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Update on Robotic Pancreatic Surgery

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Abstract
Purpose of Review This review serves as an update on the status of robotic pancreatic surgery. It will focus on major changes in the adoption, safety, patient selection, and procedural refinements in robotic pancreatic surgery over the past 5 years.
Recent Findings While the findings of this review support the notion that adoption of robotic pancreatic surgery is growing, it is still challenged by the long learning curve. A curriculum has been constructed and disseminated to address this issue. Furthermore, multiple international meetings have been organized to set helpful recommendations and guidelines.
Summary Robotic pancreatic surgery is a growing platform that is expected to expand with further advancements in technology and increased adoption of the new generation of Hepato-Pancreato-Biliary Surgeons.

Keywords Robotic surgery · Pancreatic surgery · Minimally invasive surgery · Surgical education · Pancreatoduodenectomy · Distal pancreatectomy

This article is part of the Topical Collection on *Robotic Surgery*.

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Introduction

The adoption of robotic surgery has been increasing across the breadth of general surgery. The robotic platform is particularly well-suited for complex and technically challenging surgical procedures. The complexity and challenges of laparoscopic procedures make robotic pancreatic surgery intriguing. Applications in major procedures such as pancreaticoduodenectomy and distal pancreatectomy have been described extensively, although its adoption has been slow as compared to other disciplines of surgery such as colorectal and hernia surgery [1]. Challenges such as safety, patient selection, perioperative morbidity, learning curve, and cost have been described. A major controversy has been ongoing between surgeons trained strictly in open pancreas surgery and adopters of robotic surgery. We have described the benefits, challenges, and applications of robotic pancreas surgery previously [2]. This review serves as an update on robotic pancreatic surgery. It will focus on major changes in the adoption, safety, patient selection, and procedure refinements in robotic pancreatic surgery.

Perception and Adoption of Robotic Approach Among Pancreatic Surgeons

Pancreatic surgeons have been surveyed to assess their minimally invasive pancreatic surgery practice and perception of its utility and challenges to adoption. A worldwide survey of 435 surgeons with a median annual pancreatic resection of 22 cases per surgeon was included [3]. Most respondents (90%) perceived minimally invasive pancreas surgery to be beneficial for patients. Of interest, a surgeon's overall perception of utility of minimally invasive pancreatic surgery both now and in the future is based on their current practice pattern. A minority of surgeons (35%) believed that robotic pancreas surgery is superior to laparoscopic, with variable justification, mainly enhanced dexterity (93%), superior ergonomics (72%), improved visibility (67%), 3D vision (64%), and other reasons (3%). When asked about perception of patients' quality of life after pancreas surgery by approach, 251 (58%) of surgeons believed that it was superior in patients undergoing minimally invasive pancreas surgery as opposed to open, due to decreased pain, shorter functional recovery, decrease length of hospital stay, less blood loss, earlier start of adjuvant therapy, and decreased morbidity. In fact, the literature reported that, although the operative time of minimally invasive pancreatoduodenectomy was longer than the open approach (401 vs. 541 min, $p < 0.001$), minimally invasive pancreatoduodenectomy was more favorable in regard to the estimated blood loss (195 and 1032 mL, $p < 0.001$) and length of hospital stay (8 vs 12 days, $p < 0.001$) [4].

The trend of robotic surgery adoption for gastrointestinal oncological resections within the United States was assessed by Konstantinidis et al. using data from the National Cancer Database [5]. The authors analyzed data of surgical resections of several gastrointestinal organs separately for years 2010 through 2014. Pancreas resection data reflect an increase in robotic approach utilization by nearly fourfold. Perioperative outcomes were noted to favor the robotic approach over open or laparoscopic without any compromise in oncological outcomes, such as margin status, lymph node retrieval, or overall survival.

Consensus Statements

The increasing interest in minimally invasive pancreatic surgery, coupled with the recognized challenges of safe implementation, has led to the formats for reviewing and discussing these evolving data. Thereby, the first international meeting to address issues related to minimally invasive pancreatic surgery was held in Sao Paulo at the 12th World Congress (2016) by the International Hepato-Pancreato-Biliary Association [6•]. Many topics were discussed during the meeting, including terminology, feasibility, cost, training paradigm, research, as well as outcomes such as perioperative morbidity and mortality, oncologic appropriateness, and future research. Unfortunately, a paucity of robust data limited the ability to draw conclusions. However, general key points were made. It was noted that minimally invasive pancreatic surgery is growing in clinical practice. It was also noted that the terminology used was not standardized nor precise, resulting in heterogeneity in the literature. Distal pancreatectomy was considered as an appropriate alternative to open distal pancreatectomy. This conclusion was made based on improved perioperative outcomes reported in the literature, such as operative time, estimated blood loss, and length of stay. Not enough data were found to support minimally invasive pancreatoduodenectomy, but further research was encouraged. This also applies to issues pertaining to cost-effectiveness and training in minimally invasive pancreatic surgery. While the key points made were not based on high-quality evidence, it was seminal for future work.

A subsequent minimally invasive pancreas resection meeting in Miami 2019, cosponsored by several major worldwide surgery and Hepato-Pancreato-Biliary specific associations, yielded 28 recommendations after extensively reviewing the literature. Issues pertaining to specific procedures (distal, central pancreatectomy, and pancreaticoduodenectomy), patients and techniques, implementation and training, instrumentation, and accountability were discussed. The preparation for the meeting started months earlier to the actual meeting date. Several committees were formed with different tasks assigned. The methodology committee reviewed the literature for a set of pertinent clinical questions that were eventually approved by the steering committee. These questions were then provided to expert groups formed by PhD/MD students and experts in the field. The groups were responsible of performing further literature review on the questioned poised. The quality of the evidence found was evaluated using the SIGN method [7]. The expert groups provided detailed answers to the questions assigned reflecting on the available literature, summary of the studies, recommendations, and remarks. The chairs of the steering committee created a synthesis of the work provided and distributed it among all experts involved for a Delphi vote process. A preset agreement rate of $> 85\%$ was chosen. The recommendations were presented and discussed in the Miami meeting (2019). An independent validation committee was formed to validate the guidelines using the AGREE II assessment tool to assess the quality of the guidelines [8].

In regard to robotic pancreas resections specifically, the consensus was that robotic and laparoscopic distal pancreatectomy were comparable and safe, with higher spleen-preserving rates in the robotic approach. There was no oncological difference between the two approaches. As for robotic pancreaticoduodenectomy, no evidence was noted in the literature to ascertain its superiority over the laparoscopic approach. This was left to the surgeon's expertise, preference, and available resources.

The Miami international evidence-based guideline meeting treated robotic and laparoscopic approaches as a single entity, which limits the ability to purely assess the robotic approach. However, a robotic pancreatic surgery-specific international consensus statement was developed by Liu et al. [9•]. The consensus statement consists of 19 recommendations divided by procedures, i.e., distal and central pancreatectomy; pancreatoduodenectomy; and enucleation. The recommendations of the consensus meeting are summarized in Table 1.

Training and Learning Curve

The adoption of robotic pancreatic surgery, as noted above, is mainly hindered by insufficient training. Adopters of robotic pancreatic surgery managed to do so by various pathways. Early adopters of robotic pancreas surgery are more commonly surgeons with prior experience in advanced laparoscopic surgery. Furthermore, a two-staff surgeon approach has been adopted as well to navigate through the complex task of pancreatic resection, namely pancreaticoduodenectomy.

With increasing experience and dissemination of robotic platforms, formal pancreaticoduodenectomy training programs have been designed and offered within structured fellowship programs such as the American Hepato-Pancreato-Biliary Association and Society of Surgical Oncology fellowships. Such programs consist of several phases [10]. The first phase is virtual reality simulation curriculum, followed by bio-tissue curriculum, then surgical curriculum, and finally skill maintaining with ongoing assessment. The virtual reality simulation curriculum aims to familiarize the trainee with the console in a safe and non-consequential environment. The second phase is unlocked for the trainee after successful completion of the virtual reality simulation curriculum and involves utilization of bio-tissue to practice suturing with escalating difficulty to eventually involve creating anastomoses, e.g., gastrojejunostomy, hepaticojejunostomy, and pancreaticojejunostomy. The surgical curriculum and skill maintenance with ongoing assessment are phases with real-time patient exposure with de-escalation of supervision [10]. It has been shown that the trainees significantly improved with repetition of tasks dictated in the virtual reality and bio-tissue curricula [11, 12].

Knab et al. reported on their experience introducing robotic surgery curriculum to the institution's Hepato-Pancreato-Biliary and Complex General Surgery fellowship programs. Of note, the authors utilized the curriculum described above. A total of 30 fellows over the course of four years were included in the study cohort. Educational portfolios were created to reflect experience with robotic surgery before, during and after the fellowship. Only 47% of the fellows had some prior experience through either their home residency programs or during a previous fellowship. It was noted over the course of the four years that fellow involvement with robotic cases increased, particularly operating from the console. However, this was less evident in pancreatoduodenectomy cases as opposed to distal pancreatectomy. Nevertheless, the number of steps completed in the pancreatoduodenectomy cases increased over the study period. This might reflect the curve present for educators themselves walking their trainees through the procedure. A major training obstacle faced by the authors is the difficulty of autonomy transition from the surgeon to the trainee which is easier to do in open cases. This was mainly attributed to the fact that the console can only accommodate one operator. This issue might be resolved by the introduction of the dual console setup present in the Da Vinci Xi platform. The trainer can give the trainee certain steps of procedures and intervene during each step as needed while each is on a separate console [13]. Longitudinal follow-up of fellows showed that 87.5% of the fellows incorporated robotic surgery in their first job [14].

The learning curve for robotic pancreatic surgery has been assessed for the respective procedures. Different metrics can be used to define the minimum number of cases needed to overcome the learning curve, e.g., operative time. Several studies assessed the learning curve for robotic distal pancreatectomy [15–18]. A minimum of 5 cases are needed before the operative time is significantly reduced for robotic distal pancreatectomy. Other objective metrics were noted to decrease as well such as estimated blood loss. The learning curve for robotic pancreaticoduodenectomy was found to be longer. Takahashi et al. defined the learning curve at which a single surgeon's operative time is decreased (578 vs. 457 min, $p < 0.004$) is by the 15th case for pancreatoduodenectomy, while Napoli et al. define that point to be by the 10th case for distal pancreatectomy (421.1 vs 248.9 min, $p < 0.0001$) [15, 16]. More importantly, Takahashi et al. reported that rate of postoperative morbidity decreases after the 30th case of robotic pancreatic resection in general [16].

Updates in Patient Selection

Selecting patients for the best approach is an important consideration. Selecting the appropriate patient for any minimally invasive approach, laparoscopic or robotic, would theoretically increase the odds of successful completion of the procedure without having to convert to open surgery. Unplanned conversion of minimally invasive pancreatic resection to open is associated with increased overall 30-day morbidity and mortality. This has been shown using the American College of Surgeons National Surgical Quality Improvement Program database where patients who had a completed minimally invasive pancreatic resection and those who had an unplanned conversion were propensity matched, separately for distal

Table 1 Summary of the international consensus statement on robotic pancreatic surgery

Distal pancreatectomy	
1. Oncological outcomes	RDP and LDP yield similar margin status and number of lymph nodes harvested in malignant disease
2. Perioperative safety and outcomes	The safety and feasibility of RDP and LDP are comparable
	In comparison to ODP and LDP: similar complication rate, mortality, and postoperative pancreatic fistula
	In comparison to ODP: longer operative time, less estimated blood loss, and shorter length of hospital stay
3. Splenic preservation	In comparison to LDP: Similar splenic preservation rate
	In comparison to ODP: RDP has higher splenic preservation rate in vessel preserving approach
4. Learning curve	The learning curve for an experienced laparoscopic surgeon is 10–20 consecutive cases
5. Radical antegrade modular pancreatosplenectomy (RAMPS)	Insufficient evidence to support robotic RAMPS
	May be utilized at surgeon's discretion
6. Cost-effectiveness	Insufficient evidence to conclude cost-effectiveness as compared to LDP or ODP
Pancreatoduodenectomy	
7. Oncological outcomes	In comparison to OPD: Higher R0 Resection and similar number of harvested lymph nodes
8. Indications for RPD	RPD can be utilized in the setting of benign or malignant pathology of the pancreatic head and duodenum. Specific situation:
	Large benign tumors
	Advanced stage malignancies
	Conditions requiring vascular resection and reconstruction
	RPD should be performed by surgeons who have overcome the learning curve
9. Intraoperative outcomes	In comparison to OPD: less estimated blood loss, longer operative time, no difference in transfusion rate
10. Postoperative outcomes	In comparison to OPD: similar overall morbidity and mortality, similar postoperative pancreatic fistula rate, shorter length of hospital stay
11. Learning curve	The learning curve for surgeons with extensive experience in laparoscopic pancreatectomy is overcome after 40 cases
12. Utility of the hybrid (laparoscopic/robotic) approach	The hybrid approach can be utilized during the transition phase from laparoscopic to totally robotic pancreatoduodenectomy
13. Resection/reconstruction of PV/SMV	Vascular resection and reconstruction is technically demanding and should not be performed by novice robotic surgeons
Central pancreatectomy	
14. Safety and Feasibility	Robotic central pancreatectomy is safe and feasible for benign and borderline tumors with the suggested condition of at least retaining 5 cm of the tail
15. Short-term outcomes	Insufficient evidence to favor robotic central pancreatectomy over the open approach
16. Method of pancreatic duct reconstruction	While pancreatojejunostomy is the most common technique, the suitable method is left to the surgeons' discretion
17. Inherent differences between RPD and OPD	RPD and OPD are inherently different in:
	The operative view, lack of tactile feedback, limited array of available robotic instruments
Pancreatic enucleation	
18. Indications for pancreatic enucleation	Pancreatic enucleation is indicated for superficial benign tumors
	The main pancreatic duct should be at least 2 mm away from the lesion to ascertain safe enucleation
19. Management of pancreatic duct injury during pancreatic enucleation	If the pancreatic duct is injured during the process of enucleation, either a salvage pancreatectomy or a pancreatojejunostomy can be performed

LPR laparoscopic distal pancreatectomy, *ODP* open distal pancreatectomy, *RDP* robotic distal pancreatectomy, *LPD* laparoscopic pancreatoduodenectomy, *OPD* open pancreatoduodenectomy, *RPD* robotic pancreatoduodenectomy pancreatectomy and pancreatoduodenectomy. Unplanned conversions occurred in 230/1174 (19.6%) attempted distal pancreatectomy and 86/350 (24.6%) attempted pancreatoduodenectomy procedures over the course of 2 years (2014/2015). Unplanned conversion of distal pancreatectomy was associated with high overall 30-day morbidity (54.8% vs 33.2%, $p < 0.001$) and mortality (1.7% vs 0.2%, $p = 0.016$). Specific complications noted to be significantly higher were organ space, surgical site infection, prolonged intubation, and cardiac arrest ($p < 0.001$). Similar results were noted for unplanned conversion of pancreatoduodenectomy, with higher overall 30-day morbidity (73.3% vs 38.6%, $p < 0.001$) and mortality (4.7% vs 1.1%, $p = 0.065$) compared to completed cases as planned. Furthermore, complications such as postoperative pancreatic fistula, organ space surgical site infection, pneumonia, and requirement of postoperative percutaneous drainage were noted to be increased in unplanned conversions of pancreatoduodenectomy [19].

Several attempts have been made to identify the qualities of patients who would benefit from a minimally invasive approach and conversely, characteristics of patients that would be considered high risk for minimally invasive pancreatic surgery. Klompmaker et al. utilized the American College of Surgeons National Surgical Quality Improvement Program database (2014) to identify the current selection criteria for minimally invasive distal pancreatectomy [20]. Factors that favored selection of an open approach were malignant pathology, tumor size > 5 cm, and concurrent multi-visceral resection. On the other hand, a minimally invasive approach was favored for benign pathology and a body mass index between 30 and 40 kg/m^2. Furthermore, the authors created a composite variable of major morbidity to assess the predictors of negative outcomes. None of the selection factors for surgical approach correlated with occurrence of adverse events. The authors concluded that the current presumed selection criteria for a surgical approach in distal pancreatectomy needed to be reassessed. Moreover, patients should not be denied minimally invasive distal pancreatectomy based on the factors currently used, although surgeon specific factors greatly impact appropriate patient selection.

The Miami consensus conference tried to address patient selection criteria for minimally invasive approach [21•]. In regard to distal pancreatectomy, the consensus was that for benign and low malignant pathology, a minimally invasive approach is favorable to an open approach. However, this recommendation was not as strong for pancreatic ductal adenocarcinoma due to the lack of prospective evidence. As for pancreaticoduodenectomy, no consensus was achieved for approach over another due to lack of definitive evidence; however, centers that practiced minimally invasive pancreaticoduodenectomy were encouraged to compile their data prospectively within a shared registry. The proceedings explicitly mentioned that patient age, body mass index, and complex previous abdominal procedures were not contraindications to minimally invasive pancreatic resection. Furthermore, severity of comorbidities did not clearly influence reported outcomes by a specific approach.

Pancreas Surgery-Specific Morbidity

Pancreatic resections have a unique set of potential postoperative morbidity: postoperative pancreatic fistula (POPF), post-pancreatectomy hemorrhage, and delayed gastric emptying. The definition of POPF has been revised by the International Study Group of Pancreatic Fistula (ISGPF) to include clinically relevant POPF (CR-POPF). Cai et al. studied the rate of CR-POPF in patients undergoing robotic pancreaticoduodenectomy and compared them to an open approach cohort [22]. Moreover, a propensity score matching analysis and multivariate analysis was performed to identify risk factors for CR-POPF. A total of 865 patients were included in the study, of which 460 (53.2%) patients underwent a robotic approach. The overall rate of POPF was comparable with patients who have undergone open pancreaticoduodenectomy. However, the rate of CR-POPF was lower in the robotic approach cohort (6.7% vs 15.8%; $p < 0.001$). This was further validated to be true in multivariate analysis (OD 0.278; $p < 0.001$) and after propensity score matching (coefficient = $-$ 0.113; $p = 0.001$).

Updates by Procedure

While feasibility and perioperative outcomes of pancreaticoduodenectomy and distal pancreatectomy have been extensively reported in the past [2], other procedures have been attempted robotically with reported outcomes. These procedures include enucleation, central pancreatectomy, total pancreatectomy (with or without islet cell transplantation), and ductal drainage procedures.

Enucleation

Enucleation of a pancreatic mass is usually indicated for patients with small pancreatic neuroendocrine tumors (≤ 2 cm) with a favorable peripheral location. The rational to pursue enucleation is the preservation of pancreas parenchyma that intuitively decreases risk for endocrine and exocrine pancreatic insufficiency. Moreover, enucleating a pancreatic mass does not require reconstruction. Given the low prevalence rate of pancreatic neuroendocrine tumors and typical indications to resect lesions > 2 cm, there is a paucity of reported cases, let alone by minimally invasive approach. The largest case series in the literature is Jin et al.'s case series of 56 cases performed between March 2010 and July 2015, of which 31 cases were approached robotically [23]. While the patients were similar in their baseline demographics, the robotically approached cohort had significantly less median estimated blood loss and median shorter operative time compared to open cases (30 cc vs 100 cc, $p = 0.001$; 100 min vs 140 min, $p = 0.009$). Of note, the authors conducted a subgroup analysis to assess the relationship between the development of CR-POPF and the distance between the pancreatic duct and the enucleated mass. They concluded that a distance of ≤ 3 mm correlates with higher incidence of CR-POPF ($p = 0.024$). Pancreatic fistula remains the Achilles Heel of any enucleation procedure which can make selection of this approach highly regrettable.

Central Pancreatectomy

Central pancreatectomy is indicated in cases where the mass resected is indolent in nature. The main advantage of performing a central pancreatectomy as opposed to a distal or an extended pancreaticoduodenectomy is parenchymal preservation. In a systematic review of reported central pancreatectomy cases between 1993 and 2017, a total of 38 robotic central pancreatectomy cases were compiled among a case series of 100 patients undergone a minimally invasive approach [24]. This cohort was compared to another compiled case series of open central pancreatectomy ($n = 872$). The mean morbidity and mortality rates were compared between open (43.2% and 0.24%, respectively) and minimally invasive surgery (37.3% and 0, respectively) approaches. As for the rate of POPF, the open approach had a mean overall POPF and CR-POPF rates of 28% and 19%, respectively. The rates of overall POPF and CR-POPF for minimally invasive approach were 36.3% and 17%, respectively. The number of reported robotic central pancreatectomy cases remains low; however, technical feasibility has been established in experienced hands.

Total Pancreatectomy ± Islet Cell Transplantation

Robotic total pancreatectomy remains an uncommon procedure. The National Cancer Database captured 3876 cases performed between 2010 and 2014 [25]. Only 73 (1.9%) cases were approached robotically. Having said that, an upward trend was noted over the years with the number of cases tripling from 8 to 24 cases per year over the 5-year period. Indications were pancreatic ductal adenocarcinoma (73%) followed by intraductal papillary mucinous neoplasm and mucinous adenocarcinoma. Of note, most procedures were performed at academic centers. The oncological outcomes between the robotic vs laparoscopic vs open approaches were comparable regardless of the approach selected, i.e., margin negativity (89.6% vs 89.9% vs 85.9%, respectively; $p = 0.14$) and median number of lymph node retrieved (14 vs 14 vs 15, respectively; $p = 0.06$). When 30 days (2% vs 1.2% vs 4.8%) and 90 days (4.3% vs 5% vs 9.4%) mortality were compared, minimally invasive approaches had more favorable outcomes compared to open ($p = 0.02$). Total pancreatectomy performed in the setting of chronic pancreatitis is challenging due to obscured dissection planes and distorted landmarks as a result of the ongoing inflammation. Only 9 cases were reported in the literature for chronic pancreatitis [26, 27], underscoring the difficulty of the procedure. Seven of these were combined with auto islet cell transplantation.

Applications in Chronic Pancreatitis

Other than resection procedures for chronic pancreatitis, the robotic platform has been utilized for pancreatic ductal drainage procedures, e.g., Puestow and Frey procedures. Limited number of robotic drainage procedures have been described in the literature, i.e., Puestow $n = 8$ and Frey $n = 4$. Collectively, the median operative time was 210 min, and the estimated blood loss and length of hospital stay were 45 cc and 7 days, respectively [28].

Patient Registries

Outcome registries are valuable in assessing the introduction of innovative surgical procedures. Given the relative scarce number of pancreatic resections, and the even fewer number of patients who would be suitable for a robotic approach, it is important to compile broad experience rather than wait for single-center numbers to reach a certain threshold for meaningful outcomes. Furthermore, there was consensus in the Miami International Evidence-based Guidelines statement that following outcomes through registries is important for the assurance of safety and adoption of the minimally invasive approaches [21•].

Several national, regional, and international research coalitions have started registries to gather prospective data on respective procedures. An example of such registries is the American College of Surgeons National Surgical Quality Improvement Program Database which has a pancreas-specific category with pancreas-specific variables, e.g., pancreas texture, pancreatic duct size, postoperative pancreatic fistula, delayed gastric emptying to name a few. A limitation of this registry is its confinement to 30-day outcomes. This prevents researchers from exploring further outcomes such as readmissions beyond the 30-day interval. Another registry is the National Cancer Database registry, which collects information on pancreatic cancer patients and outcomes of the selected treatment modality. Unfortunately, this database does not report long-term survival and disease recurrence either. Furthermore, it cannot be utilized to assess procedural outcomes as it is not geared towards this purpose. While valuable, these registries serve as surrogates to robotic pancreatic surgery registries. Establishing a specific registry for pancreatic surgery with the aim of compiling experiences of the different approaches utilized and their long-term outcomes is essential to better study robotic pancreatic surgery.

Summary

Robotic pancreas surgery has evolved substantially with the advent of new instrumentation and the presence of a new generation of surgeons who are comfortable with the application of minimally invasive surgery and have incorporated this technology into their practices. Furthermore, applications of robotic pancreas surgery have expanded to include a more diversity of procedures. This has led to multiple consensus meetings to be held in order to help guide practice through reviewing available guidelines. Benefits of robotic surgery are starting to surface with increased number of outcome publications. All in all, noninferiority of the robotic approach, as opposed to laparoscopic and open approaches, has been established. Finally, dedicated randomized control trials are needed to better establish the benefit of the robotic approach in pancreas surgery.

Compliance with Ethics Guidelines

Conflict of interest MW and EA declare no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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