State of the art of robotic pancreatoduodenectomy

Niccolò Napoli1 · Emanuele F. Kauffmann1 · Fabio Vistoli1 · Gabriella Amorese2 · Ugo Boggi1

Received: 13 April 2021 / Accepted: 19 April 2021 / Published online: 20 May 2021
© The Author(s) 2021

Abstract

Current evidence shows that robotic pancreatoduodenectomy (RPD) is feasible with a safety profile equivalent to either open pancreatoduodenectomy (OPD) or laparoscopic pancreatoduodenectomy (LPD). However, major intraoperative bleeding can occur and emergency conversion to OPD may be required. RPD reduces the risk of emergency conversion when compared to LPD. The learning curve of RPD ranges from 20 to 40 procedures, but proficiency is reached only after 250 operations. Once proficiency is achieved, the results of RPD may be superior to those of OPD. As for now, RPD is at least equivalent to OPD and LPD with respect to incidence and severity of POPF, incidence and severity of post-operative complications, and post-operative mortality. A minimal annual number of 20 procedures per center is recommended. In pancreatic cancer (versus OPD), RPD is associated with similar rates of R0 resections, but higher number of examined lymph nodes, lower blood loss, and lower need of blood transfusions. Multivariable analysis shows that RPD could improve patient survival. Data from selected centers show that vein resection and reconstruction is feasible during RPD, but at the price of high conversion rates and frequent use of small tangential resections. The true Achilles heel of RPD is higher operative costs that limit wider implementation of the procedure and accumulation of a large experience at most single centers. In conclusion, when proficiency is achieved, RPD may be superior to OPD with respect to CR-POPF and oncologic outcomes. Achievement of proficiency requires commitment, dedication, and truly high volumes.

Introduction

First performed by Codivilla in 1898 [1], pancreatoduodenectomy (PD) is commonly known as “Whipple procedure”, in honor of Allen Oldfather Whipple who reported the first successful one-stage PD in 1941 [2]. After 80 years of refinements, PD remains associated with high morbidity and mortality rates. A study published in the New England Journal of Medicine in 2011 showed that risk-adjusted mortality of all types of pancreatic resection in 2008 (5.5%) was only slightly inferior to that of aortic valve replacement (6.6%) and superior to that of coronary artery bypass (3.4%) [3]. Considering that these figures refer to open pancreatic surgery, it is clear that open surgery offers opportunity for improvement.

In recent years, minimally invasive surgery has improved the outcome of many abdominal operations. Feasibility of minimally invasive PD was shown over 25 years ago [4], but the procedure did not gain widespread popularity due to the intrinsic technical limitations of conventional laparoscopy, the need to overcome a steep learning curve, and the lack of clear clinical benefits. A worldwide survey on opinions and use of minimally invasive pancreatic resections demonstrated that 29% of responding surgeons performed minimally invasive PD. The most common reasons for not performing minimally invasive PD were lack of specific training (62%), difficulty of surgical technique (44%) and lack of time in surgical schedule (37%). Interestingly, while current value of minimally invasive PD was deemed superior to that of open PD (OPD) only by 17% and 7% of surgeons performing and not performing minimally invasive PD, respectively, equivalent figures for future value were 53% and 23%, respectively [5].

The da Vinci Surgical System® (Intuitive Surgical, Sunnyvale, CA, USA) enhances surgical dexterity in minimally invasive procedures and, therefore, provides the opportunity to verify if a minimally invasive approach can improve the
outcome of PD. We herein present the state of the art of robotic PD (RPD).

Historical and technical notes

The first RPD was performed in 2001. This landmark procedure was reported by Giulianotti and coworkers in 2003 in an article presenting the use of the dVSS in general surgery [6]. In the first 6 RPDs, dissection was carried out laparoscopically and robotic assistance was used only for digestive reconstruction. In the remaining two patients, a full robotic technique was adopted. A hybrid approach to RPD is still very popular, and is used even at major centers [7], mostly because of the “rigidity” of the dVSS and the lack of articulated streamlined energy devices suitable for retroperitoneal dissection. A fully robotic procedure, however, is also possible [8, 9]. Currently, there is no agreed technical standard for RPD. Evidence-based guidelines for minimally pancreatic resections recommend a minimum annual volume of 20 procedures per center without distinction between RPD and LPD [10]. There is no evidence on minimum volume requirements for individual surgeons.

Feasibility and learning curve

Feasibility of RPD has been demonstrated by several independent groups [9, 11–13]. A collaborative study reporting on the outcome of the first RPDs performed at 5 centers between January 2008 and August 2014 demonstrated that RPD can be safely implemented in selected patients at high-volume centers. In detail, in a total of 92 patients with a mean age of 65 ± 12 years, a mean body mass index of 25.8 ± 5.0 kg/m², a prevalence of male gender (53%), and a proportion of ASA III patients of 46%, median operating time was 504 min (interquartile range 133), median estimated blood loss was 242 ml (interquartile range 398), and conversion to open surgery was required in 12 procedures (13%). Regarding pancreatic anastomosis, pancreaticojunostomy was employed in all but 2 patients and temporary ducts stents were inserted in the majority of patients (69.5% overall, and 86.7% in patients with pancreatic duct diameter < 3 mm) irrespective of type of anastomosis (i.e., invaginating or duct-to-mucosa). Clinically relevant post-operative pancreatic fistula (CR-POPF) developed in 9 patients (9.9%; 4 grade B and 5 grade C). Rate of severe post-operative complications was 24% with 2 (2.2%) deaths and ten (10.9%) reoperations. A margin negative resection was achieved in 75% of the patients with pancreatic cancer with mean harvest of 16 ± 8 lymph nodes [14]. In subsequent studies, RPD was associated with extremely low rates of conversion to open surgery (ranging from 1.1% to 5.1%) [15, 16]. When compared with OPD, RPD required longer operating times [17], but reduced blood loss and need for blood transfusions [18]. In an early study, Chalikonda and coworkers reported a post-operative death caused by a portal vein injury requiring emergent conversion to open [12]. This dreadful occurrence is not specific to RPD and has already been reported also for laparoscopic PD (LPD) [19]. In a recent collaborative study, conversion to open was required in 65 of 709 minimally invasive PDs (9.1%), including 48 elective conversions (6.7%) and 12 emergency conversions (1.6%). Reasons for conversion were unknown in 5 patients. The incidence of conversion in LPD was twice as high when compared to RPD [52 of 459 (11.3%) versus 13 of 250 (5.2%); p = 0.007]. At multivariable analysis, using RPD as reference, LPD was strongly associated with conversion to open surgery (OR 5.2; 2.5–10.7; p < 0.001). Conversions were more frequent in medium-volume centers (10–19 procedures per year) than in high-volume centers (15.2% versus 4.1%; p = 0.001) [20].

Several studies have described the learning curve for RPD, mostly using cumulative summative (CUSUM) analysis of operating time. Excluding one article defining the simultaneous learning curve of two surgeons at 80 procedures [21], the number of cases required to overcome the learning curve for a single surgeon ranged between 20 and 40 RPDs [22–26]. Implementation of mentorship and a proficiency-based curriculum could not affect POPF rate, but was shown to reduce operating times, conversion rates, severe post-operative complications, and estimated blood loss [27]. A recent systematic review on the learning curve of LPD and RPD showed that the learning curve of a single surgeon was considerably longer for LPD [49.8 (95% CI 43.8–56.4) versus 28.3 (23.3–34.0); IRR: 1.76, 95% CI 1.04–2.99; p = 0.0360], while the Institutional learning curve was longer for RPD [43.6 (95% CI 38.0–49.8) versus 21.0 (95% CI 17.5–25.0)] although the difference was not statistically significant [28].

Two recent studies from extremely high-volume centers showed that true completion of the learning curve may require as many as 250 procedures [16, 17]. After this, the number of RPDs outcomes was optimized [29].

One study showed that based on operating times, 35 cases are required to overcome the learning curve of RPD with vein resection. Completion of the learning curve, however, was associated only with reduction in length of hospital stay, without improvement in estimated blood loss, margin status, post-operative pancreatic fistula, severe complications, and post-operative mortality [30].

Post-operative pancreatic fistula

Few studies, all reporting retrospective analyses, have compared the outcomes of LPD and RPD [31–35]. Most of these studies have not shown an advantage of RPD in terms
of occurrence of CR-POPF. However, a large multicenter study showed that single-row pancreatojejunostomy when performed during minimally invasive PD increased the incidence of POPF (OR 2.95, P < 0.001) and that this type of anastomosis was prevalent in LPD [36]. An additional study confirmed that the use of single-row pancreatojejunostomy in minimally invasive PD was prevalent in LPD (16%), as compared to either RPD (13%) or hybrid PD (1%), and that it was independently associated with the development of CR-POPF (OR 5.0, 95 CI 3.0–8.2). The authors of this study speculate that inferiority of laparoscopic single-row pancreatojejunostomy could be caused by the increased technical difficulty experienced in LPD, as inferiority single-row anastomosis was not seen in either RPD or OPD [37].

A recent study by Shi and coworkers reported on the outcomes of 200 RPDs performed after the first 250 cases. In this study, RPD was found to be superior to OPD for several parameters, but not for CR-POPF. However, in matched cohorts, CR-POPF occurred less frequently after RPD (10.2% versus 14.4%). The difference, although not statistically significant, was well evident for grade C POPF (3.7% versus 7.5%). RPD improved operating time, estimated blood loss, and length of hospital stay [29].

Cai and coworkers showed a lower incidence of CR-POPF after RPD when compared to OPD (6.7% versus 15.8%, p < 0.001). In detail, grade B POPF occurred more frequently after OPD (13.3% versus 2.5%, p < 0.001), while the incidence of grade C POPF was similar in the two groups (2.5% vs. 2.0%, p = 0.470). RPD was protective against CR-POPF in case moderate-risk anastomoses (7.1% vs. 15.2%, p = 0.008). Lower rates of CR-POPF were also observed in low- and high-risk anastomoses, although difference did not reach statistical significance. RPD remained an independent predictor of lower CR-POPF on multivariate analysis (OR 0.278, p < 0.001) and continued to be protective after propensity matching (coefficient = −0.113, p = 0.001) [38].

Lower rates of CR-POPF in RPD versus OPD (11.9% vs 15.6%; p = 0.026) were shown also in a retrospective analysis of the American College of Surgeons National Surgical Quality Improvement Program (ACS-NSQIP) database. In this study, RPD was also associated with decreased median time to drain removal (4 vs 7 days; p < 0.001). Despite a similar incidence of CR-POPF in RPD and LPD, more patients required a percutaneous catheter drainage after LPD (10.8% vs 15.7%; p = 0.030) [39].

Other post-operative complications

In a study by Vining and coworkers, RPD (versus OPD) was associated with shorter median length of stay (7 vs 8 days; p < 0.001), and lower rates of any complication (46.8% vs 53.3; p = 0.004), surgical complications (42.6% vs 48.6%; p = 0.008), hemorrhage requiring blood transfusions, (10.4% vs 17.7%; p < 0.001), wound complications (6.2% vs 9.1%; p = 0.029), wound dehiscence (0.2% vs 1.3%; p = 0.035), sepsis (6.2% vs 9.3%; p = 0.019) and pneumonia (1.6% vs 3.8%; p = 0.012). In comparison with LPD, RPD was associated with lower rates of bleeding requiring transfusions (10.4% vs 17.4%; p = 0.002). Rates of 30-day readmission were higher after RPD than after either OPD (24.3% vs 16.2%; p < 0.001) or LPD (24.3% vs 15.5%; p = 0.001) [39].

In a study by Shi and coworkers, RPD (versus OPD) was associated with reduced mean blood loss (297.3 ± 246.8 versus 415.2 ± 497.9 mL; 95% CI 197.8848 to −38.0510; p = 0.002), lower rate of intra-abdominal infections (21.4% versus 34.2%; p = 0.008) and shorter duration of hospital stay (22.4 ± 16.7 versus 26.1 ± 16.3 days; 95% CI −7.0837 to −0.3708; p = 0.03). No difference was noted in bile leak, delayed gastric emptying, post-operative bleeding and need for reoperation [29].

Aguayo and coworkers in a study aiming to investigate readmission rates in RPD and OPD, based on the National Readmission Database (January 2010 to December 2017), showed that out of 81,457 patients who survived the index hospitalization (96.9%), 15,823 (19.4%) required 30-day hospital readmission (RPD: 19.5% versus OPD: 18.6%; p = 0.34). RPD was associated with reduced length of index hospital stay (12.3 days versus 14.0 days; p = 0.002). Incidence of complications at index hospitalization was similar between RPD and OPD (27.7% versus 25.5%; p = 0.28), with lower rates of Clostridium difficile infections in OPD (2.6% versus 1.3%; p = 0.03), and a trend for fewer intraoperative complications in RPD (0.9% versus 4.8%; p = 0.06) [40].

Compared to LPD, RPD was associated with reduced operating time [32], lower estimated blood loss [32], fewer conversions to open surgery [32–35] and shorter hospital stay [32].

Postoperative mortality

Data from the literature show that RPD does not increase post-operative mortality when compared to either OPD [29, 35, 40] or LPD [33, 39, 41].

Adoption

Adoption of surgical innovation typically follows an S-shaped curve and occurs in five stages. Adoption accelerates to a peak when innovation enters the third stage and innovation is accepted by the “early majority” [42]. This typically occurs when safety is shown and efficacy starts to become evident.
Two studies have shown a recent increase in the use of robotic assistance for pancreatic operations. An analysis of the National Inpatient Sample database (2010–2014) showed that there was a fivefold general increase in the use of robotic surgery (compared to 1.1-fold increase in laparoscopy and 1.2-fold decrease in open surgery). The use of robotic assistance for pancreatic resections increased from <1% in 2010 to 3% in 2014. When compared with laparoscopy, the odds of having robotic pancreatic surgery increased from 3.95 (0.85–18.24) in 2011 to 7.94 (3.53–17.85) in 2014 [43]. An additional study analyzing the National Cancer Database (2010–2014) demonstrated increased use of robotic assistance for pancreatic resections, with a decrease in postoperative mortality (from 6.7 to 1.8%) and an increase in the number of examined lymph nodes (from 18 to 21) for RPD [44].

**RPD for pancreatic cancer**

Girgis and coworkers reported a retrospective analysis of 456 patients who received either a robotic (226) or open (230) pancreatectomy for pancreatic cancer (PD: 361; distal pancreatectomy: 73; distal pancreatectomy with celiac axis resection: 22). In PD the robotic approach (versus OPD) was associated with similar rates of R0 resection, but higher lymph node harvest (21.47% versus 21.72%), (31.9 ± 12.2 versus 25.9 ± 11.1; \( p < 0.0001 \)), lower estimated blood loss (250 mL (150, 400) versus 500 mL (300–925)), and lower need of blood transfusions (17.2% versus 40.4%; \( p < 0.0001 \)). A similar proportion of patients in the two groups received neoadjuvant chemotherapy (61.11% versus 61.93%), adjuvant chemotherapy (67.90% versus 71.35%), and both neoadjuvant and adjuvant chemotherapy (41.6% versus 43.5%). RPD was associated with lower rates of associated vein resection (25.2% versus 37.9%; \( p = 0.01 \)) and higher rates of administration of <6 cycles of adjuvant chemotherapy (46.6% versus 36.1%; \( p = 0.047 \)). Time to adjuvant chemotherapy was slightly longer in RPD (65 days (56–81) versus 62 days (48–83); \( p = 0.056 \)). On multivariable analysis, RPD (HR 0.75, \( p = 0.05 \)), severe complications (HR 1.45, \( p = 0.006 \)), presence of lymph node metastasis (HR 1.62; \( p = 0.003 \)) and R1 resection (HR 1.55; \( p = 0.001 \)) predicted survival [45].

Nassour and coworkers in an analysis of the National Cancer Database (2010–2016) identified 626 RPD and 17,205 OPD performed for stage I–III pancreatic cancer. RPD was associated with higher mean number of examined lymph nodes (12 vs 11; \( p < 0.001 \)) and procedures with >12 lymph nodes (81% versus 73%; \( p < 0.001 \)). There was no difference in median overall survival between RPD (22.0 months) and OPD (21.8 months). RPD was not associated with inferior overall survival [hazard ratio (HR) = 1.014; 95% CI 0.903–1.139] [46].

In an additional study, Nassour and coworkers queried the National Cancer Database (2010–2013) for RPD (\( n = 165 \)) and LPD (\( n = 1458 \)). Most procedures in both groups were performed for pancreatic cancer (89.1% versus 90.1%). RPD was associated with higher mean number of harvested lymph nodes (19.3 ± 18.0 versus 17.2 ± 17.0; \( p = 0.081 \)) and lower conversion rate (17.0% versus 27.6%; \( p = 0.003 \)). No difference was found in median overall survival (20.7 months versus 22.7 months; \( p = 0.445 \)) [34].

Little evidence is available to define feasibility and safety of RPD in patients receiving neoadjuvant treatments that are currently used in patients with borderline-resectable pancreatic cancer and in some patients with anatomically resectable tumors.

**RPD with vascular resection**

Approximately 30% of the patients with a cancer located in the pancreatic head are classified borderline resectable and may require a vein resection.

Vein resection during RPD was first reported Giulianotti and coworkers in 2 patients. The first patient received a stapled type 1 resection. The second patient had a type 2 resection using a polytetrafluoroethylene patch [47]. Our group was the first to report arterial resections in 4 RPDs [48].

Beane and coworkers reported a retrospective review of 380 consecutive RPDs (October 2011–May 2017) including 50 patients with associated vein resection and reconstruction. The majority of patients (\( n = 43 \); 86.0%) received a type 1 resection using a vascular stapler. The remaining 7 patients received either a type 2 resection (using a bovine pericardial patch for repair) or a type 3 resection. Mean operating time was 412 ± 82 min (412 ± 82 min in type 1 resections and 463 ± 109 min in type 2–3 resections). Conversion to open surgery was required in 8 of 43 type 1 resections (18.6%) and in 3 of 7 (42.8%) type 2–3 resections. Mean (range) estimated blood loss was 250 mL (200–500 mL) in type 1 resections, and 400 mL (200–1500 mL) in type 2–3 resections. RPD with vascular resection was associated with a median length of hospital stay of 7 days (6–9), an incidence of severe complications of 28.0%, a 90-day readmission rate of 43.0%, a 30-day mortality of 4.0% and a 90-day mortality of 8.0% [30].

Shyr and coworkers reported a retrospective review of the experience of the Taipei Veterans General Hospital (2012–2018). A vein resection was required in 43 of 391 PDs (10.9%), including 32/208 (15.3%) OPDs and 11/183 (6.0%) RPDs (\( p = 0.003 \)). Conversion to open surgery was required in 36.4% of RPDs with vein resection [49].

© Springer
Marino and coworkers reported a retrospective review of 83 RPDs (March 2013–October 2019), including 10 procedures with vein resection (12.0%). When compared to standard RPD, RPD with vascular resection was associated to longer mean operating time (642 ± 105.7 min versus 525 ± 92.3 min; \( p = 0.003 \)), higher median estimated blood loss [620 mL (380–1100.5) versus 290 mL (155–494.5); \( p = 0.002 \)], and more frequent use of blood transfusions (20.0% versus 5.5%; \( p = 0.002 \)). No difference was noted in rate of conversion to open surgery (10.0% versus 6.8%), reoperation (20.0% versus 8.2%), median length of hospital stay [13 days (6–19) versus 10 days (5–19)], 90-day readmission (10.0% versus 6.8%), and 90-day mortality (10.0% versus 4.1%). In patients with pancreatic cancer (6 versus 38), RPD with vein resection was associated with higher mean number of examined lymph nodes [46 ± 7 versus 32 ± 11; \( p = 0.03 \)] and equivalent rates of R0 resection (83.3% versus 92.1%), local recurrence (16.7% versus 13.2%), 1-year overall survival (85.7% versus 81.6%), and 1-year disease-free survival (71.4% versus 71.1%) [50].

A retrospective analysis of our experience revealed that between October 2008 and April 2016 14 patients had RPD with vein resection out of total of 130 RPDs (10.7%). No patients undergoing RPD with vein resection required conversion to open surgery. Type 2 vein resection was performed in one patient (7.1%), type 3 in 5 patients (35.7%), and type 4 in 8 patients (57.2%). Compared to OPD, RPD with vein resection was associated with longer mean operating time (640.7 ± 99.7 min versus 521.7 ± 98.7 min; \( p = 0.0006 \)), higher median estimated blood loss [1109.7 mL (819.4–1430.2) versus 419.5 mL (177.5–689.6); \( p < 0.0001 \)], more frequent use of intraoperative blood transfusions (28.6% versus 3.5%; 0.0047), and more frequent diagnosis of pancreatic cancer (57.1% versus 19.8%; \( p = 0.002 \)). No differences were noted in incidence of severe post-operative complications (28.6% versus 17.2%) median length of hospital stay [21.5 days (15–33.3) versus 18 days (14–25.8)], 90-day readmission (0 versus 8.8%), number of examined lymph nodes (60 ± 13.9 versus 57.2 ± 14.6), rate of R0 resections (75.0% versus 83.3%). A trend to higher 90-day post-operative mortality was noted in the RPD with vein resection (14.3% versus 1.7%; \( p = 0.06 \)), but cases were not matched for baseline characteristics that could predict survival [51].

**Costs**

In a study on feasibility, we showed that RPD, when compared to OPD, is associated with a total amount of added costs of 6193 Euro [10]. Rosemurgy and coworkers in an economic analysis showed that total costs of care was 31,389 US dollars (36,611 ± 20,545.4) for RPD and 23,132 US dollars (31,323 ± 28,885.5; \( p = 0.04 \)) for OPD [52]. On the contrary, Aguayo and coworkers showed that index costs were not significantly different between RPD and OPD ($51,956 versus $47,296, \( p = 0.28 \)) [40].

**Discussion**

Available data suggest that robotic assistance improves the outcomes of minimally invasive PD. In general, RPD is as safe ad OPD [35, 40] and LPD [33, 39, 41]. Compared to LPD, RPD reduces the overall risk of conversion to open surgery and the risk of emergency conversion due to major bleeding [20], thus addressing one of the major concerns on safety of minimally invasive PD [19]. Under appropriate conditions, RPD facilitates safe implementation of minimally invasive PD [14] and reduces the learning curve of this procedure, when compared to LPD [28]. Availability of mentorship and implementation a proficiency-based curriculum further facilitate safe implementation of RPD [27].

Despite current excellent data, the full potential of RPD could not have been fully explored yet. Indeed, two recent studies demonstrate that after 250 procedures outcomes of RPD are optimized [15, 16] and become superior to those of OPD [29]. Considering that also in OPD excellence is reached only with high institutional [53] and individual [54] volumes, RPD promises to show clear superiority over alternative approaches.

As for now, RPD is at least equivalent to OPD and LPD with respect to incidence and severity of POPF, incidence and severity of post-operative complications, and post-operative mortality [31–35]. In patients diagnosed with pancreatic cancer, RPD is associated with similar rates of R0 resections, but higher number of examined lymph nodes, lower blood loss, and lower need of blood transfusions [34, 45, 46]. Multivariate analysis shows that RPD could improve patient survival [45]. Limited evidence shows that RPD with vein resection and reconstruction is feasible [30, 49–51], but at the price of high conversion rates and frequent use of small tangential resections [30]. Thirty-five procedures are required to complete the learning curve of RPD with vein resection [30].

Considering that safety is paramount in a new procedure such as RPD, it is important to underscore that mesenteric vessels must be approached carefully to prevent massive bleeding that could be difficult to fix [12]. Although exact figures on incidence of this type of intraoperative complication are missing, emergency conversion due to bleeding was required in 12 of 709 minimally invasive PDs (1.6%), including both RPD and LPD. Multivariable analysis showed that LPD was associated with a higher risk of conversion (OR 5.2, 95% CI, 2.5–10.7; \( p < 0.001 \)) [20]. Despite RPD reduces the risk of massive intraoperative bleeding (versus LPD), we wish to emphasize that surgeons should be prepared to face
hemorrhage from major visceral vessels before embarking upon RPD.

The true, and perhaps the only, Achilles heel of RPD is high operative costs [10, 52] that constitute a barrier to implementation of RPD on a larger scale and accumulation of relevant experience at most Institutions. If robotic assistance would come to the same cost of conventional laparoscopy, there would be no rational reason to avoid/limit the use of this technology in patients suitable for minimally invasive PD. A further improvement that would also be needed is availability of dissection instruments specifically suitable for RPD, such as streamlined energy devices with endrowrist® articulation. These instruments are frequently used in either OPD or LPD with good outcomes. To obviate to this lack, some groups still prefer to use a hybrid technique, with sequential laparoscopic dissection and robotic reconstruction, or allow the assistant at the table to use laparoscopic energy devices to enhance robotic dissection.

In conclusion, RPD allows safe implementation of minimally invasive PD. Current results show that RPD is at least equivalent to OPD and LPD, with superiority becoming evident for selected outcome measures. When more centers will have gained enough experience, it is likely that RPD will show clear superiority over alternative approaches.

**Author contributions** Substantial contributions were made to the conception or design of the work (UB), the acquisition, analysis (EFK, NN, and GA), interpretation of data for the work (FV and UB), drafting of the work (GA, and UB) or revising it critically for important intellectual content (EFK, NN, FV, GA, and UB) and final approved of the version to be published (EFK, NN, FV, GA, and UB). Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved (EFK, NN, FV, GA, and UB).

**Funding** Open access funding provided by Università di Pisa within the CRUI-CARE Agreement. This state-of-the-art article did not receive any specific grant from funding agencies in public, commercial, or non-profit sectors.

**Data availability** This state-of-the-art manuscript is based on data derived from cited articles.

**Code availability** Not applicable.

**Declarations**

**Conflict of interests** The authors declare they have no conflict of interest.

**Research involving human participants and/or animals** Not applicable.

**Informed consent and ethical approval** Not applicable.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

1. Schnellstorfer T, Sarr MG (2009) Alessandro Codivilla and the first pancreatoduodenectomy. Arch Surg 144:1179–1184. https://doi.org/10.1001/archsurg.2009.219

2. Whipple AO (1941) The rationale of radical surgery for cancer of the pancreas and ampullary region. Ann Surg 114:612–615. https://doi.org/10.1097/00000658-194111440-00008

3. Finks JF, Osborne NH, Birkmeyer JD (2011) Trends in hospital volume and operative mortality for high-risk surgery. N Engl J Med 364:2128–2137. https://doi.org/10.1056/NEJMs a1010705

4. Gagner M, Pomp A (1994) Laparoscopic pylorus-preserving pancreatoduodenectomy. SurgEndosc 8:408–410. https://doi.org/10.1007/BF00642443

5. van Hilst J, de Rooij T, Abu Hilal M et al (2017) Worldwide survey on opinions and use of minimally invasive pancreatic resection. HPB (Oxford) 19:190–204. https://doi.org/10.1016/j. hpb.2017.01.011

6. Giulianiotti PC, Coratti A, Angelini M, Sbrana F, Cecconi S, Balestracci T, Caragavilios G (2003) Robotics in general surgery: personal experience in a large community hospital. Arch Surg 138:777–784

7. Nguyen KT, Zureikat AH, Chalikonda S, Bartlett DL, Moser AJ, Zeh HJ (2011) Technical aspects of robotic-assisted pancreatoduodenectomy (RAPD). J GastrointestSurg 15:870–875. https://doi.org/10.1007/s11605-010-1362-0

8. Giulianiotti PC, Mangano A, Bustos RE, Gheza F, Fernandes E, Masrur MA, Gangemi A, Bianco FM (2018) Operative technique in robotic pancreatoduodenectomy (RPD) at University of Illinois at Chicago (UIC): 17 steps standardized technique: lessons learned since the first worldwide RPD performed in the year 2001. SurgEndosc 32:4329–4336. https://doi.org/10.1007/ s00464-018-6228-7

9. Boggi U, Signori S, De Lio N, Perrone VG, Vistoli F, Belleumini M, Cappelli C, Amorese G, Mosca F (2013) Feasibility of robotic pancreatoduodenectomy. Br J Surg 100:917–925. https://doi.org/10.1002/bjs.9135

10. Ashburn, W, Moekotte AL, Vissers FL et al (2020) The miami international evidence-based guidelines on minimally invasive pancreas resection. Ann Surg 271:1–14. https://doi.org/10.1097/ SLA.0000000000003590

11. Giulianiotti PC, Sbrana F, Bianco FM, Elli EF, Shah G, Addeo P, Caravagilios G, Coratti A (2010) Robot-assisted laparoscopic pancreatic surgery: single-surgeon experience. SurgEndosc 24:1646–1657. https://doi.org/10.1007/s00464-009-0825-4

12. Chalikonda S, Aguilar-Savedra JR, Walsh RM (2012) Laparoscopic robotic-assisted pancreatoduodenectomy: a case-matched comparison with open resection. SurgEndosc 26:2397–2402. https://doi.org/10.1007/s00464-012-2207-6

13. Zureikat AH, Moser AJ, Boone BA, Bartlett DL, Zenati M, Zeh HJ 3rd (2013). 250 robotic pancreatic resections: safety
and feasibility. Ann Surg 258:554–559; discussion 559–62. doi: https://10.1097/SLA.0b013e3182a4e87c
14. Watkins AA, Kent TS, Gooding WE, Boggi U, Chalikonda S, Kendrick ML, Walsh RM, Zeh HJ 3rd, Moser AJ (2018) Multicenter outcomes of robotic reconstruction during the early learning curve for minimally-invasive pancreaticoduodenectomy. HPB (Oxford) 20:155–165. https://10.1016/j.hpb.2017.08.032
15. Shi Y, Wang W, Qu W, Zhao S, Wang J, Weng Y, Hoo Z, Jin J, Wang Y, Deng X, Shen B, Peng C (2019) Learning curve from 450 cases of robot-assisted pancreaticoduodenectomy in a high-volume pancreatic center: optimization of operative procedure and a retrospective study. Ann Surg. https://10.1097/SLA.0000000000003664
16. Zureikat AH, Beane JD, Zenati MS, Al Abbas AI, Boone BA, Moser AJ, Bartlett DL, Hogg ME, Zeh HJ 3rd (2019) 500 minimally invasive robotic pancreaticoduodenectomies: one decade of optimizing performance. Ann Surg. https://10.1097/SLA.00000000000033550
17. Boggi U, Napoli N, Costa F, Kauﬀmann EF, Menonna F, Incoppi S, Vistoli F, Amorese G (2016) Robotic-assisted pancreatic resections. World J Surg 40:2497–2506. https://10.1007/s00268-016-5565-3
18. Kauﬀmann EF, Napoli N, Menonna F, Incoppi S, Lombardo C, Bernardini J, Amorese G, CacciatoInsilla A, Funel N, Campani D, Cappelli C, Caramella D, Boggi U (2019) A propensity score-matched analysis of robotic versus open pancreaticoduodenectomy for pancreatic cancer based on margin status. Surg Endosc 33:234–242. https://10.1007/s00291-018-3631-2
19. van Hilst J, de Rooij B, Bosscha K, Brinkman DJ, van Dieren S, Diijkgraaf MG, Gerards MH, de Hingh IH, Karsten TM, Lips DJ, Luyer MD, Busch OR, Festen S, Besselink MG; Dutch Pancreatic Cancer Group. Laparoscopic versus open pancreaticoduodenectomy for pancreatic or periampullary tumours (LEOPARD-2): a multicentre, patient-blinded, randomised controlled phase 2/3 trial. Lancet Gastroenterol Hepatol. 2019;4(3):199–207. doi: https://10.1016/S2468-1253(19)30004-4
20. Lof S, Vissers FL, Klompmaker S, Berti S, Boggi U, Coratti A, Dokmak S, Fara R, Festen S, D’Hondt M, Khatrik I, Lips D, Luyer M, Manzioni A, Rosso E, Saint-Marc O, Besselink MG, Abu Hilal M, European consortium on Minimally Invasive Pancreatic Surgery (E-MIPS). (2021) Risk of conversion to open surgery during the learning curve for robotic and laparoscopic pancreaticoduodenectomy and effect on outcomes: international propensity score-matched comparison study. Br J Surg 108:80–87. https://10.1036/j.bjs.2019.026
21. Boone BA, Zenati M, Hogg ME, Steve J, Moser AJ, Bartlett DL, Zeh HJ, Zureikat AH (2015) Assessment of quality outcomes for robotic pancreaticoduodenectomy: identiﬁcation of the learning curve. JAMA Surg 150:416–422. https://10.1001/jamasurg.2015.17
22. Shyr BU, Chen SC, Shyr YM, Wang SE (2018) Learning curves for robotic pancreatic surgery—from distal pancreatectomy to pancreaticoduodenectomy. Medicine (Baltimore) 97(45):e13000. https://10.1097/md.0000000000013000
23. Kim H, Park SY, Park Y, Kron J, Lee W, Song KB, Hwang DW, Kim SC, Lee JH (2020) Assessment of learning curve and oncologic feasibility of robotic pancreaticoduodenectomy: a propensity score-based comparison with open approach. J HepatobiliaryPancreatSci. https://10.1016/j.jhbps.837
24. Napoli N, Kauﬀmann EF, Palmieri M, Miccoli M, Costa F, Vistoli F, Amorese G, Boggi U (2016) The learning curve in robotic pancreaticoduodenectomy. Dig Surg 33:299–307. https://10.1159/000445015
25. Zhang T, Zhao ZM, Gao YX, Lau WY, Liu R (2019) The learning curve for a surgeon in robot-assisted laparoscopic pancreaticoduodenectomy: a retrospective study in a high-volume pancreatic center. SurgEndosc 33:2927–2933. https://10.1007/s00464-018-6595-0
26. Chen S, Chen JZ, Zhan Q, Deng XX, Shen BY, Peng CH, Li HW (2015) Robot-assisted laparoscopic versus open pancreaticoduodenectomy: a prospective, matched, mid-term follow-up study. SurgEndosc 29:3698–3711. https://10.1007/s00464-015-4140-y
27. Rice MK, Hodges JC, Bellon J, Borrebach J, Al Abbas AI, Hamad A, Knab LM, Moser AJ, Zureikat AH, Zeh HJ, Hogg ME (2020) Association of mentorship and a formal robotic proficiency skills curriculum with subsequent generations’ learning curve and safety for robotic pancreaticoduodenectomy. JAMA Surg 155:607–615. https://10.1001/jamasurg.2020.1040
28. Chan KS, Wang ZK, Syn N, Goh BKP (2021). Learning curve of laparoscopic and robotic pancreas resections: a systematic review. Surgery S0039–6060(20)30831-X. doi: https://10.1016/j.surg.2020.11.046.
29. Shi Y, Jin J, Qu W, Weng Y, Wang J, Zhao S, Hoo Z, Qin K, Wang Y, Chen D, Peng C, Shen B (2020) Short-term outcomes after robot-assisted vs open pancreaticoduodenectomy after the learning curve. JAMA Surg 155:389–394. https://10.1001/jamasurg.2020.0021
30. Beane JD, Zenati M, Hamad A, Hogg ME, Zeh HJ 3rd, Zureikat AH (2019) Robotic pancreaticoduodenectomy with vascular resection: Outcomes and learning curve. Surgery 165:8–14. https://10.1016/j.surg.2018.01.037
31. Xourafas D, Pawlik TM, Cloyd JM (2018) Independent predictors of increased operative time and hospital length of stay are consistent across different surgical approaches to pancreaticoduodenectomy. J GastrointestSurg 22:1911–1919. https://10.1007/s11605-2017-3834-6
32. Liu R, Zhang T, Zhao ZM, Tan XL, Zhao GD, Zhang X, Xu Y (2017) The surgical outcomes of robot-assisted laparoscopic pancreaticoduodenectomy versus laparoscopic pancreaticoduodenectomy for periampullary neoplasms: a comparative study of a single center. SurgEndosc 31:2380–2386
33. Nassour I, Wang SC, Porembka MR, Yopp AC, Choti MA, Augustine MM, Polanco PM, Mansour JC, Minter RM (2017) Robotic versus laparoscopic pancreaticoduodenectomy: a NSQIP analysis. J GastrointestSurg 21:1784–1792. https://10.1007/s11605-017-3543-6
34. Nassour I, Choti MA, Porembka MR, Yopp AC, Wang SC, Polanco PM (2018) Robotic-assisted versus laparoscopic pancreaticoduodenectomy: oncological outcomes. SurgEndosc 32:2907–2913. https://10.1007/s00464-017-6002-2
35. Zimmerman AM, Roye DG, Charpentier KP (2018) A comparison of outcomes between open, laparoscopic and robotic pancreaticoduodenectomy. HPB (Oxford) 20:364–369. https://10.1016/j.hpb.2017.10.008
36. Klompmaker S, van Hilst J, Wellner UF, Busch OR, Coratti A, D’Hondt M, Dokmak S, Festen S, Kerem M, Khatkov I, Lips DJ, Lombardo C, Luyer M, Manzioni A, Molenaar IQ, Rosso E, Saint-Marc O, Vansteenkiste F, Wittel UA, Bonsing B, Groot Koerkamp B, Abu Hilal M, Fuks D, Poves I, Keck T, Boggi U, Besselink MG; European consortium on Minimally Invasive Pancreatic Surgery (E-MIPS) (2020). Outcomes after minimally-invasive versus open pancreaticoduodenectomy: a pan-european propensity score matched study. Ann Surg 271:356–363. doi: https://10.1097/SLA.0000000000002850
37. Mungroop TH, Klompmaker S, Wellner UF, Steyerberg EW, Coratti A, D’Hondt M, de Pastena M, Dokmak S, Khatkov I, Saint-Marc O, Wittel U, Abu Hilal M, Fuks D, Poves I, Keck T, Boggi U, Besselink MG; European Consortium on Minimally Invasive Pancreatic Surgery (E-MIPS) (2021). Updated Alternative Fistula Risk Score (ua-FRS) to Include Minimally Invasive
Pancreatoduodenectomy: Pan-European Validation. Ann Surg 273:334–340. doi: https://doi.org/10.1097/SLA.0000000000003234

38. Cai J, Ramanathan R, Zenati MS, Al Abbas A, Hogg ME, Zeh HJ, Zureikat AH (2020) Robotic pancreatoduodenectomy is associated with decreased clinically relevant pancreatic fistulas: a propensity-matched analysis. J GastrointestSurg 24:1111–1118. https://doi.org/10.1007/s11605-019-04274-1

39. Vining CC, Kuchta K, Schultevoerder D, Paterakos P, Berger Y, Roggin KK, Talamonti MS, Hogg ME (2020) Risk factors for complications in patients undergoing pancreatoduodenectomy: A NSQIP analysis with propensity score matching. J Surg Oncol 122:183–194. https://doi.org/10.1002/jso.25942

40. Aguayo E, Antonios J, Sanaiha Y, Dobaria V, Kwon OI, Sareh S, Benharash P, King JC (2020) Readmission and resource use after robotic-assisted versus open pancreatoduodenectomy: 2010–2017. J Surg Res 255:517–524. https://doi.org/10.1016/j.jss.2020.05.084

41. Kamarajah SK, Bundred J, Marc OS, Jiao LR, Manas D, Abu Hilal M, White SA (2020) Robotic versus conventional laparoscopic pancreatoduodenectomy: a systematic review and meta-analysis. Eur J Surg Oncol 46:6–14. https://doi.org/10.1016/j.ejso.2019.08.007

42. Wilson CB (2006) Adoption of new surgical technology. BMJ 332(7533):112–114. https://doi.org/10.1136/bmj.332.7533.112

43. Stewart CL, Ituarte PHG, Melstrom KA, Warner SG, Melstrom LG, Lai LL, Fong Y, Woo Y (2019) Robotic surgery trends in general surgical oncology from the national inpatient sample. Surg Endosc 33:2591–2601. https://doi.org/10.1007/s00464-018-6554-9

44. Hoehn RS, Nassour I, Adam MA, Winters S, Pancià A, Zureikat AH (2020) National trends in robotic pancreatic surgery. J GastrointestSurg. https://doi.org/10.1007/s11605-020-04591-w

45. Girgis MD, Zenati MS, King JC, Hamad A, Zureikat AH, Zeh HJ, Hogg ME (2019) Oncologic outcomes after robotic pancreatic resections are not inferior to open surgery. Ann Surg. https://doi.org/10.1097/SLA.0000000000003615

46. Nassour I, Winters SB, Hoehn R, Tohme S, Adam MA, Bartlett DL, Lee KK, Pancià A, Zureikat AH (2020) Long-term oncologic outcomes of robotic and open pancreatectomy in a national cohort of pancreatic adenocarcinoma. J Surg Oncol 122:234–242. https://doi.org/10.1002/jso.25958

47. Giulanotti PC, Addeo P, Buchs NC, Ayloo SM, Bianco FM (2011) Robotic extended pancreatectomy with vascular resection for locally advanced pancreatic tumors. Pancreas 40:1264–1270. https://doi.org/10.1097/MPA.0b013e318220e3a4

48. Kauffmann EF, Napoli N, Cacace C, Menonna F, Vistoli F, Amorese G, Boggi U (2020) Resection or repair of large peri-pancreatic arteries during robotic pancreatectomy. Updates Surg 72:145–153. https://doi.org/10.1007/s13304-020-00715-8

49. Shyr BU, Chen SC, Shyr YM, Wang SE (2020) Surgical, survival, and oncological outcomes after vascular resection in robotic and open pancreatoduodenectomy. Surg Endosc 34(1):377–383. https://doi.org/10.1007/s00464-019-06779-x

50. Marino MV, Giovinazzo F, Poddà M, Gomez Ruiz M, Gomez Fleitas M, Pisanu A, Lattieri MA, Takaori K (2020) Robotic-assisted pancreatoduodenectomy with vascular resection. Description of the surgical technique and analysis of early outcomes. Surg Oncol 35:344–350. https://doi.org/10.1016/j.suronc.2020.08.025

51. Kauffmann EF, Napoli N, Menonna F, Vistoli F, Amorese G, Campani D, Pollina LE, Funel N, Cappelli C, Caramella D, Boggi U (2016). Robotic pancreatoduodenectomy with vascular resection. Langenbecks Arch Surg: 1111–1122, doi: https://doi.org/10.1007/s00423-016-1499-8.

52. Rosemurgy A, Ross S, Bourdeau T, Jacob K, Thomas J, Przetocki V, Lubricke K, Sucandy I (2021) Cost analysis of pancreatoduodenectomy at a high-volume robotic hepatopancreaticobiliary surgery program. J Am Coll Surg S1072–7515(21):00100–00109. https://doi.org/10.1016/j.jamcollsurg.2020.12.062

53. Bassi C, Marchegiani G, Giuliani T, Di Gioia A, Andrianello S, Zingaretti CC, Brentegani G, De Pastena M, Fontana M, Pea A, Paila S, Maleo G, Tuveri M, Landoni L, Esposito A, Casetti L, Butturini G, Fulconi M, Salvia R (2021) Pancreatoduodenectomy at the Verona Pancreas Institute: the evolution of indications, surgical techniques and outcomes: a retrospective analysis of 3000 consecutive cases. Ann Surg. https://doi.org/10.1097/SLA.0000000000004753

54. Cameron JL, He J (2015) Two thousand consecutive pancreatoduodenectomies. J Am Coll Surg 220:530–536. https://doi.org/10.1016/j.jamcollsurg.2014.12.031

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.