Surgical Endoscopy (2025) 39:3921–3929
https://doi.org/10.1007/s00464-025-11768-4

Reduced pancreatic fistula rates and comprehensive cost analysis of robotic versus open pancreaticoduodenectomy

Taiga Wakabayashi[1] · Federico Gaudenzi[1] · Yusuke Nie[1] · Kohei Mishima[1] · Yoshiki Fujiyama[1] · Kazuharu Igarashi[1] · Yu Teshigahara[1] · Sho Mineta[2] · Emre Bozkurt[3] · Go Wakabayashi[1]

Received: 21 January 2025 / Accepted: 16 April 2025 / Published online: 12 May 2025

Abstract

Background Robotic pancreaticoduodenectomy (RPD) has emerged as a promising surgical approach for the treatment of periampullary neoplasms, offering the potential benefits of minimally invasive surgery. However, the impact of RPD on clinically relevant pancreatic fistula (CR-PF) rates and overall costs compared to open pancreaticoduodenectomy (OPD) remains unclear, limiting its widespread adoption.

Methods This retrospective cohort study was conducted at a high-volume Japanese referral center from 2017 to 2023. A total of 193 patients diagnosed with periampullary neoplasms underwent either RPD ($n = 81$) or OPD ($n = 112$). To account for potential selection bias, propensity score matching (PSM) was used to balance patient demographics and clinical characteristics, resulting in two well-matched groups of 60 patients each. Perioperative outcomes, CR-PF rates, and a comprehensive cost analysis were evaluated.

Results RPD resulted in a significantly lower rate of CR-PF (10%) compared to OPD (33.3%) ($p = 0.003$). Additionally, patients who underwent RPD experienced shorter hospital stays (15 days) compared to those in the OPD group (22.5 days) ($p < 0.001$). Despite longer operative times for RPD (633 vs. 395 min; $p < 0.001$), total hospital costs were comparable between the two groups. The higher operative costs associated with RPD were offset by reduced postoperative complications and shorter hospitalization.

Conclusions RPD offers significant clinical advantages, including lower CR-PF rates and reduced hospital stays, without increasing overall hospital costs compared to OPD. These findings support the feasibility and potential benefits of adopting RPD for the management of periampullary neoplasms in clinical practice.

Keywords Robotic pancreaticoduodenectomy · Open pancreaticoduodenectomy · Pancreatic fistula · Periampullary neoplasms · Cost analysis · Postoperative outcomes

Taiga Wakabayashi and Federico Gaudenzi have contributed equally to this work and share the first authorship.

Meeting Presentation: Presented at the 37th Annual Meeting of the Japan Society for Endoscopic Surgery, Fukuoka, Japan, July 2024.

✉ Taiga Wakabayashi
taiga.wakabayashi@me.com

[1] Center for Advanced Treatment of Hepatobiliary and Pancreatic Diseases, Ageo Central General Hospital, 1-10-10 Kashiwaza, Ageo, Saitama 362-8588, Japan

[2] Department of Surgery, Chiba Tokushukai Hospital, Chiba, Japan

[3] Department of General Surgery, Koç University School of Medicine, Istanbul, Turkey

Abbreviations

RPD	Robotic pancreaticoduodenectomy
OPD	Open pancreaticoduodenectomy
CR-PF	Clinically relevant pancreatic fistula
PJ	Pancreaticojejunostomy
HJ	Hepaticojejunostomy
GJ	Gastrojejunostomy
PDAC	Pancreatic ductal adenocarcinoma
ISGPS	International Study Group of Pancreatic Surgery
DGE	Delayed gastric emptying
PPH	Postpancreatectomy hemorrhage
PSM	Propensity score matching
ICU	Intensive care unit
DPC/PDPS	Diagnosis Procedure Combination/Per-Diem Payment System

DRG/PPS	Diagnosis-Related Group/Prospective Payment System
CUSUM	Cumulative Sum

While robotic pancreaticoduodenectomy (RPD) has gained increasing adoption for patients with periampullary neoplasms in recent years, it has not yet become the universal standard. The initial report by Prof. Giulianotti in 2003 [1, 2] marked the beginning of this approach, and subsequent studies have confirmed its feasibility and safety in selected patient cohorts, comparing it to open pancreaticoduodenectomy (OPD) [3–5]. Although RPD adoption is expanding, its role as a standard of care remains under discussion, and further evidence is needed to establish its superiority over OPD.

While RPD may entail longer operative times, we hypothesized that the high level of precision offered by the robotic platform during the reconstruction phase, especially concerning the pancreaticojejunostomy (PJ), may reduce clinically relevant pancreatic fistula (CR-PF), offering benefits such as a shorter hospital stay without increasing the total in-hospital charges. Previous studies have suggested that RPD may reduce the incidence of CR-PF, but solid empirical evidence remains limited [6]. Inconsistent pancreaticoenteric reconstruction techniques across studies, often due to multicenter designs or variability among surgeons, further complicate comparisons.

At our institution, the RPD program began in 2017 under the proctorship of Prof. Giulianotti [7–9]. Since then, we have consistently used a standardized robotic pancreaticojejunostomy (PJ) with a modified Blumgart anastomosis (MBA) for over eight years [10, 11]. This single-center approach helps reduce variability in perioperative care and allows for a more direct comparison with OPD. We hypothesize that the precision of robotic techniques may contribute to lower CR-PF rates.

Furthermore, in recent years, a common belief has emerged within the surgical community that RPD is more expensive than open surgery due to the use of multiple robotic and laparoscopic instruments. However, the economic implications of these two techniques (RPD vs. OPD) remain underexplored. Previous investigations have been limited, including a small retrospective cohort study with fewer than 100 cases and a systematic review with meta-analysis, which was hindered by significant heterogeneity in the included studies that grouped laparoscopic and robotic procedures under the broad term "minimally invasive surgery" [12, 13]. Therefore, another key aim of the present study was to provide a direct cost comparison of RPD and OPD within the context of high-volume centers in regions where healthcare systems and resource utilization may differ from Western models.

Materials and methods

Study design and setting

This was a retrospective single-center study of consecutive patients underwent RPD or OPD, between January 2017, when our RPD program begun, and December 2023. Clinical data were retrospectively collected from the prospective database at our center. This study was approved by the institutional review board of Ageo Central General Hospital and followed the principles of the Declaration of Helsinki. Due to the retrospective design of the study, patient consent requirements were waived.

Surgical technique

RPD setup and procedure

RPD was performed under the supervision of a single proctor using a dual-console system. Patients were placed in lithotomy position, pneumoperitoneum was established via a Veress needle, and robotic ports were positioned accordingly. The da Vinci Surgical System™ was used, and the resection phase mirrored the OPD technique (Online Video 1). Hemostasis was primarily achieved through suturing and coagulation; however, SURGICE NU-KNIT™ (Ethicon, Inc., Raritan, NJ, USA) was occasionally used when necessary.

Reconstruction

PJ, hepaticojejunostomy (HJ), and gastrojejunostomy (GJ) were performed using a standardized approach. PJ was performed using an MBA technique (Online Video 2). HJ was sutured with 5/0 PDS, and GJ was stapled with the entry hole closed by barbed suture.

Patient selection and variables

Prior to insurance coverage in 2020, RPD was indicated for distal cholangiocarcinoma, ampulla of Vater carcinoma, IPMN, and similar conditions. After 2020, pancreatic ductal adenocarcinoma (PDAC) was also included. As our surgical team gained experience, the selection criteria for RPD evolved. Initially, RPD was limited to low-risk cases, but over time, it was expanded to include more complex cases. Patients requiring vascular resection were primarily treated with OPD, while other cases were managed with RPD. While vascular resection cases are still preferentially treated with OPD, some are now selectively considered for RPD. Additionally, tumors with significant fibrosis or adhesion risks are carefully evaluated for feasibility. The RPD group included conversions to open surgery due to factors like vascular resection, multivisceral resection, or limited workspace. The indication for resection as the preferred treatment approach for each patient was based on established Japanese clinical guidelines [14]. Preoperative diagnoses were classified as PDAC, pancreatitis (low risk of fistula), or other conditions. CR-PF was defined as grade B or C pancreatic fistula based on the International Study Group of Pancreatic Fistula (ISGPF) criteria [15, 16]. Surgical procedures were categorized into four groups following Büchler's classification [17]. Pancreatic duct diameter was measured intraoperatively and classified as > 5 mm (low risk of fistula) or ≤ 5 mm. Lymph nodes were classified according to the Japan Pancreas Society's 7th/8th edition [14]. Postoperative morbidity within 30 days was graded using the Clavien-Dindo system (CD ≥ 3 for severe complications) [18]. Mortality was recorded at 30 and 90 days. Pancreas-specific complications, including CR-PF, delayed gastric emptying (DGE), and postpancreatectomy hemorrhage (PPH), were graded per ISGPS criteria. Biliary fistula was defined using ISGLS criteria [15, 16, 19–21]. The primary endpoint was CR-PF incidence. Secondary endpoints included surgical outcomes, 30- and 90-day mortality, pathological data, and operative and total hospital costs.

Charges for pancreaticoduodenectomy recording

We analyzed cost data from consecutive patients treated between April 2020 and December 2023, after the implementation of insurance coverage for RPD in Japan. This study aimed to compare total charges and operating room costs between RPD and OPD, with a detailed breakdown of operative and non-operative costs.

Operative costs

Operative costs encompassed all expenses directly related to the surgical procedure. Surgical equipment costs included both disposable and reusable instruments. Disposable instruments were priced based on market rates, while reusable instruments were calculated by dividing their original purchase price by the expected number of uses. Personnel costs were determined using the average hourly wages of attending surgeons and nurses, multiplied by the total operative time. Operating room maintenance expenses were primarily calculated from electricity costs, which were estimated based on per-minute usage during surgeries. This data was derived from a two-week observation of operating room electricity consumption and scaled to the duration of each procedure. Robotic platform costs included the acquisition, maintenance, and depreciation of the robotic system. These costs were combined and divided by the average monthly usage across all departments to calculate the per-case expense.

Non-operative costs

Non-operative costs included all charges associated with hospitalization, covering both pre- and postoperative care. Personnel costs were calculated by multiplying the daily wages of nutritionists, pharmacists, two attending physicians, nurses, and radiology technicians by the patient's length of stay. Physician costs were further refined by dividing daily compensation by the average number of patients managed by each doctor. Hospital fees encompassed bed charges, utilities, and general inpatient services, which were calculated based on standard daily inpatient costs. Medical services, including diagnostic tests, therapeutic procedures, and postoperative care, were factored into the total hospitalization charges. These services covered a range of activities such as drug administration, laboratory tests, imaging, and any necessary interventions for postoperative complications.

Special considerations for comprehensive cost analysis

Electricity costs were derived from the average electricity usage of an operating room over a two-week period and scaled to reflect the surgical durations. Additionally, certain costs, such as bed charges and facility fees, were calculated based on billed amounts (equivalent to reimbursement rates) rather than direct expenses, aligning with the reimbursement structure of the Japanese healthcare system. This cost analysis provides a detailed comparison of operative and non-operative expenses for RPD and OPD. By incorporating surgical equipment, personnel costs, robotic system expenses, and hospitalization-related charges, this study offers valuable insights into the economic implications of these surgical approaches in Japan.

Statistical analysis

Patients were stratified into two groups based on surgical technique (RPD vs. OPD), and baseline characteristics and outcomes were compared before and after propensity score matching (PSM). Subgroup analysis was performed using PSM after excluding converted cases in the RPD group. Normality of continuous variables was assessed by visually inspecting histograms and Q-Q plots. Non-normally distributed continuous data were expressed as medians with interquartile ranges (IQR) and compared using the Mann–Whitney U test. Categorical data were expressed as percentages and compared using the chi-square test or Fisher's exact test, as appropriate.

To minimize potential confounders, covariates for PSM included age, American Society of Anesthesiologists (ASA) classification, type of pancreaticoduodenectomy, pathology, preoperative albumin level, and blood loss. The diameter of the main pancreatic duct was categorized as < 5 mm or ≥ 5 mm [17]. Patients in the RPD group were matched to OPD patients using 1:1 nearest-neighbor matching without replacement and a caliper width of 0.2. Balance between groups was assessed using standardized differences (SD), with SD < 0.1 indicating optimal balance. After matching, categorical data were compared using McNemar's test, and continuous data were compared using the Wilcoxon signed-rank test.

Learning curves for operative time and robotic PJ in RPD were evaluated using Cumulative Sum (CUSUM) analysis. CUSUM analysis calculated cumulative deviations from the cohort mean, and a pooled CUSUM plot illustrated the performance trends to determine the number of procedures required to achieve proficiency.

Single imputation based on the median was used to address missing data for blood loss, as this was not a primary outcome measure. Main outcome data were not imputed. Statistical analyses were performed using SPSS Statistics® version 28.0 (IBM, Armonk, NY, USA) and R for Mac OS X version 4.2.1, with the MatchIt package for PSM [22]. CUSUM analysis was conducted using JMP version 11 (SAS Institute, Cary, NC, USA). Statistical significance was set at a two-tailed p value of < 0.05.

Results

A total of 193 patients were included, with 112 undergoing OPD and 81 undergoing RPD.

Patient demographics and perioperative outcomes before PSM

The RPD group had a lower incidence of PDAC compared to the OPD group (23.5% vs. 46.9%, $p < 0.001$). Concomitant vascular or multivisceral resection was less frequent in the RPD group (8.6% vs. 29.5%, $p < 0.001$). Other demographic characteristics were comparable between the groups (Table 1).

Regarding perioperative outcomes, the RPD group had significantly less blood loss (median 175 vs. 386 ml, $p < 0.001$) but longer operative time (median 639 vs. 419 min, $p < 0.001$). The length of hospital stay was shorter in the RPD group (median 14.5 vs. 21 days, $p < 0.001$). The RPD group also had lower rates of major complications (19.8% vs. 35.7%, $p = 0.024$) and CR-PF rates (8.6% vs. 32.1%, $p < 0.001$) (Table 2).

Two cases in the RPD group required conversion to open surgery: one due to the need for portal vein resection and the other due to limited workspace. Although not statistically significant, the converted cases had higher rates of major complications (50% vs. 18.9%, $p = 0.358$) and longer hospital stays (median 29.5 vs. 14 days, $p = 0.266$) (Table S1).

Patient demographics and perioperative outcomes after PSM

After propensity score matching (PSM), 60 RPD cases were matched with 60 OPD cases, achieving well-balanced covariates (Fig. S1). Operative time remained longer in the RPD group (median 633 vs. 395 min, $p < 0.001$). Postoperative length of stay was still shorter for RPD (median 15 vs. 22.5 days, $p < 0.001$). Although major complication rates were similar between groups, the CR-PF rate remained significantly lower in the RPD group (10% vs. 33.3%, $p < 0.001$) (Table 2).

Excluding converted cases, 57 patients in each group were compared. The RPD group continued to show shorter hospital stays (median 14 vs. 21 days, $p < 0.001$) and lower rates of major complications (21% vs. 42.2%, $p = 0.026$) and CR-PF (10.5% vs. 40.4%, $p < 0.001$).

Learning curve analysis

In all RPD cases, a chief surgeon (GW), who had surpassed the OPD learning curve, acted as the primary or mentoring console surgeon. CUSUM analysis showed that operative time and robotic pancreaticojejunostomy (PJ) time improved after 18 and 20 cases, respectively (Fig. S2a, 2b). The resection phase demonstrated a bimodal distribution (Fig. S2c).

Comprehensive cost analysis

Cost analysis included 62 RPD patients (76.5%) and 83 OPD patients (74.1%). The in-hospital total charges for RPD and OPD were comparable (median 1,842,642 JPY [~ 12,509 USD, ~ 11,500 EUR] vs. 1,850,656 JPY [~ 12,564 USD, ~ 11,548 EUR], $p = 0.376$), despite higher operating room costs for RPD (986,472 JPY [~ 6,696 USD, ~ 6,155 EUR] vs. 437,401 JPY [~ 2,969 USD, ~ 2,731 EUR], $p < 0.001$). After PSM, total in-hospital charges remained similar between RPD and OPD (median 1,876,564 JPY [~ 12,741 USD, ~ 11,726 EUR] vs. 1,850,656 JPY [~ 12,564 USD, ~ 11,548 EUR], $p = 0.212$) (Table 3). Currency conversion was based on the exchange rates as of March 11, 2025 (1 USD = 147.37 JPY, 1 EUR = 160.85 JPY).

Table 1 Baseline, intraoperative and oncological characteristics of patients undergoing robotic and open pancreatoduodenectomy

	Overall			After PSM		
	RPD	OPD	*p*	RPD	OPD	*p*
	n = 81	*n* = 112		*n* = 60	*n* = 60	
Baseline patient characteristics						
Age, years	73 [13]	75 [9]	**0.175**	73 [13]	76 [10]	**0.063**
Sex, male	54 (66.7)	74 (66.1)	**0.931**	37 (61.6)	40 (66.7)	**0.703**
BMI, kg/m^2	22.9 [3.6]	22.1[4.05]	**0.050**	22.8 [3.3]	22.2 [4.02]	**0.210**
ASA grade						
ASA 1	6 (7.4)	3 (2.7)		4 (6.6)	2 (3.4)	
ASA 2	69 (85.2)	92 (82.1)		51 (85)	54 (90)	
ASA 3	6 (7.4)	17 (15.2)		5 (8.4)	4 (6.6)	
ASA 4	0 (0)	0 (0)	**0.095**	0 (0)	0 (0)	**0.713**
Preoperative diagnosis†						
PDAC	19 (23.5)	53 (47.4)		17 (28.3)	23 (38.3)	**0.332**
Other	62 (76.5)	59 (52.6)	**< 0.001***	43(71.7)	37 (61.7)	
Distal CCa	28 (34.6)	25 (22.3)		16 (26.7)	14 (23.3)	
Vater Ca	13 (16.0)	10 (8.9)		9 (15)	7 (11.7)	
IPMN/C	10 (12.3)	10 (8.9)		8 (13.3)	5 (8.4)	
Others	11 (13.6)	14 (12.5)		10 (16.7)	11(18.3)	
Tumor size, (millimeters)	29 [24.5]	27.5 [16.5]	**0.544**	29 [21.5]	25 [13]	**0.426**
Neoadjuvant chemotherapy for PDAC	13 (16)	23 (20.5)	**0.547**	11 (18.3)	9 (15)	**0.806**
Adjuvant chemotherapy	30 (37)	44 (39.3)	**0.751**	21 (35)	17 (28.3)	**0.431**
Previous abdominal surgery	5 (6.2)	7 (6.3)	**1**	4(6.6)	4 (6.6)	**1**
Pancreaticoduodenectomy type **						
Type1	74 (91.4)	70 (70.5)		54 (90)	53 (88.4)	
Type2	1 (1.2)	18 (16.1)		1 (1.6)	0 (0)	
Type3	6 (7.4)	15 (13.4)		5 (8.4)	7 (11.6)	
Type4	0	0	**< 0.001***	0 (0)	0 (0)	**0.762**
Albumin, mg/dl	3.8 [0.6]	3.7 [0.73]	**0.377**	3.8 [0.6]	3.8 [0.7]	**0.555**
Intraoperative and oncological outcome						
Diameter of Wirsung duct (> 5 mm)	18 (22.2)	42 (37.5)	**0.035***	13 (21.7)	14(23.3)	**1**
Operative time, minutes	639 [181]	419 [128]	**< 0.001***	633[187]	395 [77.5]	**< 0.001***
Estimated blood loss, (mL)	175 [285]	386 [408]	**< 0.001***	210 [333]	303 [284]	**0.178**
Blood transfusions	6 (7.4)	21 (18.8)	**0.042***	6 (10)	8 (13.3)	**0.776**
Number of harvested lymph nodes	24 [11.5]	23.5 [16.2]	**0.224**	24 [11.5]	23 [18.5]	**0.439**
Concomitant vascular resection	1 (1.2)	25 (22.3)	**< 0.001***	1 (1.6)	4 (6.6)	**0.364**
Radical resection margin (R0)	78 (96.3)	111 (99.1)	**0.400**	58 (96.6)	59 (98.4)	**1**

Values are expressed in counts (percentages) or in median [IQR]

†Based on International Study Group of Pancreatic Fistula classification

**Based on classification of Büchler et al. [16]

PSM propensity score match, *RPD* robotic pancreatoduodenectomy, *OPD* open pancreatoduodenectomy, *IQR* interquartile range, *BMI* body mass index, *ASA* American Society of Anesthesiology, *PDAC* pancreatic ductal adenocarcinoma, *Distal CCa* distal cholangiocarcinoma, *Vater Ca* ampulla of Vater carcinoma

Discussion

Our retrospective cohort study highlights the advantages of the robotic platform in addressing this traditionally complex surgical procedure. Beyond demonstrating the clinical benefits associated with RPD, our study provides compelling findings from a cost analysis, challenging the widely held belief that RPD is inherently more expensive than OPD. With a cohort comprising 193 patients (RPD and OPD combined), this study represents one of the largest datasets from Japan, contributing valuable insights to the global discourse on robotic surgery. By addressing the current scarcity of

Table 2 Postoperative and complications of patients undergoing robotic and open pancreatoduodenectomy

	Before PSM			After PSM		
	RPD	OPD	*p*	RPD	OPD	*p*
	n = 81	*n* = 112		*n* = 60	*n* = 60	
Postoperative outcomes						
ICU stay, days	1 [0]	1 [1]	**0.745**	1 [0.25]	1 [1]	**0.858**
Hospital LOS, days	14.5 [8.25]	21 [21]	**< 0.001***	15 [9.5]	22.5 [25.5]	**< 0.001***
30-day mortality	1 (1.2)	0 (0)	**0.419**	1 (1.6)	0 (0)	**1**
90-day mortality	2 (2.5)	4 (3.6)	**1**	1 (1.6)	1 (1.6)	**1**
90-day readmission	13 (16.0)	22 (19.6)	**0.652**	10 (16.7)	12 (20)	**0.813**
Complications						
Overall complication	39 (48.1)	63 (56.2)	**0.333**	31 (51.6)	35 (58.4)	**0.581**
Major complication (CD ≥ 3)	16 (19.8)	40 (35.7)	**0.024***	13 (21.6)	22 (36.6)	**0.108**
Reoperation	3 (3.7)	1 (0.9)	**0.311**	3 (5)	0 (0)	**0.243**
Biliary Fistula	1 (1.2)	7 (6.3)	**0.141**	1 (1.6)	5 (8.4)	**0.206**
Pancreas-specific complications						
CR-PF (ISGPS grade ≥ B)	7 (8.6)	36 (32.1)	**< 0.001***	6 (10)	20 (33.3)	**0.003***
PPH	5 (6.2)	12 (10.7)	**0.400**	5 (8.4)	7 (11.6)	**0.760**
DGE	5 (6.2)	8 (7.1)	**1**	4 (6.6)	4 (6.6)	**1**

Values are expressed in counts (percentages) or in median [IQR]

ICU intensive care unit, *LOS* length of stay, *CD* Clavien-Dindo, *CR-PF* clinically relevant pancreatic fistula, *ISGPS* International Study Group in Pancreatic Surgery, *PPH* post pancreatectomy hemorrhage, *DGE* delayed gastric emptying

Table 3 Cost analysis of robotic and open pancreatoduodenectomy

Charged amount	Before PSM			After PSM		
	RPD	OPD	*p*	RPD	OPD	*p*
	n = 62	*n* = 83		*n* = 47	*n* = 47	
Operating room cost, (Japanese yen)	986,472 [80,894]	437,401 [79,122]	**< 0.001***	992,597 [124,567]	428,670 [76,740]	**< 0.001***
Non-operative cost, (Japanese yen)	875,725 [380,325]	1,447,246 [1,109,381]	**< 0.001***	935,320 [420,298]	1,431,874 [1,155,966]	**< 0.001***
In-hospital total charge, (Japanese yen)	1,842,642 [453,292]	1,850,656 [1,103,516]	**0.376**	1,876,564 [473,883]	1,850,656 [1,146,421]	**0.212**

Values are expressed in median [IQR]

cost–benefit analyses in this field, our findings offer meaningful evidence with international relevance, bridging the gap in the literature and informing surgical practices worldwide.

Over the past few decades, studies have explored alternative surgical approaches to the traditional open Whipple procedure due to its significant invasiveness. Laparoscopic surgery was introduced in the late 1980s, but widespread adoption was delayed by technical limitations [23]. Minimally invasive pancreatic surgery (MIPS) faced challenges related to oncological efficacy and the steep learning curve [24, 25]. The advent of robotic platforms has since revived MIPS, offering advantages such as lower conversion rates, reduced blood loss, higher lymph node retrieval, and comparable operative times and complication rates [26]. Additionally, mid-term oncological outcomes appear to be comparable [27].

Several comparative studies, case-matched studies, and propensity score matched studies have reported comparable or better outcomes for RPD over OPD, including reduced blood loss, fewer complications, and shorter hospital stays [5, 6, 28–34]. However, many of these studies have been limited by small sample sizes. In our study, the two groups exhibited significant heterogeneity in certain characteristics, particularly the absence of vascular resection in the RPD cohort. To address this, we employed propensity score matching (PSM), facilitating a balanced comparison and robust evaluation of outcomes reflective of real-world practices. In addition, excluding conversion cases—associated with worsened outcomes—more clearly highlights the advantages of RPD (Table S1), including reduced CR-PF rates and fewer major complications, reinforcing its clinical benefits over OPD.

The most noteworthy findings are that patients undergoing RPD experienced significant reductions in CR-PF rates and total hospital length of stay. ICU stay and overall complication rates did not differ significantly between the RPD and OPD groups. One potential bias to acknowledge is Japan's DPC/PDPS (Diagnosis Procedure Combination/Per-Diem Payment System), which reimburses hospitals with a fixed daily amount rather than a lump sum per admission. This creates an incentive to maintain longer hospital stays to avoid financial losses. In contrast, the American DRG/PPS (Diagnosis-Related Group/Prospective Payment System) reimburses per admission, encouraging shorter hospital stays for financial efficiency. Despite these system differences, since the discharge practice applies to both cohorts in the present study, the comparison remains valid. Moreover, the time to adjuvant chemotherapy after the Whipple procedure is an important factor in evaluating postoperative recovery and oncologic outcomes [35]. Given the observed reduction in total hospital length of stay, the faster recovery associated with RPD may facilitate earlier initiation of adjuvant chemotherapy, potentially contributing to improved long-term survival.

Reported CR-PF rates vary widely due to differences in study design, duration, and procedural parameters. The global incidence of postoperative pancreatic fistula (POPF) ranges from 3 to 41% [36, 37]. Despite this variability, our standardized approach yielded a CR-PF rate of 10% after PSM, supporting our hypothesis. The lower incidence of CR-PF in RPD may be due to the robotic platform's precise dissection capabilities, improved visualization, and enhanced dexterity, which reduce tissue trauma and infection risk [6, 8].

A major strength of our study is that all procedures were performed under the mentorship of a single senior surgeon who had surpassed the learning curve, ensuring consistency in technique and postoperative care. While RPD is not yet universally recognized as the gold standard, our findings indicate that it has the potential to become a preferred approach in high-volume centers with experienced teams. We also analyzed the learning curve based on team performance. The mean number of cases to proficiency was 18 for RPDs and 20 for robotic PJs, which is lower than previously reported [38, 39]. These findings highlight that beyond individual surgical proficiency, standardizing team performance plays a crucial role in efficiently overcoming the learning curve.

Another notable finding is our direct cost comparison of RPD and OPD in a single high-volume referral center in Japan. As expected, operating room costs were higher for RPD. However, in-hospital total charges did not significantly differ between the cohorts. This equivalence is largely due to the shorter hospital stays for RPD patients. While our findings are significant within Japan's cost-sharing healthcare system, the present analysis is based on direct costs and may serve as a model applicable to other healthcare systems. This could support efficient hospital management practices internationally. However, it is important to distinguish between costs (actual resource consumption) and charges (insurance reimbursements). Equivalent charges with higher costs may imply revenue loss for the hospital. Therefore, our results should not be interpreted as proof of "cost-effectiveness." Further value-based analyses, such as evaluations of complication rates, patient outcomes, and societal impact (e.g., earlier return to work), are needed to fully understand the economic implications. Previous studies have highlighted the importance of these factors in assessing the broader value of robotic surgery [40].

Despite the limitations of our retrospective design, our study provides valuable insights. Achieving the level of evidence from ongoing randomized controlled trials (RCTs) remains challenging [41–43]. In experienced centers, the benefits of robotic surgery are well-recognized, making it ethically difficult to assign frail patients to OPD within an RCT framework. Our cost analysis, however, comprehensively includes personnel costs, robot depreciation, maintenance fees, and utilities, providing a thorough evaluation of the financial implications. As surgical robotics patents expire, increased competition may lower purchase and maintenance costs [44]. A comprehensive understanding will further benefit from large, multicenter studies with standardized procedures, long-term follow-up, and careful consideration of ethical constraints.

In conclusion, this study confirms that standardized RPD can overcome the challenges of this complex procedure, particularly by reducing CR-PF rates. These findings challenge the belief that RPD is inherently more expensive than OPD. In high-volume centers with standardized management, RPD offers significant clinical benefits at comparable costs. Further studies with larger cohorts are necessary to explore the economic, quality, and efficiency aspects across different healthcare systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00464-025-11768-4.

Data availability Anonymized data and informed consent forms will be shared by the corresponding author. Data requesters must sign a data access agreement and receive approval from the institutional review board for data sharing.

Declarations

Disclosures Taiga Wakabayashi, Federico Gaudenzi, Yusuke Nie, Kohei Mishima, Yoshiki Fujiyama, Kazuharu Igarashi, Yu Teshigahara, Sho Mineta, Emre Bozkurt, Go Wakabayashi have no conflicts of interest or financial ties to disclose.

References

1. Lefor AK (2019) Robotic and laparoscopic surgery of the pancreas: an historical review. BMC Biomed Eng 1:2
2. Giulianotti PC (2003) Robotics in general surgery. Arch Surg 138:777
3. Zureikat AH, Beane JD, Zenati MS, Al Abbas AI, Boone BA, Moser AJ, Bartlett DL, Hogg ME, Zeh HJ 3rd (2021) 500 minimally invasive robotic pancreatoduodenectomies: one decade of optimizing performance. Ann Surg 273(5):966–972
4. Shi Y, Jin J, Qiu W, Weng Y, Wang J, Zhao S, Huo Z, Qin K, Wang Y, Chen H, Deng X, Peng C, Shen B (2020) Short-term outcomes after robot-assisted vs open pancreaticoduodenectomy after the learning curve. JAMA Surg 155(5):389–394
5. McMillan MT, Zureikat AH, Hogg ME, Kowalsky SJ, Zeh HJ, Sprys MH, Vollmer CM Jr (2017) A propensity score-matched analysis of robotic vs open pancreatoduodenectomy on incidence of pancreatic fistula. JAMA Surg 152(4):327–335
6. Cai J, Ramanathan R, Zenati MS, Al Abbas A, Hogg ME, Zeh HJ, Zureikat AH (2020) Robotic pancreaticoduodenectomy is associated with decreased clinically relevant pancreatic fistulas: a propensity-matched analysis. J Gastrointest Surg 24(5):1111–1118
7. Wakabayashi T, Wakabayashi G (2023) Invited commentary: perspective on technique for robotic pancreaticojejunostomy. J Am Coll Surg 236(5):e15–e16
8. Vining CC, Kuchta K, Berger Y, Paterakos P, Schuitevoerder D, Roggin KK, Talamonti MS, Hogg ME (2021) Robotic pancreaticoduodenectomy decreases the risk of clinically relevant postoperative pancreatic fistula: a propensity score matched NSQIP analysis. HPB (Oxf) 23(3):367–378
9. Giulianotti PC, Mangano A, Bustos RE, Fernandes E, Masrur MA, Valle V, Gangemi A, Bianco FM (2020) Educational step-by-step surgical video about operative technique in robotic pancreaticoduodenectomy (RPD) at University of Illinois at Chicago (UIC): 17 steps standardized technique-lessons learned since the first worldwide RPD performed in the year 2001. Surg Endosc 34(6):2758–2762
10. Wang SE, Shyr BU, Chen SC, Shyr YM (2018) Comparison between robotic and open pancreaticoduodenectomy with modified Blumgart pancreaticojejunostomy: a propensity score-matched study. Surgery 164(6):1162–1167
11. Liu Q, Zhao Z, Gao Y, Zhao G, Jiang N, Lau WY, Liu R (2021) Novel technique for single-layer pancreatojejunostomy is not inferior to modified blumgart anastomosis in robotic pancreatoduodenectomy: results of a randomized controlled trial. Ann Surg Oncol 28(4):2346–2355
12. Baker EH, Ross SW, Seshadri R, Swan RZ, Iannitti DA, Vrochides D, Martinie JB (2016) Robotic pancreaticoduodenectomy: comparison of complications and cost to the open approach. Int J Med Robot Comput Assist Surg 12(3):554–560
13. Lee S, Varghese C, Fung M, Patel B, Pandanaboyana S, Dasari BVM (2023) Systematic review and meta-analysis of cost-effectiveness of minimally invasive versus open pancreatic resections. Langenbecks Arch Surg 408(1):306
14. Ishida M, Fujii T, Kishiwada M, Shibuya K, Satoi S, Ueno M, Nakata K, Takano S, Uchida K, Ohike N, Masugi Y, Furukawa T, Hirabayashi K, Fukushima N, Yi SQ, Isayama H, Itoi T, Ohtsuka T, Okusaka T, Inoue D, Kitagawa H, Takaori K, Tani M, Nagakawa Y, Yoshitomi H, Unno M, Takeyama Y (2024) Japanese classification of pancreatic carcinoma by the Japan Pancreas Society: Eighth edition. J Hepatobiliary Pancreat Sci 31(11):755–768
15. Bassi C, Marchegiani G, Dervenis C, Sarr M, Abu Hilal M, Adham M, Allen P, Andersson R, Asbun HJ, Besselink MG, Conlon K, Del Chiaro M, Falconi M, Fernandez-Cruz L, Fernandez-Del Castillo C, Fingerhut A, Friess H, Gouma DJ, Hackert T, Izbicki J; International Study Group on Pancreatic Surgery (ISGPS) (2017) The 2016 update of the International Study Group (ISGPS) definition and grading of postoperative pancreatic fistula: 11 years after. Surgery 161(3):584–591
16. Bassi C, Marchegiani G, Dervenis C, Sarr M, Abu Hilal M, Adham M, Allen P, Andersson R, Asbun HJ, Besselink MG, Conlon K, Del Chiaro M, Falconi M, Fernandez-Cruz L, Fernandez-Del Castillo C, Fingerhut A, Friess H, Gouma DJ, Hackert T, Izbicki J; International Study Group on Pancreatic Surgery (ISGPS) (2024) Corrigendum to "The 2016 update of the International Study Group (ISGPF) definition and grading of postoperative pancreatic fistula: eleven years after." Surgery 161(3):584–591 (2017). Surgery 176(3):988–989 (2016)
17. Mihaljevic AL, Hackert T, Loos M, Hinz U, Schneider M, Mehrabi A, Hoffmann K, Berchtold C, Müller-Stich BP, Diener M, Strobel O, Büchler MW (2021) Not all Whipple procedures are equal: proposal for a classification of pancreatoduodenectomies. Surgery 169(6):1456–1462
18. Dindo D, Demartines N, Clavien PA (2004) Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. Ann Surg 240(2):205–213
19. Wente MN, Bassi C, Dervenis C, Fingerhut A, Gouma DJ, Izbicki JR, Neoptolemos JP, Padbury RT, Sarr MG, Traverso LW, Yeo CJ, Büchler MW (2007) Delayed gastric emptying (DGE) after pancreatic surgery: a suggested definition by the International Study Group of Pancreatic Surgery (ISGPS). Surgery 142(5):761–768
20. Wente MN, Veit JA, Bassi C, Dervenis C, Fingerhut A, Gouma DJ, Izbicki JR, Neoptolemos JP, Padbury RT, Sarr MG, Yeo CJ, Büchler MW (2007) Postpancreatectomy hemorrhage (PPH): an International Study Group of Pancreatic Surgery (ISGPS) definition. Surgery 142(1):20–25
21. Koch M, Garden OJ, Padbury R, Rahbari NN, Adam R, Capussotti L, Fan ST, Yokoyama Y, Crawford M, Makuuchi M, Christophi C, Banting S, Brooke-Smith M, Usatoff V, Nagino M, Maddern G, Hugh TJ, Vauthey JN, Greig P, Rees M et al (2011) Bile leakage after hepatobiliary and pancreatic surgery: a definition and grading of severity by the International Study Group of Liver Surgery. Surgery 149(5):680–688

22. Ho DE, Imai K, King G, Stuart EA (2011) MatchIt: nonparametric preprocessing for parametric causal inference. J Stat Softw 42:1–28
23. Gagner M, Pomp A (1994) Laparoscopic pylorus-preserving pancreatoduodenectomy. Surg Endosc 8:408–410
24. van Hilst J, de Rooij T, Bosscha K, Brinkman DJ, van Dieren S, Dijkgraaf MG, Gerhards MF, de Hingh IH, Karsten TM, Lips DJ, Luyer MD, Busch OR, Festen S, Besselink MG; Dutch Pancreatic Cancer Group (2019) Laparoscopic versus open pancreatoduodenectomy for pancreatic or periampullary tumours (LEOPARD-2): a multicentre, patient-blinded, randomised controlled phase 2/3 trial. Lancet Gastroenterol Hepatol 4(3):199–207
25. Nassour I, Winters SB, Hoehn R, Tohme S, Adam MA, Bartlett DL, Lee KK, Paniccia A, Zureikat AH (2020) Long-term oncologic outcomes of robotic and open pancreatectomy in a national cohort of pancreatic adenocarcinoma. J Surg Oncol 122(2):234–242
26. Ouyang L, Zhang J, Feng Q, Zhang Z, Ma H, Zhang G (2022) Robotic versus laparoscopic pancreaticoduodenectomy: an up-to-date system review and meta-analysis. Front Oncol 12:834382
27. Nassour I, Choti MA, Porembka MZ, Yopp AC, Wang SC, Polanco PM (2018) Robotic-assisted versus laparoscopic pancreaticoduodenectomy: oncological outcomes. Surg Endosc 32(6):2907–2913
28. Zhou NX, Chen JZ, Liu Q, Zhang X, Wang Z, Ren S, Chen XF (2011) Outcomes of pancreatoduodenectomy with robotic surgery versus open surgery. Int J Med Robot Comput Assist Surg 7(2):131–137
29. Buchs NC, Addeo P, Bianco FM, Ayloo S, Benedetti E, Giulianotti PC (2011) Robotic versus open pancreaticoduodenectomy: a comparative study at a single institution. World J Surg 35(12):2739–2746
30. Lai EC, Yang GP, Tang CN (2012) Robot-assisted laparoscopic pancreaticoduodenectomy versus open pancreaticoduodenectomy—a comparative study. Int J Surg (Lond, Engl) 10(9):475–479
31. Meyyappan T, Wilson GC, Zeh HJ, Hogg ME, Lee KK, Zureikat AH, Paniccia A (2023) Robotic approach mitigates the effect of major complications on survival after pancreaticoduodenectomy for periampullary cancer. Surg Endosc 37(2):1181–1187
32. Chalikonda S, Aguilar-Saavedra JR, Walsh RM (2012) Laparoscopic robotic-assisted pancreaticoduodenectomy: a case-matched comparison with open resection. Surg Endosc 26(9):2397–2402
33. Nickel F, Wise PA, Müller PC, Kuemmerli C, Cizmic A, Salg GA, Steinle V, Niessen A, Mayer P, Mehrabi A, Loos M, Müller-Stich BP, Kulu Y, Büchler MW, Hackert T (2024) Short-term outcomes of robotic versus open pancreatoduodenectomy: propensity score-matched analysis. Ann Surg 279(4):665–670
34. de Graaf N, Zwart MJW, van Hilst J, van den Broek B, Bonsing BA, Busch OR, Coene PLO, Daams F, van Dieren S, van Eijck CHJ, Festen S, de Hingh IHJT, Lips DJ, Luyer MDP, Mieog JSD, van Santvoort HC, van der Schelling GP, Stommel MWJ, de Wilde RF, Molenaar IQ, Groot Koerkamp B, Besselink MG (2024) Early experience with robotic pancreatoduodenectomy versus open pancreatoduodenectomy: nationwide propensity-score-matched analysis. Br J Surg 111(2):znae043
35. Gumbs AA, Chouillard E, Abu Hilal M, Croner R, Gayet B, Gagner M (2021) The experience of the minimally invasive (MI) fellowship-trained (FT) hepatic-pancreatic and biliary (HPB) surgeon: could the outcome of MI pancreatoduodenectomy for peri-ampullary tumors be better than open? Surg Endosc 35(9):5256–5267
36. Petrucciani N, Crovetto A, Felice DE, F, Pace M, Giulitti D, Yusef M, Nigri G, Valabrega S, Kassir R, D'Angelo F, Debs T, Ramacciato G, Aurello P, (2022) Postoperative pancreatic fistula: is minimally invasive surgery better than open? A systematic review and meta-analysis. Anticancer Res 42(7):3285–3298
37. Pedrazzoli S (2017) Pancreatoduodenectomy (PD) and postoperative pancreatic fistula (POPF): a systematic review and analysis of the POPF-related mortality rate in 60,739 patients retrieved from the English literature published between 1990 and 2015. Medicine 96(19):e6858
38. Tseng JF, Pisters PW, Lee JE, Wang H, Gomez HF, Sun CC, Evans DB (2007) The learning curve in pancreatic surgery. Surgery 141(5):694–701
39. 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(5):416–422
40. Childers CP, Maggard-Gibbons M (2018) Estimation of the acquisition and operating costs for robotic surgery. JAMA 320(8):835–836
41. Liu Q, Li M, Gao Y, Jiang T, Han B, Zhao G, Lin C, Lau WY, Zhao Z, Liu R (2024) Effect of robotic versus open pancreaticoduodenectomy on postoperative length of hospital stay and complications for pancreatic head or periampullary tumours: a multicentre, open-label randomised controlled trial. Lancet Gastroenterol Hepatol 9(5):428–437
42. Klotz R, Mihaljevic AL, Kulu Y, Sander A, Klose C, Behnisch R, Joos MC, Kalkum E, Nickel F, Knebel P, Pianka F, Diener MK, Büchler MW, Hackert T (2024) Robotic versus open partial pancreatoduodenectomy (EUROPA): a randomised controlled stage 2b trial. Lancet Reg Health Europe 39:100864
43. Probst P, Hüttner FJ, Meydan Ö, Hilal MA, Adham M, Barreto SG, Besselink MG, Busch OR, Bockhorn M, Del Chiaro M, Conlon K, Castillo CF, Friess H, Fusai GK, Gianotti L, Hackert T, Halloran C, Izbicki J, Kalkum E, Kelemen D et al (2021) Evidence map of pancreatic surgery—a living systematic review with meta-analyses by the International Study Group of Pancreatic Surgery (ISGPS). Surgery 170(5):1517–1524
44. Cepolina F, Razzoli R (2024) Review of robotic surgery platforms and end effectors. J Robot Surg 18(1):74