Robotic Pancreaticoduodenectomy: Technical Approaches and Outcomes

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11.1 Robotic Pancreaticoduodenectomy: Technical Approaches and Outcomes

11.1.1 Introduction

Pancreatic resections for both benign and malignant disease remain one of the most complex and challenging procedures for surgeons today. The retroperitoneal location of the gland, the complexities of the different gland textures, and its close proximity to major vascular structures all contribute to the intricacy of pancreatic resections. The pancreaticoduodenectomy (PD) has added complexity inherent in the necessity of reconstruction of gastrointestinal, biliary, and pancreatic continuity, requiring the construction of three separate anastomoses. As such, perioperative morbidity and mortality remained almost prohibitively high for many decades following the description of the PD by Allen O. Whipple in 1935 [1]. Improvements in mortality have been achieved at high volume centers with postoperative mortality rates as low as 1–2%, compared to mortality rates of 30% at the same center in the 1970s [2]. These improvements in postoperative PD mortality with increasing operative volume were demonstrated across many studies within the United States [3, 4], as well as other multiple European and Asian countries, as illustrated in a meta-analysis by Hata and others [5]. This drastic improvement in mortality rates in hospitals with increased

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PD volume has led to centralization of the procedure to these high volume centers [3, 4]. However, improvements in morbidity have not been as encouraging.

Over the course of approximately 30 years of evolving PD experience, postoperative morbidity rates have largely remained unchanged. In one series of 1175 PDs from 1970 to 2006 at a single institution, morbidity rates remained elevated in the 30–40% range over more than three decades [2]. Another retrospective review of 17,761 PDs from multiple states in the Unites States from 2002 to 2011 shows significant trends towards decreased complication rates in high volume centers. Decreases in infectious, bleeding, respiratory, and gastrointestinal tract complications were noted. However, complication rates by organ systems individually remained in the range of 5–17%, even among high volume centers [4]. As improvements in perioperative morbidity have been realized with minimally invasive operative approaches for a myriad of other procedures, recent interest has been towards optimizing minimally invasive PD.

The first laparoscopic PD was described by Gagner and Pomp in 1994 [6]. However, widespread adoption of this technique did not follow. The technique has been performed by multiple surgical teams throughout the world [7–11], with most series showing decreased intraoperative estimated blood loss (EBL) [8–10], increased median lymph node harvest [8, 9], decreased length of postoperative stay, and R1 resection rates better than or equal to open PD [8–11]. Multiple series have shown increased operative time for this minimally invasive approach [8, 9, 11]. However, some groups have found improvements in operative time, even approaching open PD, with increased operative experience [9, 11] and equal operative time at one higher volume center [10]. A meta-analysis of series published before 2010 revealed only 285 laparoscopic PDs in the literature, with only 225 completed from start to finish in a minimally invasive fashion. Weighted analysis of these studies showed complication and mortality rates similar to published rates for open approaches, at 48% and 2%, respectively. Similarly, lymph node harvest (weighted average 15) and margin positivity rates (0.4%) were within range for open procedures, and EBL was significantly lower [12]. A retrospective review of the National Cancer Center database of patients undergoing PD for pancreatic ductal adenocarcinoma in the United States between 2010 and 2011 found that laparoscopic PD is associated with decreased postoperative length of stay, as well as increased lymph node harvest and decreased R1 resections, suggesting benefits for the approach. However, this analysis also showed increased 30-day postoperative mortality in hospitals performing less than ten laparoscopic PDs, suggesting the steep learning curve associated with implementation of the approach [13]. While laparoscopic PD has been shown to have some benefits over traditional open PD in terms of decreased EBL, decreased postoperative length of stay and possibly increased lymph node yield, the technical challenges of the approach and steep learning curve have prevented widespread adoption.

Following the introduction of robotic-assisted surgical systems in the late 1990s, there has been increasing application across varying surgical specialties. The benefits of robotic-assisted surgery, including 20–30x field magnification with stereotactic binocular vision, improved surgical instrument dexterity with nearly 540 degrees of range of motion, elimination of surgeon tremor, and improved ergonomics for operating surgeons, provide the ability to overcome some of the obstacles of laparoscopic pancreatic surgery [14]. As such, interest has grown in applying the robotic surgical platform to advanced pancreatic resections. The first robotic-assisted PD was described by Giulianotti and others in Italy in 2003, in a series of eight cases [15]. This very early robotic-assisted PD experience showed that the procedure was feasible with this minimally invasive approach, and soon the technique began to increase in popularity, with our institution beginning robotic pancreatic surgery in 2008 [16].

11.1.1.1 Preoperative Evaluation and Operative Technique

Upon initiation of the robotic-assisted pancreatic surgery program at this institution, care was taken to ensure that the principles of open pancreatic surgery were followed meticulously. Early cases were performed by two experienced pancreatic surgeons for safety and logistic surgical volume concerns to gain momentum and shared experience. Selection of early patients was for patients with ampullary cancers, pancreatic neuroendocrine tumors, and purely resectable pancreatic adenocarcinomas. This had the added benefit of a more favorable resection, but soft glands and small ducts could also lead to more difficult reconstruction and increased risk for perioperative morbidity from postoperative pancreatic fistulae [17, 18]. Another important aspect of our robotic surgical application, to ensure patient safety, is diligent preoperative evaluation. Over the course of our experience, the inclusion criteria have expanded considerably and the numbers of PDs being performed via the robotic approach has increased substantially (Fig. 11.1). Currently, approximately 80% of PDs are performed robotically, even for borderline resectable pancreatic adenocarcinomas (PDA). The only absolute contraindication to robotic PD is vascular encasement of a long segment of the portal vein (PV) or superior mesenteric vein (SMV), which will likely need an interposition graft. To evaluate for resectability, all patients undergo preoperative triphasic CT scan imaging,

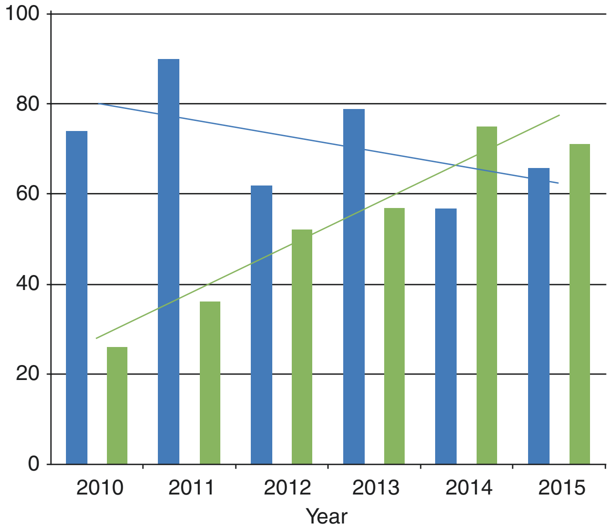

Fig. 11.1 Open vs robotic PD trends between 2010 and 2015. Percentages of total PD completed via open (*blue*) and robotic (*green*) approach at the University of Pittsburgh Medical Center, Pittsburgh, PA, USA, between 2010 and 2015. The overall trend is towards increasing utilization of the robotic surgical platform for performance of PD procedures

as well as endoscopic ultrasound evaluation, which in combination, have been shown to better predict successful margin negative resection [19]. Our current bias is for neoadjuvant therapy for all borderline resectable PDAs, and most resectable PDAs on clinical trial, as well. On average, 70% of our patients with PDA undergo neoadjuvant chemotherapy or chemoradiation. In the past year, 60.6% of our robotic PDs were performed for PDA, while the remaining cases were for ampullary cancer (9.9%), IPMN (9.9%), neuroendocrine tumors (5.6%), duodenal adenocarcinoma (4.2%), cholangiocarcinoma (4.2%), and other benign lesions (5.6%).

Our operative approach has previously been described [14, 20, 21] and utilizes the daVinci Robotic Surgical System (Intuitive Surgical, Sunny Valley, CA, USA). At the beginning of our experience, the S console system was utilized. Once the company upgraded to the Si, the computer interface and wrist capabilities of the robotic platform were better suited for this complex operation. We also have a Xi system and have performed robotic PDs on this system, as well; however, our preference remains use of the Si system. The procedure begins with laparoscopic evaluation. The configuration of port placements begins with placement of a 5 mm access port placed in the left subcostal region, utilizing an optical separator. This port will later be converted to a robotic 8 mm port. For malignant pathologies, once we confirm there is no metastatic disease, we place the remaining ports under direct visualization in the following fashion (Fig. 11.2):

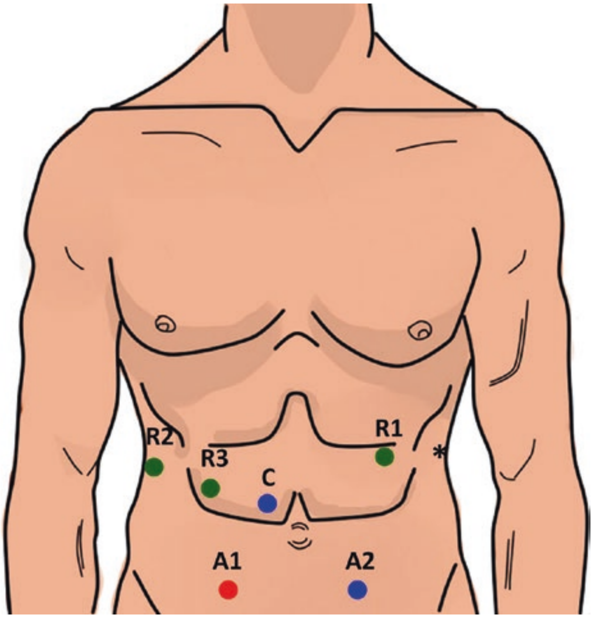

Fig. 11.2 Port placement configuration for robotic-assisted pancreaticoduodenectomy. Robotic 8 mm ports (R1, R2, R3) are used for the robotic arms. The 12 mm camera port (C) is placed above and to the right of the umbilicus. Assistant ports include a 5 mm port in the right lower quadrant (A1) and a 12 mm port in the left lower quadrant (A2), which then serves as specimen extraction site. The *asterisk* indicates a 5 mm self-retaining liver retractor

12 mm camera port 2–3 cm above and to the right of the umbilicus in a patient with an average body habitus, and two additional 8 mm ports for the robotic arms in the right midclavicular line and the right anterior axillary line. A 12 mm port is placed in the left lower quadrant, which serves as a port for the assistant and later for specimen extraction, and a 5 mm port is also placed in the right lower quadrant for the assistant. These are situated between the camera port and its neighboring port on either side. Additionally, a self-retaining liver retractor is placed in the left upper quadrant. When placing these ports, care is taken to ensure that at least a hands-breath, or 5–6 cm, is between ports to allow for free movement of instruments. For the first 6 years, the beginning of the procedure was performed laparoscopically; however, in the past 2 years, we have converted to an almost entirely robotic approach, where we dock the robot after port placement. One key maneuver is to close the camera 12 mm port with a “figure of 8” stitch using a suture passer prior to docking the robot (Fig. 11.2).

The robot is then docked directly over the head of the patient using the Si or at the patient’s right shoulder using the Xi. Our primary instruments for a majority of the resection include the hook monopolar in the right hand, the fenestrated bipolar in the left hand, and the cadiere or prograsp in the 3rd hand. The resection begins after entering the lesser sac through the gastrocolic omentum, followed by mobilization of the right colon then the duodenum by means of a Kocher maneuver. One trick to the operation is delivering the jejunum into the right upper quadrant by dissecting the ligament of Treitz until it is freed up about 40 cm, and then it is divided approximately 10 cm from the uncinate process. Then, the right gastric artery is taken with an energy device on the lesser curve, followed by the gastroepiploic artery along the greater curve. The stomach or proximal duodenum is transected. We favor a classic PD, but will occasionally perform a pylorus-preserving PD.

Once the stomach is divided, we move to the next step, which is dissection of the porta hepatis (Fig. 11.3). We start this dissection with removal of the hepatic artery lymph node. We think this is an important step for identification of the hepatic artery, portal vein (PV), and gastroduodenal artery (GDA). Once these structures are identified, we move lateral on the porta hepatis and identify the lateral aspect of the common bile duct (CBD), and then the lateral and posterior portal lymph nodes are dissected off the CBD and left attached to the specimen. Once this area is clear, we try to identify the PV and create a plane between it and the CBD. Then, we go back to the GDA and test clamp to make sure there is still adequate hepatic artery flow once clamped. If any question, we perform an ultrasound of the artery and test clamp under Doppler and ultrasound flow. We ligate the GDA with a vascular stapler and leave a clip on the staple line to mark the stump. Then, we dissect the CBD medially off the PV and once encircled, staple with a vascular load, as well. The benefit to dissecting laterally prior to stapling the GDA and CBD is to assure that there are no replaced or accessory hepatic vessels that need to be preserved (Fig. 11.3).

Next, we dissect the inferior border of the pancreas, locate the SMV, and create a retro-pancreatic tunnel (Fig. 11.4). The pancreas is then divided with hot scissor electrocautery half way from anterior to posterior and inferior to superior. Then, care is taken to divide the pancreatic duct with “cold” scissor transection. Attention is then

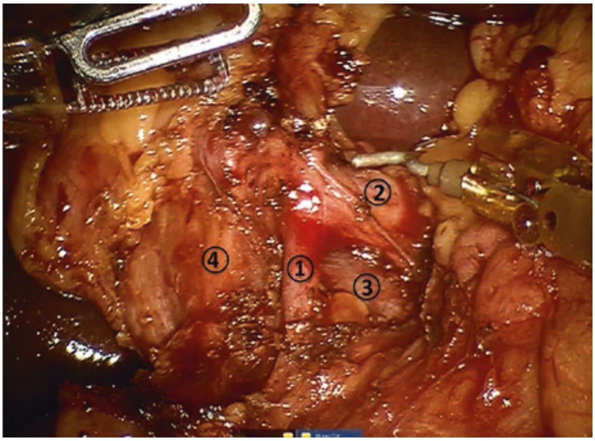

Fig. 11.3 Detailed view of portal dissection. The gastroduodenal artery (1) is isolated for ligation, typically via a vascular stapler and the stump is further reinforced with a clip. The common hepatic artery (2) and portal vein (3) can also be identified. The common bile duct (4) will also be transected using a stapler

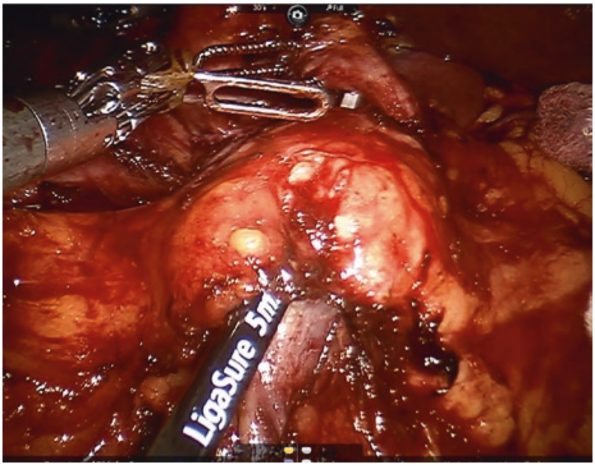

Fig. 11.4 Creation of the retro-pancreatic tunnel. Dissection proceeds along the inferior and superior borders of the pancreas, at the level of the pancreatic neck, and allows for creation of a tunnel beneath the pancreas and above the mesenteric vasculature

turned towards identifying the gastroepiploic and middle colic veins in relation to the SMV. The SMV is dissected fully to reveal the origin of these vessels prior to ligation. When possible, depending on the presence of a common trunk, the middle colic vein is preserved. The gastroepiploic vein is taken at its origin on the SMV. Once this is complete, we roll the SMV off the uncinate process and identify the first jejunal branches. We preserve these where possible; however, there are often numerous recurrent branches to the uncinate process requiring delicate dissection. Once the first

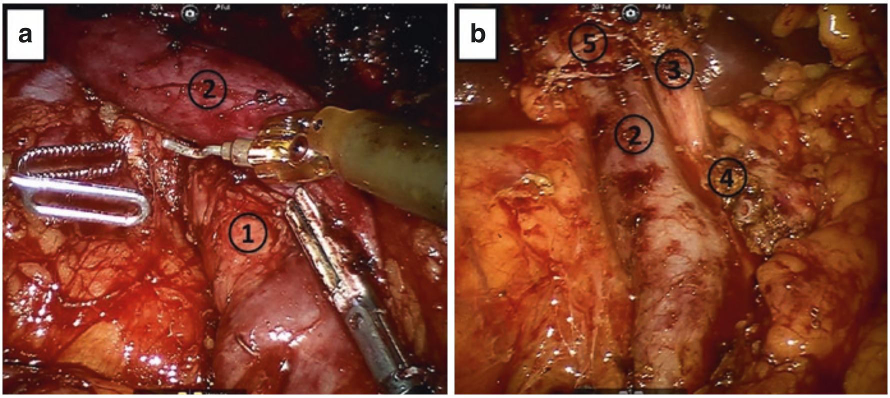

Fig. 11.5 Completed pancreaticoduodenectomy resection view. (**a**) The resection bed, with retraction of the superior mesenteric vein, shows careful dissection and removal of all the perivascular tissue along the plane of Leriche, clearing the superior mesenteric artery (1) and portal vein (2) margins. (**b**) After removal of the specimen, the view prior to reconstruction shows the dissected portal vein margin (2), the gastroduodenal artery stump (3), which is reinforced with a surgical clip, the cut edge of the pancreas (4), with a readily identifiable pancreatic duct, and the divided common bile duct (5)

jejunal is dissected off the uncinate, we identify the superior mesenteric artery (SMA). The magnified field of vision and articulating instruments of the robotic platform allow for both careful identification and management of the GDA and inferior and superior pancreaticoduodenal arteries, as well as smaller jejunal branches, which are often taken with an energy device. Where possible, a clip is placed on the staying side of the pancreaticoduodenals on the SMA. Furthermore, the visualization of the robotic system also allows for thorough resection of perivascular and peripancreatic tissue on the plane of Leriche (Fig. 11.5), allowing for thorough oncologic resection. The approach of the vascular groove and retroperitoneal margin varies based on gland texture and vascular involvement. A soft gland allows for a “back and forth” approach from anterior to posterior utilizing primarily an energy device. Anything with SMV involvement or a very firm gland may necessitate an “artery first” approach from inferior to posterior. If there is SMA involvement, we prefer a “hanging maneuver,” where the SMV is dissected above and below the first jejunal, which is then taken with a stapler or energy device. The SMA is then dissected under the SMV from medial to lateral. The advantages of the robotic approach assist in meticulous resection, but further aid in reconstruction (Figs. 11.4 and 11.5).

The reconstructive process of PD is of utmost importance given the morbidity and mortality associated with anastomotic leakage and failure. We utilize a duct-to-mucosa fashion modified Blumgart pancreaticojejunostomy technique (Fig. 11.6) [22]. This two-layer anastomosis is typically constructed over a pancreatic duct stent (4, 5, or 7 French, Hobbs Medical, Stafford Springs, CT, USA). We use three 2-0 silk stitches on a V-20 needle for the outer layers and 5-0 monofilament sutures for the duct to mucosa stitches. We usually place 2 posterior and 2–5 anterior stitches depending on duct size. The hepaticojejunostomy or choledochojejustomy

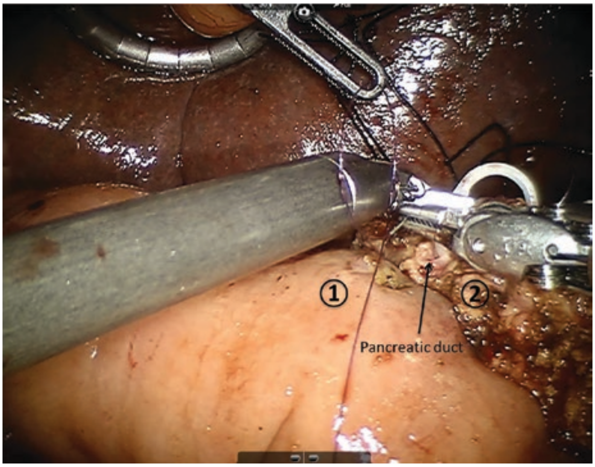

Fig. 11.6 Creation of pancreaticojejunostomy in modified Blumgart technique. The jejunum (1) is approximated to the pancreatic parenchyma (2) with 2-0 silk horizontal mattress sutures through the seromuscular layer of jejunum. Electrocautery is utilized to create a small enterotomy in the jejunum. Then, a duct-to-mucosa pancreaticojejunostomy is created using 5-0 PDS sutures over a Hobbs pancreatic stent (Hobbs Medical, Inc., Stafford Springs, CT, USA) to ensure duct patency. Finally, the anterior layer is created using 2-0 silk sutures to approximate the seromuscular layer of the jejunum to the pancreatic parenchyma

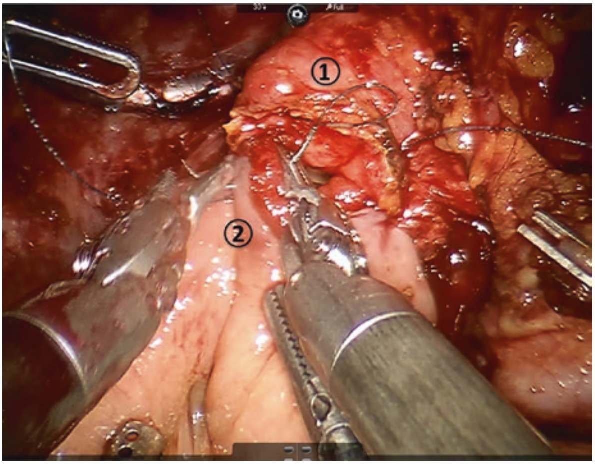

Fig. 11.7 Creation of the choledochojejunostomy. The common hepatic duct (1) is sutured to the jejunum (2) using interrupted absorbable 5-0 sutures for small ducts with or without a stent or running 4-0 V-LOC suture (Covidien, New Haven, CT, USA) for larger, thicker ducts (shown here)

is then created, and bile duct texture and size are considered in determining the technique employed: a running technique is used with larger, thicker bile ducts and an interrupted technique is utilized with smaller, softer ducts (Fig. 11.7). Next, the gastrojejunostomy or duodenojejunostomy is created. For the past year, we have used a stapled technique where we sew the common enterotomy in two layers. Previously, we had performed a two-layer gastrojejunostomy or duodenojejunostomy. The advantages of the robotic surgical platform allow for complete minimally invasive reconstruction, as the magnified view allows for identification of even the smallest pancreatic duct, and the articulating instruments allow for dexterity and precision of suture placement. Following creation of the anastomoses, a 19 French round surgical drain is placed anterior to the pancreaticojejunostomy and the hepaticojejunostomy and posterior to the gastrojejunostomy. We use the falciform to create a pedicled tissue flap to cover the GDA stump. We hope this creates a tissue barrier to protect the artery from pancreatic secretions in the setting of a leak.

Early Experience and Outcomes

Early experience with robotic-assisted PD, as with laparoscopic PD, began slowly with small case series (Table 11.1). As previously discussed, Giulianotti performed and reported the first series of eight robotic PD in 2003. This robotic group had a longer mean operative time compared to open PD (490 vs 250 min), but roughly equivalent morbidity and length of stay (37.5% vs 32.1% and 20 vs 18 days, respectively) [15]. Continued experience by the same surgeon, at hospitals both in Italy and Chicago, IL, USA, was reported as a series of 50 robotic PD, 30 in Italy and 20 in the United States. In this series, mean operative time was 421 min with a conversion rate of 18.3%. Notably, a pancreatic fistula rate of 31.3% was reported. However, this elevated fistula rate includes patients who had sclerosis of the pancreatic duct performed in place of an anastomosis. The fistula rate in patients who had a pancreatic duct anastomosis performed was equivalent to reported rates for open procedures at 21% [23]. The first series of 24 robotic-assisted PD performed at this institution similarly had a postoperative pancreatic fistula rate of 21%, with 8% clinically significant fistula (International Study Group on Pancreatic Fistula grade B/C) and 29% Clavien-Dindo grade 3–5 complication rate [16]. Another series of 44 robotic PD at the University of Illinois at Chicago published in 2011 [24] showed decreased EBL (387 vs 827 ml), as well as increased lymph node retrieval (16.8 vs 11) compared to the open group. Overall, complication rates, including pancreatic fistula were similar between groups, as was the R0 resection rate. Notably, in this series, patients undergoing robotic PD were significantly older (63 vs 56 years), had higher ASA classifications (2.5 vs 2.15) and had higher BMI (27.7 vs 24.8). Despite this seemingly more complicated patient population, operative time in the robotic group was significantly shorter, with a mean of 444 min compared to a mean time of 559 min in the open PD group [24]. These first series of robotic PD showed overall trends towards prolonged operative times with equivalent rates of postoperative pancreatic fistula, but were encouraging enough to continue perfecting the approach.

As experience with the robotic platform developed, larger operative series were reported. Another single surgeon series of 34 robotic PD in Italy showed prolonged mean operative time (597 min) and an excess cost of 55,400 USD (€6193) per patient [25]. This trend of increased operative time was seen in multiple studies, with mean operative times ranging from 431 to 718 min [26, 27, 29, 30]. Multiple series also

Table 11.1 Outcomes of early robotic-assisted pancreaticoduodenectomy (PD)

Study	Time frame	Patients (n)	Operative time (min)	EBL (ml)	Lymph node (n)	R0 rate (%)	POPF[a] (%)	Morbidity (%)	LOS (days)	30-Day mortality (%)
Giulianotti et al. [15]	10/00–11/02	8	490	–	–	–	–	37.5	20	12.5
Giulianotti et al. [23]	10/00–01/09	50 – 30 Italy – 20 USA	421 – 312 (Italy) – 351 (USA)	394 – 261 (Italy) – 323 (USA)	– 21 (Italy) – 14 (USA)	– 100 (Italy) – 79 (USA)	31.3 – 21 (PJ)	–	22 – 28.7 (Italy) – 12.5 (USA)	1.5
Buchs et al. [24]	01/02–05/10	44	444	387	16.8	90.9	18.2	36.4	13	4.5
Zureikat et al. [16]	10/08–02/10	24	512	320	–	–	21	– 33 Clavien 1–2 – 25 Clavien 3–4	9	4.2
Boggi et al. [25]	10/08–12/11	34	597	220	32	100	38.2	55.8 – 41.2 Clavien 1–2 – 14.7 Clavien 3–4	23	0
Zhou et al. [26]	01/09–12/09	8	718	153	–	100	50	25	16.4	0
Chalikonda et al. [27]	03/09–12/10	30	476	485	13.2	100	6.7	30	9.79	3.3
Chan et al. [28]	05/09–12/10	8	478	200	–	–	33.3	33	12	0
Lai et al. [29]	05/09–02/12	20	491.5	247	10	73.3	35	50	13.7	–
Bao et al. [30]	11/09–07/11	28	431	100	15	63	29	–	7.4	7 (90 days)

[a] POPF: postoperative pancreatic fistula

showed decreased EBL compared to classic open PD [26, 27, 29]. Oncologic parameters, such as R0 resection rate and lymph node harvest varied across series; most studies showed equivalent lymph node harvest (10 in both groups) [29] or greater yield (13.2 vs 11.76) [27], while a single series reported significantly lower lymph node retrieval (15 vs 20) [30]. Similarly, R0 resection rates were excellent with the robotic approach [26, 29]. A series of 50 patients undergoing robotic PD for periampullary lesions at our institution found that 73.3% of patients who met criteria for adjuvant chemotherapy were able to be treated within a mean of 11.5 weeks from surgery [31]. Most notably, postoperative complications were found to be equivalent [29] or decreased [26, 27] and most studies showed decreased length of postoperative length of stay, with mean hospital stays ranging from 9.7 to 16.4 days compared to 13.26–25.8 days [26, 27, 29].

Though these early small number series had variability in measured outcomes, overall trends suggested that robotic-assisted PD is at least equivalent to open PD in regard to oncologic outcomes, R0 resection rates, and lymph node harvest, as well as perioperative morbidity and mortality. Overall, complication rates, including postoperative pancreatic fistula rates similarly were typically equivalent to established open rates. Similar to other minimally invasive approaches, robotic PD was associated with decreased EBL. Though operative times were most often significantly increased, length of stay was generally shorter. Given early promising outcomes, robotic pancreatic resections, and PD in particular, have continued to expand in popularity.

Evolution of Experience: How Far Have We Come?

Initial approaches to robotic PD often began with smaller tumors with no evidence of vascular involvement so that techniques could be honed and skills could be developed. However, the success of these early surgeries allowed for further development of the procedure and application of the technique to a larger number of patients. The first reported robotic PD with vascular resection was described by Giulianotti and others in 2011, with two robotic-assisted PD with portal vein resections between 2007 and 2010: one with tangential vein resection and another with resection and reconstruction with a PTFE patch. These procedures were able to be completed in entirety utilizing a minimally invasive approach, with R0 resection in both and minimal EBL (150–200 ml), as well as no perioperative mortality. Furthermore, the operative time averaged 430 min (400–460 min), reflecting operative times for other robotic PD around the same time period [32]. Similarly, our group completed a series of 30 robotic PD in patients with aberrant or anomalous hepatic arterial anatomy diagnosed on preoperative triphasic computed tomography (CT) scans. Despite the anomalous arteries, all procedures were completed in a minimally invasive fashion, with a mean operative time of 501 min and a median EBL of 250 ml, which did not differ significantly from a robotic group with normal arterial anatomy during the same time period. Similarly, complications, including pancreatic fistula and 90-day mortality, were equal [33]. These studies showed that robotic-assisted PD was both feasible and also safe in the setting of vascular involvement and hepatic artery anomalies, leading to increased utilization of the approach.

Recently, larger series of robotic PD have been performed, and in some cases, matched to classic open PD to compare operative outcomes and cost (Table 11.2). A matched study of patients undergoing PD in Shanghai, China between 2010 and 2013 again found that patients undergoing robotic PD had decreased EBL (400 vs 500 ml) and shorter postoperative hospital stay (20 vs 25 days), with similar R0 resection rates, lymph node harvest, and postoperative morbidity and mortality rates. Oncological outcomes were also similar with no difference in disease-free survival (DFS) and overall survival (OS) between the approaches (DFS 14 vs 13 months, OS 23 vs 22 months). Again, this series did show prolonged operative times (410 vs 323 min); however, operative times decreased with building robotic operative experience: mean operative time from 2010 to 2012 was 445 min, but decreased to 340 min in 2013 for the robotic approach group. This study also further highlighted benefits of a minimally invasive operative approach, with

Table 11.2 Outcomes of recent robot-assisted pancreaticoduodenectomy (PD)

Study	Time frame	Patients (n)	Operative time (min)	EBL (ml)	Lymph node (n)	R0 rate (%)	POPF[a] (%)	Morbidity (%)	LOS (days)	30-Day mortality (%)
Zureikat et al. [34]	08/08–11/12	132	527	300	19	87.7	17	62.8 21% Clavien grade 3–4	10	1.5
Chen et al. [35]	01/10–12/13	60	410	400	13.6	97.8	13.3	35	20	1.7
Baker et al. [36]	08/12–07/13	22	454	425	–	77.8	4.6	40.9	7	0

[a] POPF: postoperative pancreatic fistula

earlier postoperative ambulation (3.2 vs 4.8 days), faster return of bowel function (3.6 vs 5.2 days), and less pronounced negative impact on postoperative nutritional laboratory studies [35].

The potential benefits of minimally invasive PD in terms of faster postoperative recovery have been demonstrated multiple times, but the prolonged operative times and the increased cost of the robotic operating platform, the robotic instruments, and increased operative time have led to questions about the cost-effectiveness of the approach. The financial impact of robotic-assisted PD was evaluated in a series of open and robotic PD by Baker and others in 2015 [36]. In comparing operative, postoperative and financial variables of 71 PD (22 robotic PD, 49 open PD), it was again found that robotic PD was associated with increased median operative time (454 vs 364 min), as well as increased operative costs (50,535 vs 32,309 USD). This was, however, offset by roughly equivalent postoperative inpatient costs (141,581 vs 136,246 USD) and decreased postoperative outpatient follow-up costs (283 vs 519 USD) in the robotic surgical groups, adding up to equivalent total costs with each surgical approach (142,149 vs 150,473 USD). The equivalency in total costs is likely reflective of the decreased overall complication rates (40.9% vs 67.4%) and decreased total number of complications per patient in the robotic group, as well as decreased need for ICU care in the robotic PD patients [36]. A similar trend in total operative cost was seen in the Shanghai series, with decreased postoperative costs (8529 vs 10,559 USD), but increased overall cost (19,755 vs 12,111 USD), likely reflecting the increased operating room cost for the robotic approach [35]. Though the robotic surgical platform itself and its instruments do lend to higher operative costs, the operative costs can be decreased as operating times decrease with increased experience.

The increased operative time of robotic PD has been shown in many series [15, 26, 27, 29, 30, 35, 36], but multiple studies have evaluated whether operative times decrease with increased experience on the robotic platform. As previously described, the Shanghai cohort saw a decrease in mean operative time from 445 to 340 min after their first 40 robotic PD cases, at which time the mean operative time approached the open PD time of 322–324 min. This improvement after the initial 40 procedures was also reflected in median EBL, which decreased from 500 to 200 ml

(500 ml for open PD group) [35]. Our group evaluated our first 200 consecutive robotic PD to determine if the learning curve for the technique could be identified. After the initial 20 robotic PD, there was significant improvement in both rates of conversion to open PD (35–3%) and EBL (600–250 ml). Postoperative pancreatic fistula rates decreased from 27.5 to 14.4% after the first 40 procedures, and the median number of lymph nodes harvested improved after 80 cases (17–26). Most notably, the mean operative time decreased significantly after the initial 80 cases (581–417 min) [37]. In analysis of 80 of our recent cases, median operating time is now 362 min, despite integration of surgical fellow trainees in performance of the procedure. Thorough quality analysis of our early robotic pancreatic experience identified significant improvements in most operative measures after the initial 80 cases, suggesting that benchmark as the number of procedures required to reach proficiency. This is similar to reports in open surgery showing a learning curve in excess of >60 cases before perioperative outcomes are improved. However, this robotic program was developed and implemented through an “on-the-job-training” model by innovative early adopting surgeons. Once our learning curve was met, emphasis focused on the necessary training to safely adopt the platform. A regimented “mastery learning” robotic hepatobiliary training program has been developed utilizing simulation, deliberate practice with inanimate modules, and operative coaching. We have seen tremendous success after 2 years of full integration, where novice hepatobiliary surgeons are able to reach their learning curve after 1 year of training followed by 3 months on service.

As has been described, multiple single center series have published promising outcomes of robotic PD over the last decade. A review of studies published before 2012 included 5 series of robotic PD, with 131 patients. The weighted mean operative time was 510 min and complications occurred in 38.9% of patients, with 26% postoperative pancreatic fistula and 2.3% mortality [38]. This review of the earliest reported robotic PD shows complication and mortality rates within established ranges for open PD with higher operative time. A meta-analysis of seven studies comparing robotic and open PD, including studies highlighted here [24, 26, 27], showed increased mean operation length in all robotic procedures, but significant heterogeneity (I^2 96%). Similarly, EBL and postoperative length of stay were decreased in all robotic groups compared to open, but data was again heterogeneous (I^2 92% and 47%, respectively). Significant risk reduction with robotic approach was found for multiple variables, including reoperation with 12% risk reduction (I^2 0%), positive margins with 18% risk reduction (I^2 0%), and overall complication rates with risk reduction of 12% (I^2 0%). These risk reductions in reoperation, R1 resections, and postoperative complications were seen without significant differences in postoperative pancreatic fistula and postoperative mortality rates [39].

The one variable that has consistently shown to be improved with robotic PD compared to the classical open approach is decreased intraoperative blood loss. This is likely due to the magnified binocular view that allows for easy identification and ligation of the small blood vessels around the uncinate process and retroperitoneal margin, which often account for significant operative blood loss. A multi-institutional study reviewing 700 open PDs for patients with pancreatic adenocarcinoma found that patients receiving any transfusion had decreased median disease-free (13.8 vs 18.3 months) and overall survival (14 vs 21 months). The effect of perioperative transfusion requirements on overall survival was further illustrated with a dose-dependent effect: median survival without blood transfusion, 1–2 units of blood, and >2 units of blood transfused was 21, 16, and 11.1 months, respectively. Also notably, intraoperative blood transfusion greater than 2 units and postoperative transfusions (1–2 units and >2 units) were both independent risk factors for decreased disease-free survival (HR 1.92, HR 1.55, and HR 2.06, respectively) [40]. Though blood transfusion requirements with robotic PD have been varied, most series show trends towards decreased perioperative transfusion rates when compared to the open approach [24, 30]. Decreased intraoperative blood loss with the robotic approach [24, 26, 27, 29, 30, 35, 36], combined with trends towards decreased blood transfusion requirements postoperatively may afford protection against the deleterious effects of transfusion.

These most recent series of robotic PD have shown that the procedure can be performed utilizing a robotic surgical platform and that acceptable oncologic outcomes can be achieved, with lymph node retrieval and R0 resection rates comparable to standard open approach. Similarly, rates of postoperative pancreatic fistula are also comparable. Some studies also show trends towards decreased postoperative complication rates with equivalent postoperative mortality. While median operative times remain longer than those of open PD, decreasing operative times, approaching open PD have been observed with higher volume centers. Similarly, operative costs associated with robotic approach tend to be higher; however, decreased length of postoperative stay and decreasing overall complications may allow for equivalent total costs for the procedure and subsequent hospitalization.

Conclusions

The robotic surgical platform offers unique advantages to the minimally invasive surgical approach with magnified binocular vision, articulating instruments, and elimination of surgeon tremor. These benefits help to overcome the challenges of laparoscopic pancreaticoduodenectomy, allowing for wide application of the minimally invasive approach. Robotic-assisted pancreaticoduodenectomy experience thus far has shown that the approach can be performed with equivalent oncologic measures, including lymph node retrieval and R0 resection rates. Similarly, postoperative morbidity, including pancreatic fistula rates, is equivalent or decreased compared to the classic open approach. Intraoperative blood loss is also decreased when robotic-assistance is employed. Though median operative times and operative costs are higher, operative times have decreased with increased experience with the approach, and decreased duration of postoperative hospitalization and decreasing complication rates may lead to equivalent overall costs. As minimally invasive surgery gains popularities in all surgical fields, especially in pancreatic surgery, it is paramount to ensure a structured training so that new generations of surgeons will master skills of minimally invasive pancreas surgery while still maintaining the tenets of open surgery. Furthermore, as with any new surgical technology, it is imperative to continue rigorous analysis of operative measures, postoperative morbidity and mortality, and oncologic measures of disease-free and overall survival.

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