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Mini-invasive Surgery

Review

Advances in pancreas surgery: robotic pancreaticoduodenectomy

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Abstract

Surgeon technical improvements made in the 1980s significantly decreased the morbidity and mortality associated with pancreaticoduodenectomy (PD). While minimally invasive surgery (MIS) is now the standard surgical approach for many benign and malignant pathologies, the technical complexity associated with PD presents many challenges to MIS adoption. However, advancements in robotic technology have done much to ameliorate mechanical impediments. Compared to laparoscopic surgery, the robotic platform provides surgeons with enhanced visualization, greater degrees of freedom and range of motion, tremor elimination, and superior ergonomic positioning. Although cost and availability concerns persist, training programs have increasingly incorporated robotic curricula, boosting the prevalence of robotic procedures, including robotic PD (RPD). While prospective data are limited, studies evaluating RPD demonstrate safety, equivalent short-term oncological outcomes, and longer operating times compared to open PD. Furthermore, exciting avenues exist for the future of RPD, ranging from continued instrument innovations to AI-enhanced adjuncts. Robotics has the potential to improve PD for patients and surgeons alike; however, further evaluation of oncologic and surgical outcomes requires well-powered, randomized, prospective trials to confirm the results of earlier retrospective studies, given the significant biases present. In this article, we review the progression of minimally invasive PD, present outcomes from studies evaluating RPD, and discuss areas of innovation for RPD.

Keywords: Pancreaticoduodenectomy, whipple, robotic surgery, robotic pancreaticoduodenectomy

INTRODUCTION

Pancreatic ductal adenocarcinoma (PDAC) remains one of the most lethal malignancies, with a 5-year overall survival rate of 11%[1,2]. By 2030, PDAC is expected to be the second leading cause of cancer-related mortality in the United States[3]. For patients with PDAC, complete surgical resection provides the only opportunity for long-term survival. Pancreaticoduodenectomy (PD), commonly referred to as the Whipple procedure, is the surgical procedure of choice for tumors in the head and/or uncinate process of the pancreas[4]. PD has undergone significant modification and refinement over the decades but remains a technically demanding procedure associated with significant morbidity.

In 1898, the first documented PD was performed by Dr. Alessandro Codivilla in Italy, and a successful resection of ampullary cancer was performed by his contemporary Dr. William Stewart Halsted in Baltimore[5]. The procedure was later modified by Dr. Walter Kausch to include en bloc resection of parts of the pancreas and duodenum in 1912[6]. The procedure was further developed by its namesake, Dr. Alan Oldfather Whipple, into a two-stage procedure in 1935 and finally into a one-stage procedure in 1940[6].

For much of the 20th century, PD-associated mortality prohibited wider adoption due to mortality rates of up to 25%. However, in the 1980s, advances in surgical technique and perioperative management led to a dramatic decrease in perioperative mortality and improved outcomes[7]. Today, patients treated at high-volume centers by experienced surgeons can expect post-operative mortality rates of less than 5%[8]. Despite improvements in mortality, PD is associated with post-operative morbidity rates of 30%-60%. Complications include delayed gastric emptying, pancreatic fistula (POPF), chyle leaks, anastomotic leaks, hemorrhage, surgical site infections, and intra-abdominal abscesses[9,10].

Minimally invasive techniques were first utilized in the approach to PD in 1994 when Ganger and Pomp reported the first totally laparoscopic PD (LPD)[11]. Less than a decade later, the first robotic PD (RPD) was performed by Giulianotti in Italy[12]. Today, due to the development and implementation of robotic training curricula in residency and fellowship programs, the prevalence of RPDs has significantly increased. While prospective randomized trials comparing the different approaches to PD are lacking, recent retrospective studies demonstrate that RPD can be performed safely with comparable outcomes in appropriately selected patients. In this article, we discuss the progression of minimally invasive PD, the available data on the different approaches to PD, and, finally, active areas of innovation involving RPD.

LAPAROSCOPIC PANCREATICODUODENECTOMY

Compared to open surgery, minimally invasive surgery (MIS) results in less post-operative pain, shorter length of stay, improved cosmetic results, and faster return to activities of daily life[13]. However, to access these benefits for patients, surgeons must develop entirely new skill sets to perfect laparoscopic techniques. Challenges include optimizing a 2-dimensional screen in a 3-dimensional field, using visual cues to overcome reduced tactile sensation, and suturing and dissecting with fewer degrees of freedom[14]. However, due to the integration of laparoscopic training curricula into residency and fellowship education, the innovation of more efficacious MIS instruments, and the refinement of MIS technique, the laparoscopic approach has become the standard of care for many surgical procedures including oncologic resections[15-19].

Unlike laparoscopic distal pancreatectomy, the standard of care approach for distal pancreatectomy in most patients, LPD has failed to gain similar traction among surgeons that perform PD aside from a few select institutions[20,21]. Two potential reasons to explain the lack of broader adoption of LPD include the challenging learning curve and unclear association with improved outcomes compared with open PD. First, the reported threshold for proficiency in LPD varies between studies, with some reports suggesting improved outcomes after 10 LPD cases; however, outcomes may not plateau until 50 cases[22,23]. In 2010, of the institutions with surgeons that actively performed LPD, only 8% performed at least 10 LPDs per year[24]. Therefore, even when a surgeon achieves proficiency with LPD, there may not be a sufficient case volume to maintain said proficiency. Second, the outcomes data are equivocal regarding the superiority of LPD compared to open PD. Early retrospective studies demonstrated shorter lengths of stay, decreased rates of complications, and oncologically safe outcomes[25,26]. Conversely, other studies suggested increased morbidity and mortality after LPD[24,27]. Recently, three randomized controlled trials published data comparing perioperative outcomes between open PD and LPD[28-30]. The first two published trials (PLOT and PADULAP) were single-institution studies, each involving two surgeons, that randomized 64 patients (32 LPD and 32 open PD) and 66 patients (34 LPD and 32 open PD), respectively[28,29]. Both studies demonstrated shorter lengths of hospital stay and longer operating times with LPD. While both studies showed equivalent oncologic outcomes between the two approaches, the PADULAP trial also showed better post-operative morbidity outcomes with LPD. Of note, only one patient required conversion to open in the PLOT trial, whereas eight patients (23.5%) were converted to an open approach in the PADULAP trial. The LEOPARD-2 trial was a multicenter, patient-blinded, randomized phase 2/3 trial involving four high-volume centers in the Netherlands[30]. After 99 patients underwent surgery, the study was terminated early due to higher 90-day complication-related mortality in the LPD group (five [10%] *vs.* 1 [2%]; $P = 0.20$), and no clear demonstrated advantage. There were no significant differences in time to functional recovery, Clavien-Dindo grade III or higher complications, or grade B/C POPF between the two approaches. Lower annual volume of LPDs at participating institutions during LEOPARD-2 (median 11) may partially explain the conflicting results compared to PLOT and PADULAP trials. While these studies provided prospective data, the generalizability of the results is limited by low enrollment, varying experience, or high approach conversion rates. A 2020 systematic review and meta-analysis of these randomized controlled trials revealed no statistically significant differences between either PD approach regarding the length of stay, post-operative complications, and mortality[31]. As it stands, LPD remains the dominant minimally invasive approach in areas where cost and availability limit alternative minimally invasive approaches.

ROBOTIC SURGERY

Dr. Kwoh performed the first robotic/computer-assisted surgery, a brain biopsy, with the PUMA 560 in 1985[32]. Private and government collaborations over the next decade led to many advances in robotic technology, culminating in Mona (Intuitive®), the first robotic surgical system to move to human trials. In 1997, Dr. Himpens, with Dr. Cardiere at the bedside operating the endoscopic camera, performed a cholecystectomy using the Mona robotic surgical system[33]. Despite the early success of the Mona system, certain limitations prohibited further implementation, which then informed the development of the da Vinci robotic system. Since receiving FDA approval for abdominal surgeries in July 2000, da Vinci iterations have expanded across the globe[34]. Their global reach even includes real-time tele-surgery, as was demonstrated in 2001 when a New York-based surgeon performed a tele-robotic cholecystectomy on a patient in Strasbourg, France[35].

Robotic surgery has multiple advantages compared to laparoscopic surgery. First, the instruments move in the same direction as the surgeon's hand, providing strong hand-eye coordination. As a result, the instruments more accurately function as an extension of the surgeon's hands rather than a device needing counterintuitive movements to get the desired effect. Second, the robotic platform eliminates physiologic tremors, both for the instruments and the camera, and provides greater degrees of freedom than the human hand. This allows for fine, precise movements performed with a greater range of motion. Third, the surgeon can have immediate control of up to three instruments. The surgeon also maintains control of the camera throughout the operation. Furthermore, the robotic camera uses a 3D high-definition camera with superior spatial awareness and visualization compared to laparoscopic cameras[36]. Fourth, dual console robotic platforms offer educational training advantages over other forms of MIS, such as expeditious instrument exchange between the primary surgeon and assistant, as well as an interactive screen to guide tissue plane and target identification. Finally, operating on the robotic console provides an ergonomically superior experience to both open and laparoscopic surgery for the surgeon[37].

However, robotic surgery has some notable hurdles to broader adoption. Significant upfront costs and maintenance fees are prohibitive for many institutions. Moving forward, device competition may drive down costs over the next decade as multiple robotic platforms enter the market[38]. Second, the absence of tactile sensation can lead to unintended instrument action and accidental patient injury, especially when the instrument is not within view[39]. Furthermore, despite technological advancements in the field, the sterilization of robotic tools with sodium hydroxide or sodium hypochlorite poses a challenge in the development of sensors able to withstand these corrosive chemicals[40]. Soon, emerging haptic innovations may provide solutions to resolve these force feedback issues[40]. Finally, the need for an accompanying legal framework for the robotic platform provides another logistical hurdle for any prospective institution looking to incorporate robotic surgery[41].

Despite these challenges, robotic surgery offers a novel evolution in MIS, providing many mechanical advantages over laparoscopic and even open surgery, expanding the indications for MIS, and improving patient outcomes for a variety of conditions. In healthcare settings with sufficient expertise and resources, robotic approaches have achieved broad adoption for many procedures in urology, colorectal surgery, cardiothoracic surgery, otolaryngology, and gynecology. As such, robotic surgery utilization is growing, while rates of laparoscopic procedures have stalled and, in some cases, decreased[42,43].

ROBOTIC PANCREATICODUODENECTOMY

In 2010, Giulianotti *et al.* published an early multi-institutional study of RPDs showing R0 resection rates and mortality rates comparable to open PD and LPD[44]. Despite these promising results, the rate of POPF was 31.3%, highlighting a clear area for improvement. Several other retrospective studies of RPD have been published since, demonstrating acceptable rates of POPF while achieving an adequate lymphadenectomy and acceptable mortality, morbidity, and margin-negative resection rates [Table 1][45-54]. A study by Nguyen *et al.* revealed that RPD was safe for patients with aberrant artery anatomy, such as a replaced or accessory left hepatic, right hepatic, or common hepatic artery[55]. Jin *et al.* reviewed PDs with venous resection and reconstruction (VR) in a single high-volume institution and found that RPD-VR had lower lymph node resections but no difference in 3-year survival rates, reconstructed venous patency, or post-operative mortality when compared to open PD-VR[56].

In general, retrospective studies comparing RPD to open PD demonstrate shorter length of hospital stay, less estimated blood loss, and longer mean operating times for RPD with comparable mortality, morbidity, POPF, and margin-negative resection rates[54,57-60]. Multiple studies using propensity score matching confirm these results for patients that underwent RPD[61-63]. Additional retrospective and non-randomized prospective studies have demonstrated comparable and even favorable outcomes with RPD compared to open PD [Table 2][64-72]. A recent meta-analysis by Fu *et al.* evaluated 21 studies comparing RPD to open PD, five of which contained patients with pancreatic cancer[73]. Their analysis demonstrated significantly longer operative times in RPD as well as less estimated blood loss, fewer overall complications, including POPF, shorter length of hospital stay, and lower 90-day mortality. While subgroup analysis was not performed due to the clumping of patients with multiple diseases in each study, the results suggest that RPD has a favorable short-term outcome profile compared to open PD in appropriately selected patients. Another recent meta-

Table 1. Surgical and oncologic outcomes of RPD

Author	N	EBL (mean in ml)	OR time (mean in minutes)	Con. (%)	LN (mean)	RORR (%)	POPF (%)	CS-POPF (%)	Morb. (%)	CDS ≥ III (%)	Mort. (%)	LOS (days)
Giulianotti *et al.*[44]	60	394	421	18.3	18.7	91.7	31.3	NR	NR	NR	3.3	22
Boggi *et al.*[48]	34	220	597	0	32	100%	38.2	11.7	55.8	11.7	2.9	23
Zureikat *et al.*[45]	132	300	527	8	19	87.7	17	7.4	62.7	21	1.5	10
Boone *et al.*[46]	200	250	483	6.5	22	92	17	8.5	67.5	26	3.3	9
Boggi *et al.*[49]	83	NR	527	1.5	37	87.5	36	28	73.5	9	1.5	17
Takahashi *et al.*[50]	65	150	498	3	17	98.5	11.6	9.2	30.8	10.7	0	7
Guerra *et al.*[51]	59	150	515	18.6	26	96	16.9	11.8	37.3	35.4	3	9
Rosemurgy *et al.*[52]	155	200	423	17	NR	NR	5	1.25	26	13*	6	5
Valle *et al.*[53]	39**	200	477	15.2**	23	90	7.6	7.6	38.4	17.8	2.5	10
Zureikat *et al.*[47]	500	363	415	5.2	28	87.8	20.8	7.8	68.8	24.8	3	8

CDS: Clavien dindo score; Con.: conversion to OPD; CS-POPF: clinically significant POPF, i.e., Grade B or C; EBL: estimated blood loss; LN: lymph nodes harvested; LOS: length of stay; Morb: morbidity; NR: not reported; N: number of patients that underwent RPD; OR: operating room; RORR: R0 resection rate; *percentage of serious complications as defined by ACS NSQIP; **conversions were excluded from the study group; the rest of the values are relative to the 39 remaining RPD patients.

analysis by Dong *et al.* focused on oncological outcomes in comparing RPD with open PD and found that R0 resection rates were significantly higher in RPD with non-inferior overall survival outcomes. In addition, RPD demonstrated lower wound infection rates, higher lymphadenectomy rates, and less estimated blood loss[74]. Furthermore, a review by Mantzavinou *et al.* showed that, compared to open PD, RPD had a higher therapeutic index, a calculated measure that includes lymphadenectomy rate, R0 resection rate, and 30-day mortality where higher values are associated with improved outcomes[75].

While the available evidence supports RPD utilization, challenges persist, limiting the widespread implementation of RPD. First, no appropriately powered randomized controlled trial exists directly comparing RPD to open PD. In 2020, the International Study Group on Minimally Invasive Pancreas Surgery published the first evidence-based guidelines on minimally invasive pancreas resection. In their publication, The Miami International Evidence-Based Guidelines on Minimally Invasive Pancreas Resection, the authors cite insufficient level 1 data to recommend minimally invasive PD over open PD[76]. However, the PORTAL trial, an active multicenter non-inferiority randomized controlled phase III trial in China, will compare open PD and RPD in over 225 patients with benign, premalignant, and malignant disease, with patient recruitment expected to have ended in December 2022[77]. The primary outcome is time to functional recovery with secondary outcomes of recurrence-free survival and overall survival. Second, despite the increasing presence of robotic surgery over the last two decades, costs remain high. Recurring maintenance fees and instrument costs add to the initial expenses associated with implementing a robotic surgery program[78]. Furthermore, generally longer operating times with RPD compared to open PD also drive up intraoperative costs[79,80]. However, after factoring in costs across a patient's totality of care, including post-operative care, net costs are not significantly different[79,81]. Third, the threshold of procedures needed to develop and maintain proficiency in RPD is not attainable at many centers since 82% of centers average less than 1 case

Table 2. Studies comparing RPD to Open PD

Author	N RPD *vs.* N OPD	EBL RPD *vs.* OPD (mean in ml) (*P*-value)	OR time RPD *vs.* OPD (mean in minutes) (*P*-value)	LN RPD *vs.* OPD (mean) (*P*-value)	R0RR RPD *vs.* OPD (%) (*P*-value)	POPF RPD *vs.* OPD (%) (*P*-value)	CS-POPF RPD *vs.* OPD (%) (*P*-value)	Morb. RPD *vs.* OPD (%) (*P*-value)	CDS ≥ III RPD *vs.* OPD (%) (*P*-value)	Mort. RPD *vs.* OPD (%) (*P*-value)	LOS RPD *vs.* OPD (days) (*P*-value)
Zhou *et al.*[57]	8 *vs.* 8	153 *vs.* 210 (P = 0.045)	718 *vs.* 420 (P = 0.011)	NR	87.5 *vs.* 100 (P = 0.05)	50 *vs.* 37.5 (P = 0.05)	0 *vs.* 12.5 (NR)	25 *vs.* 75 (P = 0.05)	NR	0 *vs.* 12.5 (P = 0.05)	16.4 *vs.* 24.3 (P = 0.04)
Buchs *et al.*[58]	44 *vs.* 39	387 *vs.* 827 (P < 0.01)	444 *vs.* 559 (P < 0.01)	16.8 *vs.* 11 (P = 0.02)	90.9 *vs.* 81.5 (P = 0.45)	18 *vs.* 20.5 (P = 1.00)	50 *vs.* 37.5 (NR)	36.4 *vs.* 48.7 (0.27)	NR	4.5 *vs.* 2.6 (P = 1.00)	13 *vs.* 14.6 (P = 0.4)
Chalikonda *et al.*[64]	30 *vs.* 30	485 *vs.* 775 (P = 0.13)	476 *vs.* 366.4 (P < 0.01)	NR	0 *vs.* 13 (P = 0.02)	6.7 *vs.* 16.7 (NR)	6.7 *vs.* 16.7 (NR)	30 *vs.* 44 (P = 0.14)	NR	1 *vs.* 0 (P = 0.09)	9.8 *vs.* 13.3 (P = 0.043)
Lai *et al.*[59]	20 *vs.* 67	247 *vs.* 775 (P = 0.03)	492 *vs.* 265 (P = 0.01)	10 *vs.* 10 (P = 0.99)	73.3 *vs.* 64.1 (P = 0.92)	35 *vs.* 17.9 (P = 0.11)	NR	50 *vs.* 49.3 (P = 0.95)	NR	0 *vs.* 3 (P = 0.43)	13.7 *vs.* 25.8
Chen *et al.*[65]	60 *vs.* 120	*400 *vs.* 500 (P < 0.01)	*410 *vs.* 323 (P < 0.01)	13.6 *vs.* 12.5 (P = 0.350)	**94.7 *vs.* 92.1 (P = 1.00)	13.3 *vs.* 24.2 (P = 0.09)	8.3 *vs.* 15.0 (NR)	35 *vs.* 40 (P = 0.515)	11.7 *vs.* 13.3 (P = 0.752)	1.7 *vs.* 2.5 (P = 1.00)	20 *vs.* 25 (P < 0.01)
Zureikat *et al.*[54]	211 *vs.* 817	200 *vs.* 300 (P < 0.01)	402 *vs.* 300 (P < 0.01)	27.5 *vs.* 19 (P < 0.01)	R1RR: 50 *vs.* 31 (P < 0.01)***	NR	13.74 *vs.* 9.04 (P = 0.04)	NR	23.7 *vs.* 23.9 (P = 0.96)	1.9 *vs.* 2.89 (P = 0.46)	8 *vs.* 8 (P = 0.98)
Boggi *et al.*[49]	83 *vs.* 36	NR	527 *vs.* 425 (P < 0.01)	37 *vs.* 36 (P = 0.51)	87.5 *vs.* 54.5 (P = 0.08)	33.8 *vs.* 16.7 (P = 0.06)	18.1 *vs.* 5.6 (NR)	73.5 *vs.* 77.9 (P = 0.62)	18.1 *vs.* 11.2 (NR)	2.4 *vs.* 0 (P = 1.00)	17 *vs.* 14 (P = 0.06)
Wang *et al.*[63]	87 *vs.* 87ˆ	202 *vs.* 298 (P < 0.01)	455 *vs.* 375 (P < 0.01)	15 *vs.* 13 (P < 0.01)	96.6 *vs.* 94.3 (P = 0.363)	NR	8 *vs.* 12.6 (P = 0.456)	43.7 *vs.* 53.2 (P =0.612)	9.1 *vs.* 8.0 (NR)	0 *vs.* 0	24 *vs.* 24 (P = 0.884)
Varley *et al.*[66]	133 *vs.* 149	200 *vs.* 500 (P < 0.01)	393 *vs.* 432 (P < 0.01)	NR	82% *vs.* 81% (P = 0.851)	12 *vs.* 24 (P = 0.013)	5 *vs.* 18 (P < 0.01)	NR	24 *vs.* 28 (P = 0.464)	3.8 *vs.* 5.4 (P = 0.52)	8 *vs.* 10 (P < 0.01)
Girgis *et al.*[67]	163 *vs.* 198	250 *vs.* 500 (P < 0.01)	402 *vs.* 421 (P = 0.081)	31.9 *vs.* 25.9 (P < 0.01)	82.5 *vs.* 82.3 (P = 0/055)	NR	NR	NR	24.5 *vs.* 29.8 (P = 0.265)	4.29 *vs.* 4.55 (P = 0.908)	7 *vs.* 9 (P < 0.01)
Jin *et al.*[62]	22 *vs.* 22ˆ	75 *vs.* 300 (P < 0.01)	225 *vs.* 275 (P = 0.294)	3.5 *vs.* 1 (P = 0.205)	100 *vs.* 100 (NR)	68.2 *vs.* 68.2 (NR)	9.1 *vs.* 18.2 (P = 0.0664)	NR	9 *vs.* 4.5 (P = 1.00)	NR	15 *vs.* 19 (P = 0.493)
Mejia *et al.*[68]	102 *vs.* 54	321 *vs.* 378 (P = 0.121)	353 *vs.* 212 (P < 0.01)	24.2 *vs.* 23.7 (P = 780)	66.7 *vs.* 70 (P = 0.663)	4 *vs.* 0 (NR)	4 *vs.* 0 (NR)	14.7 *vs.* 37.0 (NR)	9.3 *vs.* 5.9 (NR)	3 *vs.* 2 (NR)	7 *vs.* 11.8 (P < 0.01)
Shi *et al.*[61]	187 *vs.* 187ˆ	297 *vs.* 415 (P < 0.01)	279 *vs.* 298 (P = 0.02)	16.6 *vs.* 15.8 (P = 0.495)	94.7 *vs.* 93 (P -0.68)	NR	10.2 *vs.* 14.4 (P = 0.09)	NR	NR	2.1 *vs.* 3.7 (P = 0.47)	22.4 *vs.* 26.1 (P = 0.03)
Nassour *et al.*[70]	626 *vs.* 17,205	NR	NR	22 *vs.* 17 (P < 0.01)	77 *vs.* 78 (NR)	NR	NR	NR	NR	4 *vs.* 6 (P = 0.061)	10 *vs.* 11 (P < 0.01)
Nassour *et al.*[69]	155 *vs.* 3,329	NR	NR	30 *vs.* 18 (P < 0.01)	79 *vs.* 84 (NR)	NR	NR	NR	NR	3.4 *vs.* 2.6 (P = 0.570)	8 *vs.* 10 (P < 0.01)
Shyr *et al.*[60]	304 *vs.* 172	197 *vs.* 531	468 *vs.* 438 (P = 0.015)	18 *vs.* 18 (P =	NR	NR	13 *vs.* 11.2 (P =	48.2 *vs.* 56.8	12.3 *vs.* 8.3 (NR)	2.1 *vs.* 1.8 (P =	20 *vs.* 24 (P =

		(P < 0.01)		0.652)			0.659)	(P = 0.040)		1.00)	0.014)
Weng *et al.*[71]	105 *vs.* 210	300 *vs.* 300 (P = 0.567)	300 *vs.* 300 (P = 0.365)	11 *vs.* 11 (P = 0.622)	88.6 *vs.* 89 (P = 0.899)	13.3 *vs.* 16.7 (P = 0.442)	5.7 *vs.* 6.4 (P = 0.744)	NR	29.5 *vs.* 27.6 (P = 0.723)	1 *vs.* 1 (P = 1.00)	17 *vs.* 17 (P = 0.716)
Meyyappan *et al.*[72]	116 *vs.* 74	17.2% *vs.* 34.3%**** (P < 0.01)	386 *vs.* 388 (P = 0.896)	NR	93.1 *vs.* 93.2 (NR)	25.9 *vs.* 39.2 (P = 0.053)	8.6 *vs.* 25.7 (P < -0.01)	NR	28.3 *vs.* 40.5 (P = 0.011)	NR	NR

CDS: Clavien dindo score; CS-POPF: clinically significant POPF, i.e., Grade B or C; EBL: estimated blood loss; LOS: length of stay; LN: lymph nodes harvested; Morb: morbidity; Mort: mortality within 90 days post-op; NR: not reported; N: number of patients; OR: operating room; POPF: post-operative pancreatic fistula; R0RR: R0 resection rate; *median; **Pancreatic ductal adenocarcinoma sub-group; ***on multivariate analysis; the operative approach was NOT independently associated with R1 resection rates; ****reported as a percentage of patients with EBL > 500mL; ^propensity score matched.

per year[82]. Proposed thresholds for RPD proficiency vary significantly between studies, with some studies recognizing notable improvements even after 200 cases[47,83]. Over the last decade, academic and high-volume centers have integrated robotic pancreas training programs into their training curriculum[84]. These efforts have helped strengthen the RPD technique in new surgeon graduates and overcome some initial trepidation towards minimally invasive pancreatic surgery. This is a contributing factor to the steady increase in the number of RPDs performed each year[85].

FUTURE OUTLOOK FOR ROBOTIC PANCREATICODUODENECTOMY

The future for RPD, and for robotic surgery as a whole, is bright. Technological advancements have greatly advanced the field of robotic surgery, with many exciting innovations currently in development. One such area involves haptic technology. Initial iterations of robotic platforms contained varying degrees of haptic feedback. Unfortunately, the haptic technology at the time inadequately detected contact with soft tissue and hindered surgeon performance[86]. Surgeons reported that visual cues more aptly assisted them in determining tissue tension and pressure than haptic feedback. As a result, haptic technology was largely abandoned. Recently, advances in tactile sensors may help overcome prior haptic limitations. Emerging microfluidic-based sensors may improve tissue grasping and manipulation tasks by conforming to the surface of the instrument, thus increasing contract friction allowing for stable grasping with a smaller exertional force and detection of mechanical properties[40].

While fully autonomous surgery is not currently possible, areas of active investigation have demonstrated significant progress toward this goal using artificial intelligence (AI)-based technology such as machine learning (ML), computer vision, and natural language processing[87,88]. Current applications of AI in MIS include surgical phase recognition, instrument recognition, gesture and error recognition, and autonomic landmark recognition[89]. The Smart Tissue Autonomous Robot (STAR) incorporates many of these AI-based technologies and has demonstrated some of the most autonomous robotic surgical skills to date[90,91]. In a porcine model, STAR performed a minimally invasive small bowel anastomosis completing 83% of the suturing tasks autonomously while outperforming surgeons in consistency of suture spacing, bite depth, and hesitancy events[90].

Finally, by superimposing images onto organs during surgery, augmented reality (AR) has demonstrated feasibility in the operating room. In liver surgery, AR allows the surgeon to see the tumor and the relationships to major intra-parenchymal vasculature in real time[92]. In PD cases, AR can assist with margin-negative resection during superior mesenteric vein resection and reconstruction, as well as identification of the inferior pancreaticoduodenal artery in an artery-first approach for PD[93,94].

CONCLUSIONS

In conclusion, through the development of more efficient and advanced technology, RPD continues to surmount the technical challenges that previously limited the progression of minimally invasive pancreatic surgery. Active prospective randomized control trials will help elucidate the relationship between RPD and surgical outcomes. Continued development and implementation of educational curricula for residency and fellowship training programs is critical to the expansion and improvement of robotic surgery. Finally, advancements in AI offer innovative solutions to reduce errors and improve outcomes.

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Authors' contributions

Design, literature research and review, critical review of the manuscript, final approval: Riachi ME, Hewitt DB
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