 patients. Of note, the conversion rate in the present study for RPD-VR was also about 10%, but greater than the 3% conversion rate of RPD alone ($P = .035$). As shown by a recent American College of Surgeons National Surgical Quality

Improvement Program analysis, conversion to an open approach during PD has important implications regarding postoperative complications and needs to be scrutinized in patients undergoing minimally invasive PD.[25,37] Since their initial report, the Mayo Clinic group has reported an updated series of 31 patients who underwent laparoscopic PD with vascular resection compared with 58 patients who underwent open PD with vascular resection.[27] The mortality in this series was 3% and overall morbidity was 35%, with no apparent differences in outcomes. The authors concluded that laparoscopic PD with vascular resection achieved similar morbidity, mortality, and oncologic outcomes compared with open PD.

Reports of RPD-VR have also been sparse.[26,28] Kauffmann et al[28] analyzed the outcomes of 14 RPD-VRs and compared them with 114 patients who underwent RPD alone ($n = 114$). Morbidity was comparable (29% vs 17.0%, $P = .29$) with a 91.6% venous patency rate. Similar to our study, RPD-VR was associated with increased operative time (522 vs 640 minutes, $P = .0006$) and a greater median estimated blood loss (420 mL vs 1,110 mL, $P < .0001$). They reported increased blood transfusion requirements and more postpancreatectomy hemorrhage, which were not observed in the present study. The Mayo clinic study by Croome et al[27] compared the treatment arm with open PD with vascular resections. Our present study was designed as a safety and feasibility study, and therefore no conclusions regarding the efficacy of RPD-VR compared with open PD-VR can be made. We found no differences in major (Clavien > 2) complications, CR-POPF, DGE, and postpancreatectomy hemorrhage between RPD-VR and RPD. Our results suggest comparable postoperative outcomes of patients who underwent RPD-VR compared with those who underwent RPD alone.

Studies of open PD-VR have reported an increased morbidity and mortality when compared with historic controls of PD alone,[9,10,38,39] the degree of which may be related to the type and extent of vascular resection.[36] In the study by Kauffmann et al,[28] the 90-day mortality for PD-VR was 14%, and the study by Kendrick and Sclabas[35] reported a 30-day mortality of 3.4%. In our study, we noted a 30-day mortality of 4% and a 90-day mortality of 8%. Although not statistically significant, our 90-day mortality likely reflects multiple factors, including a small sample size, added complexity of a major vascular resection in general, impact of the learning curve, and the importance of following PD outcomes to 90 days. In our case, the second 90-day mortality was attributable to disease recurrence and not related to the operative procedure. Of note, our 90-day mortality rate is consistent with that reported for open PD-VR.[9,10,38,39] Regardless, outcomes of minimally invasive pancreatic resections should be reported and closely monitored.

Our second aim was to describe our learning curve and benchmarks for improved performance during implementation of RPD-VR in our center. In an initial study on the learning curve of RPD alone, we demonstrated improvements in estimated blood loss and conversion rate after 20 cases, decrease in the incidence of pancreatic fistula, improvements in lymph node yield after 40 cases, and improvements in operative time after 80 cases.[18] In the present study, a CUSUM analysis of operative time in patients who underwent RPD-VR identified a consistent improvement during the first 35 cases. Although improvements were observed after 35 cases, it is crucially important to distinguish that these cases were performed after the initial learning curve of 80 cases of RPD alone by our experienced robotic surgeons and that the learning curve reported in this study is a culmination of the experience of 3 surgeons. As such, the learning curve for an individual surgeon may be greater, especially if the surgeon is not experienced in robotic or laparoscopic PD.

Similar to the improvements observed with operative time, there was a steady decrease in the postoperative length of stay. This decrease is likely multifactorial and attributable to a combination of improved technical performance, surgeon comfort, and the implementation of an enhanced recovery pathway that occurred during this period. Additional metrics of performance were analyzed consecutively, including estimated blood loss, conversion rate, lymph node yield, pancreas-specific morbidity, serious morbidity, and mortality, but events occurred infrequently, and the incidence remained mostly constant throughout the experience. It may perhaps be likely that the learning curve for these outcomes is greater for RPD-VR than that for RPD alone, and improvements will be observed with a larger sample size; however, a more likely explanation is that these outcomes were optimized during the initial learning curve of 80 patients who were excluded from this analysis.

The learning curve for minimally invasive PD should be taken within the context of published data on the learning curve for open PD. In a report from Indiana University, Schmidt et al[23] found increased morbidity, pancreatic fistula, estimated blood loss, and operative time in surgeons with fewer than 50 cases compared with those with greater than 50 cases. Similarly, Tseng et al[21] found improvements in estimated blood loss, operative time, duration of stay, and improved margin status after 60 cases. Considering the data for open PD, the number of cases needed to see improvements during RPD (80 cases) and RPD-VR (+35 cases) has important implications for new adopters within their proficiency curve.[22]

This study has several limitations, most important of which is its retrospective nature. Also, differences in sample size between the two cohorts precluded any formal statistical estimate of any differences in outcomes. In addition, and because of careful patient selection during this early experience, there was a disproportionate number of patients who underwent a tangential resection because we approach more extensive abutment or encasement in an open fashion. Our results suggest that this strategy minimizes morbidity and provides a sound oncologic outcome with comparable rates of R0 resection to historic controls of open PD-VR.[1–3]

In summary, RPD-VR is a safe and feasible procedure in select patients when performed by surgeons experienced in RPD. For surgeons who have surpassed their initial learning curve of 80 RPDs, improvements in operative time for RPD-VR may be able to be achieved in as few as 35 cases.

Conflicts of interest

The authors have indicated that they have no conflicts of interest regarding the content of this article.

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