Robotic Pancreatic Surgery: Experience and Lessons Learned from 1010 Cases (Postprint)

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Abstract

Objective: To thoroughly demonstrate the safety, feasibility, and superiority of robotic pancreatic surgery (RPS) through a large sample size from a single surgical team. Methods: From November 2011 to September 2017, the Liu Rong surgical team at the Chinese PLA General Hospital completed a total of 1010 RPS cases, with prospective collection and retrospective analysis of relevant clinical data. The surgeries were primarily performed using the third-generation da Vinci robotic surgical system. Results: Among all cases, there were 417 robotic pancreaticoduodenectomies, 428 distal pancreatectomies, 60 middle pancreatectomies, 53 pancreatic tumor enucleations, 3 Appleby procedures, and 49 other surgeries (including 4 innovative robotic retroperitoneoscopic procedures, 4 tumor enucleations combined with main pancreatic duct bridging repair, 1 single-port robotic pancreatic tumor enucleation, and 2 middle pancreatectomies combined with end-to-end pancreatic reconstruction). The median operative time was 210 min (30–720 min), median intraoperative blood loss was 80 mL (10–2000 mL), conversion rate was 4.06% (41/1010), transfusion rate was 6.7% (68/1010), postoperative hospital stay was 10.87±6.70 days, Clavien-Dindo grade III or higher complication rate was 8.0% (81/1010), grade B or higher pancreatic fistula rate was 9.21% (93/1010), 30-day mortality was 0.69% (7/1010), and 90-day mortality was 1.31% (12/934). The proportion of RPS increased from 10.44% in 2012 to 72.06% in 2017. Conclusion: This study represents the largest reported series of RPS cases worldwide. Clinical practice demonstrates that with accumulated experience and optimized techniques, RPS can develop rapidly and gradually replace open and laparoscopic surgeries to become the preferred approach for pancreatic procedures. After overcoming the learning curve, all RPS procedures, including pancreaticoduodenectomy and Appleby, are safe and feasible. Mature experience should be drawn upon when initially implementing RPS to reduce complication rates.

Full Text

Preamble

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Abstract

Objective: To assess the safety, feasibility, and advantages of robotic pancreatic surgery (RPS) based on a single-team experience with 1010 cases. **Methods:** Clinical data from 1010 RPS procedures performed by a single surgical team from November 2011 to September 2017 were prospectively collected and retrospectively analyzed. The majority of surgeries were performed using the third-generation da Vinci robotic surgical system. **Results:** The 1010 RPS procedures included 417 robotic pancreatoduodenectomies (RPD), 428 robotic distal pancreatectomies, 60 robotic central pancreatectomies, 53 robotic pancreatic tumor enucleations, 3 Appleby procedures, and 49 other operations (including 4 innovative robotic retroperitoneal laparoscopic surgeries, 4 robotic pancreatic tumor enucleations combined with main pancreatic duct bridging repair, 1 single-incision robotic pancreatic tumor enucleation, and 2 robotic central pancreatectomies with end-to-end pancreatic reconstruction). The median operative time was 210 minutes (range 30–720 min), median intraoperative blood loss was 80 mL (range 10–2000 mL), conversion rate was 4.06% (41/1010), transfusion rate was 6.7% (68/1010), mean postoperative hospital stay was 10.87 ± 6.70 days, Clavien-Dindo grade III–V complication rate was 8.0% (81/1010), grade B or higher pancreatic fistula rate was 9.21% (93/1010), 30-day mortality was 0.69% (7/1010), and 90-day mortality was 1.31% (12/934). The proportion of RPS increased from 10.44% in 2012 to 72.06% in 2017. **Conclusion:** This study represents the largest reported series of robotic pancreatic resections worldwide. Clinical practice demonstrates that with accumulated experience and optimized techniques, RPS can develop rapidly and gradually replace open and laparoscopic surgery as the preferred approach for pancreatic operations. After completing the learning curve, all RPS procedures—including pancreatoduodenectomy and Appleby—are safe and feasible. Early adoption of RPS should draw upon established experience to reduce complications.

Keywords: robotic surgery; minimally invasive surgery; pancreas; distal pancreatectomy; pancreaticoduodenectomy

Introduction

The 21st century is the era of minimally invasive surgery, with laparoscopic and robotic surgery as its main components. However, inherent limitations of

laparoscopic surgery restrict its application in procedures requiring fine manipulation and complex reconstruction, particularly when vascular reconstruction is involved, which demands exceptional surgical skill and a well-coordinated team [1-3]. The robotic surgical system overcomes some of these limitations, offering advantages including precise and stable manipulation, automatic filtration of hand tremor, seven degrees of freedom in the instrument arms, and a stable, magnified 3D high-definition field with coordinated hand-eye movement [1, 4-6]. These features make robotics particularly advantageous in operations requiring meticulous dissection, working in confined spaces, complex reconstruction, and vascular manipulation. Some procedures have already become "gold standard" operations, such as radical prostatectomy [7] and hysterectomy [8], and robotic surgery is gradually replacing laparoscopic surgery as the mainstream approach in abdominal surgery.

The pancreas is located deep in the retroperitoneum with complex adjacent anatomy, closely abutting major vessels. Malignant tumors readily infiltrate surrounding structures, necessitating meticulous dissection, complex and reliable gastrointestinal reconstruction, and essential vascular repair techniques—areas where robotic surgery offers clear advantages. Nevertheless, the long learning curve and high surgical risks have constrained the widespread adoption of robotic pancreatic surgery (RPS). According to the learning curve standards proposed by Zureikat—80 cases for robotic pancreatoduodenectomy (RPD) [9] and 40 cases for robotic distal pancreatectomy (RDP) [10]—most centers remain in the early phase and have not surpassed the learning curve, resulting in relatively high complication rates and mortality in clinical practice. In October 2013, Zureikat from the University of Pittsburgh Medical Center published a series of 250 RPS cases in *Annals of Surgery* [1], which preliminarily confirmed the safety and feasibility of RPS. However, due to limited sample sizes in subgroup analyses and data drawn predominantly from cases within the learning curve, the superiority of robotic surgery was not clearly demonstrated. We now present a single-team experience with 1010 RPS procedures—the largest reported series worldwide—to describe the implementation of RPS under Chinese healthcare conditions, summarize our experience and lessons learned, and further demonstrate the safety, feasibility, and superiority of this approach.

Methods

All 1010 cases were performed by the Liu Rong surgical team at the General Hospital of PLA, with a consistent primary surgeon, one bedside assistant, and one to two instrument nurses. Clinical data were prospectively collected and retrospectively analyzed. All patients provided informed consent preoperatively. Between November 2011 and February 2015, the second-generation da Vinci S system was used, with one operating day per week. From February 2015 to September 2017, the third-generation da Vinci Si-HD system (dedicated to the team) was primarily employed, with the S system used occasionally (less than one day per week). Postoperative complications were classified according to the

Clavien-Dindo system [11], and pancreatic fistula was graded using the 2016 International Study Group on Pancreatic Fistula (ISGPF) criteria [12]. Since most RPS procedures were performed in the last two years, long-term follow-up data have not yet been analyzed.

Statistical analysis was performed using SPSS 20.0 software. Normally distributed continuous variables are expressed as mean ± standard deviation, non-normally distributed variables as median (range), and categorical variables as number (percentage).

Results

2.1 Surgical Composition

Among the 1010 procedures, 894 were performed with the Si system and 116 with the S system. The series included 417 RPDs, 428 RDPs, 60 central pancreatectomies, 53 pancreatic tumor enucleations, 3 Appleby procedures, and 49 other operations (comprising 4 innovative robotic retroperitoneal laparoscopic surgeries, 4 robotic tumor enucleations with main pancreatic duct bridging repair, 1 single-incision robotic tumor enucleation, and 2 robotic central pancreatectomies with end-to-end pancreatic reconstruction).

2.2 General Clinicopathological Data

Patient age was 53.99 ± 14.04 years (range 13–87), with 486 males and 524 females. Mean BMI was 22.7 ± 4.7 (range 14.5–40.2), and 11.5% (116/1010) had prior upper abdominal surgery. Pathology revealed malignant disease in 516 cases and benign disease in 494 cases, including 321 pancreatic ductal adenocarcinomas, 195 distal cholangiocarcinomas, duodenal adenocarcinomas, and periampullary carcinomas, 102 neuroendocrine tumors (25 grade G2 or higher, 77 below G2), 60 serous cystadenomas, 102 mucinous cystadenomas (92 benign, 10 malignant), 91 solid pseudopapillary tumors, 28 intraductal papillary mucinous neoplasms, and 111 other lesions.

2.3 Surgical Safety (Table 1)

The overall 30-day mortality was 0.69% (7/1010) and 90-day mortality was 1.31% (12/934). In the RPD subgroup, 30-day mortality was 0.96% (4/417) and 90-day mortality was 1.61% (6/373). In the RDP subgroup, 30-day mortality was 0.23% (1/428) and 90-day mortality was 0.5% (2/398). The overall Clavien-Dindo grade III–V complication rate was 8.0% (81/1010), with 13.2% (55/417) in the RPD group and 5.8% (25/428) in the RDP group. The overall pancreatic fistula rate was 44.16% (446/1010), including biochemical leak (BL) in 34.95% (353/1010, accounting for 79.15% of all fistulas) and grade B or higher fistula in 9.21% (93/1010, accounting for 20.85%). In the RPD group, the fistula rate was 50.36% (210/417), with BL in 41.01% (171/417, 81.43%) and grade B or higher in 9.35% (39/417, 18.57%). In the RDP group, the fistula rate was

43.22% (185/428), with BL in 35.51% (152/428, 82.16%) and grade B or higher in 7.71% (33/428, 17.84%).

Median intraoperative blood loss was 80 mL (range 10–2000 mL) overall, 100 mL (range 20–2000 mL) in the RPD group, and 50 mL (range 20–1800 mL) in the RDP group. The overall transfusion rate was 6.7% (68/1010), with 8.6% (36/417) in the RPD group and 4.2% (18/428) in the RDP group. The overall reoperation rate was 2.67% (27/1010), with 3.84% (16/417) in the RPD group and 1.64% (7/428) in the RDP group.

2.4 Surgical Feasibility and Oncological Outcomes (Table 2)

The median operative time was 210 minutes (range 30–720 min) overall, 300 minutes (range 120–720 min) in the RPD group, and 170 minutes (range 30–340 min) in the RDP group. The overall conversion rate was 4.06% (41/1010), with 4.56% (19/417) in the RPD group and 2.8% (12/428) in the RDP group. The positive margin (R1) rate for malignant tumors was 3.46% (17/492) overall, 3.44% (11/320) in the RPD group, and 2.09% (5/139) in the RDP group. The mean number of harvested lymph nodes in malignant cases was 14.1 ± 8.3 (range 4–31) overall, 14.9 ± 6.7 (range 4–31) in the RPD group, and 11.6 ± 9.6 (range 6–28) in the RDP group.

2.5 Annual Volume and Proportion of Robotic, Laparoscopic, and Open Surgeries in Liu Rong' s Team (Figure 1 [Figure 1: see original paper])

The volume and proportion of RPS procedures increased annually. In 2017 (January–September), RPS accounted for 72.06% of all pancreatic surgeries, far exceeding open surgery (25.82%) and laparoscopic surgery (2.12%).

Discussion

The promotion of new surgical techniques requires high-level evidence from randomized controlled trials, but such prospective studies are difficult to implement in clinical practice [2]. Factors including patient and surgeon preferences, staff turnover, regional healthcare policies, and patients' financial capacity all affect the successful execution of randomized trials. Therefore, in China' s current healthcare environment, large case series hold significant value. In 2013, Zureikat from the University of Pittsburgh Medical Center reported a series of 250 RPS cases, including 132 RPDs, 83 RDPs, 13 central pancreatectomies, 10 enucleations, 5 total pancreatectomies, 4 Appleby procedures, and 3 Frey procedures [1]. Their prospectively collected data showed 30-day and 90-day mortality rates of 0.8% and 2.0%, respectively, Clavien grade III–V complication rates of 14% and 6%, and a grade C fistula rate of 4% (using the 2006 ISGPF criteria). Operative times were 529 ± 103 minutes for RPD and 257 ± 93 minutes for RDP. This study preliminarily confirmed the safety and feasibility of robotics in various pancreatic procedures. Our larger series, encompassing

more procedure types, further validates the safety, feasibility, and superiority of robotic surgery for both conventional and innovative pancreatic operations.

Safety is paramount when introducing new techniques, and mortality is the key metric. Our 30-day mortality of 0.69% and 90-day mortality of 1.31% are lower than Zureikat' s reported 0.8% and 2.0% [1], likely due to differences in malignant disease burden and sample size, as nearly half of their cases were performed during the learning curve. Our mortality rates for both RPD and RDP are comparable to or better than those of open surgery [13-16]. Most RPD mortality cases occurred early in our experience, primarily due to improper arterial management leading to early postoperative hemorrhage or secondary bleeding from pancreatic fistula. We recommend suture ligation for vascular control in the early phase, as the use of arterial clips and energy devices requires specific skills, and in-situ clamping and division are critical. The Appleby procedure is one of the most complex pancreatic operations, requiring extended multivisceral resection, lymphadenectomy, and en bloc celiac axis resection for invasion. Robotic Appleby procedures are rarely reported [1]. All three of our robotic Appleby cases were performed as one-stage operations. One patient with a positive margin died of multi-organ failure two months postoperatively due to poor oral intake and tumor progression. Another developed a large gastric ulcer at 1.5 months that healed conservatively, with no recurrence at one-year follow-up. The third experienced tumor recurrence at seven months. Robotic Appleby is technically feasible with acceptable short-term outcomes and no severe complications, but strict patient selection and timing are essential. Western centers currently favor a staged approach: neoadjuvant chemotherapy, hepatic artery embolization, then surgery [17].

Pancreatic fistula is the most common complication after RPS, directly affecting mortality and safety. Our grade B or higher fistula rate of 9.21% is similar to other reports [1, 6, 9-10, 15], though comparability is limited by differing diagnostic criteria. Our pancreaticojejunostomy technique has evolved through multiple optimizations in suturing methods, suture materials, and stent placement. We currently use a 1+2 or 1+1 duct-to-mucosa technique with externalized main pancreatic duct stenting [18-19], which simplifies the anastomosis and includes secondary reinforcement, making it simple, safe, and efficient. Using the 2006 ISGPF criteria, our grade B or higher fistula rate in the last 200 RPD cases has decreased to 4.5%, significantly lower than reported literature [9, 20-21], open surgery [22-24], and laparoscopic series [25-26]. The key to reducing fistula after RDP is proper management of the pancreatic duct stump. When using a linear stapler, the main duct is typically sealed in multiple layers, preventing severe fistula. When using energy devices, we recommend identifying and meticulously ligating the main duct or performing U-shaped appositional sutures near the duct. Overall, reported fistula rates after RDP are similar across centers. For enucleation, avoiding main duct injury is critical, especially when lesions have displaced the duct. For ductal injury, we innovatively employed R-mpd-BR and R end-to-end PAR techniques instead of segmental resection or pancreaticojejunostomy as recommended in guidelines. All four R-mpd-BR and two R

end-to-end PAR cases had smooth postoperative courses with successful drain removal, demonstrating safety and effectiveness. These approaches provide new concepts for managing benign pancreatic disease and may transform surgical strategies. Other safety metrics including transfusion and reoperation rates are comparable to or better than open surgery and consistent with other large series [15, 22-28].

Operative time reflects surgical efficiency. Early RPS experiences involved longer operative times, but these decrease significantly with experience and technique refinement [9, 20], though most studies still report longer times than open surgery. Our early RPD average was 387 minutes [29], but has now decreased to approximately 200 minutes, rivaling open surgery [30-32]. Our operative times are substantially lower than other reports [9, 20], likely due to surgical methodology, team experience, and time calculation methods. Based on 410 consecutive cases since August 2015, we have developed a mature RPD technique [19] featuring standardized 5-port placement with Trocar-in-Trocar technique, horizontal Y-shaped resectability assessment, "anterior-posterior-superior-inferior" programmatic dissection, 1+2 or 1+1 pancreaticojejunostomy [18], and transverse mesocolon LR hole application [33], all contributing to improved efficiency, safety, and oncological radicality. Due to variations in pathological examination thoroughness, lymph node harvest and margin status cannot be directly compared across institutions. However, compared with open surgery data from our own hospital, robotic surgery now achieves equivalent oncological outcomes. The minimal trauma, reduced immunological impact, and faster recovery associated with robotic surgery may allow earlier initiation of adjuvant chemotherapy, suggesting potentially better long-term outcomes than open surgery [16], a hypothesis supported by current evidence [34-38].

We present a comparative chart of our team' s annual volumes of robotic, laparoscopic, and open pancreatic surgeries from 2011 to 2017. Initially, open surgery volume remained stable, increasing proportionally with expanded ward capacity. Robotic surgery growth was modest before 2015, similar to laparoscopic proportions. After the installation of a dedicated robotic system in February 2015, RPS volume increased rapidly, displacing both open and laparoscopic procedures. From January to September 2017, RPS accounted for 72.06% of all pancreatic surgeries, far exceeding open surgery (25.82%) and nearly eliminating laparoscopic surgery (2.12%). Robotic surgery has become the preferred approach for nearly all pancreatic procedures. Similarly, the University of Pittsburgh Medical Center reported that robotic pancreatic surgery volume surpassed open surgery in 2012 [1].

The occupational hazards of high-intensity robotic surgery warrant attention. Prolonged work at the 3D console negatively impacts vision and the lumbar, thoracic, cervical, and wrist joints, necessitating adapted training models for young surgeons. Robotic surgery remains costly [16], and safe robotic vascular reconstruction requires new techniques and dedicated instruments. In China, robotic application faces constraints: costs are not covered by medical insurance,

procurement is subject to strict quotas, and existing systems are preferentially used in urology and gynecology where cost recovery is faster. These factors limit RPS development. Based on our experience, we believe that with wider adoption, decreasing costs, and application of mature techniques, RPS will inevitably become the mainstream and "gold standard" approach in pancreatic surgery.

Conclusion

This large-volume clinical study demonstrates that with accumulated experience and optimized techniques, RPS can develop rapidly and gradually replace open and laparoscopic surgery as the preferred approach for pancreatic operations. After completing the learning curve, all RPS procedures—including RPD and Appleby—are safe and feasible. Early adoption of RPS should incorporate established experience to reduce complications.

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Note: Figure translations are in progress. See original paper for figures.