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Surgical approaches to chronic pancreatitis: indications and imaging findings

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Abstract

Chronic pancreatitis (CP) is an irreversible, inflammatory process characterized by progressive fibrosis of the pancreas that can result in abdominal pain, exocrine insufficiency, and diabetes. Inadequate pain relief using medical and/or endoscopic therapies is an indication for surgery. The surgical management of CP is centered around three main operations including pancreaticoduodenectomy (PD), duodenum-preserving pancreatic head resection (DPPHR) and drainage procedures, and total pancreatectomy with islet autotransplantation (TPIAT). PD is the method of choice when there is a high suspicion for malignancy. Combined drainage and resection procedures are associated with pain relief, higher quality of life, and superior short-term and long-term survival in comparison with the PD. TPIAT is a reemerging treatment that may be promising in subjects with intractable pain and impaired quality of life. Imaging examinations have an extensive role in pre-operative and post-operative evaluation of CP patients. Pre-operative advanced imaging examinations including CT and MRI can detect hallmarks of CP such as calcifications, pancreatic duct dilatation, chronic pseudocysts, focal pancreatic enlargement, and biliary ductal dilatation. Post-operative findings may include periportal hepatic edema, pneumobilia, perivascular cuffing and mild pancreatic duct dilation. Imaging can also be useful in the detection of post-operative complications including obstructions, anastomotic leaks, and vascular lesions. Imaging helps identify unique post-operative findings associated with TPIAT and may aid in predicting viability and function of the transplanted islet cells. In this review, we explore surgical indications as well as pre-operative and post-operative imaging findings associated with surgical options that are typically performed for CP patients.

Key words: Chronic pancreatitis—Pancreaticoduodenectomy—Duodenum-preserving pancreatic head resection—Total pancreatectomy—Islet autotransplantation—Imaging

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Introduction

Chronic pancreatitis (CP) is a chronic progressive inflammatory disease that results in fibrosis of the pancreas [1]. CP can result in tremendous morbidity and disproportionately high financial burden to the health care system [2, 3]. The aggregated cost of CP in the United States in 2012 was estimated at approximately 150 million dollars [3]. CP has annual incidence and prevalence of 5–14 (per 100,000 persons) and 14–150 (per 100,000 persons), respectively [2, 4]. A variety of genetic, autoimmune, environmental, and obstructive etiologies have been attributed to CP (Fig. 1) [5, 6]. Abdominal pain is an earlier symptom, while steatorrhea, malnutrition, and endocrine insufficiency are among the later clinical manifestations of CP [5–7]. Accurate and early diagnosis is necessary for optimal management of CP patients, especially when structural and clinical findings are subtle [7]. Various treatment options have been developed to alleviate chronic pain in patients suffering from CP [8]. In patients with advanced disease, medical and endoscopic treatments are frequently associated with inadequate or short-term pain relief, rendering the patients toward alternative surgical options for long-term and effective pain control [7, 8].

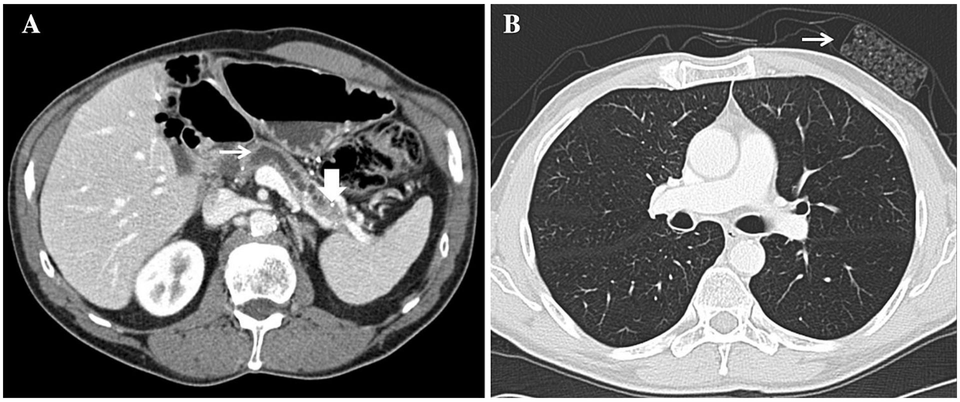

Fig. 1. 62-year-old man with history of chronic pancreatitis. CT showing pancreatic calcifications (**A** *thick arrow*), dilated main duct (**A** *thin arrow*), and a pack of cigarettes (**B** *thin arrow*) in his breast pocket indicative of association of smoking with chronic pancreatitis.

Surgery has been traditionally considered as the last choice in the course of CP management [8, 9]. Earlier surgical interventions accompanied a high rate of post-operative morbidity and mortality [9, 10]. However, advancements in surgical techniques, as well as improved patient selection, have increased the utility of surgical procedures in the treatment of CP [11, 12]. A variety of surgical operations have been introduced in this regard [13–15]. In fact, choice of surgical procedure depends on the disease status such as site of inflammation, functional biliary obstruction, whether the pancreatic duct is dilated, and if there is suspicion of malignancy [9, 13–15]. In addition to optimized surgical techniques, endoscopic procedures and endotherapy have shown to be clinically beneficial in certain clinical scenarios, such as short-term pain management of CP patients [16, 17].

In this article, we review the pre-operative imaging findings and surgical options available to CP patients. We also demonstrate the modified post-surgical anatomy using selected illustrations and imagings, focusing on the role of imaging in the detection of post-operative changes and commonly associated complications.

Imaging protocols

Computed Tomography (CT)

At our institution, we use a dual-phase, contrast-enhanced abdominal CT scan for the imaging of pancreas [18, 19]. Multi-detector CT (MDCT) slices are obtained after the administration of intravenous contrast agent. Images are obtained at 25–30, and 60 s after the contrast administration for the arterial and the portal venous phase, respectively [20, 21]. Iodinated contrast agents (Visipaque 320 or Omnipaque 350, GE Healthcare, Waukesha WI, USA) are administrated at a rate of 4–5 mL/s. Water is used as a neutral Hounsfield unit (HU) oral contrast. Axial images are reconstructed as thin (0.75–1.5 mm) or thick (3–5 mm) intervals depending on institutional preference. Multi-planar reconstruction (MPR), maximum intensity projection (MIP), and three-dimensional (3D) volume rendering are included in the interpretation [20].

Magnetic Resonance Imaging (MRI)

Abdominal MRI and magnetic resonance cholangiopancreatography (MRCP) are performed by a standard protocol and a phased array torso coil [20]. Images are acquired before and after administrating intravenous gadopentetate (0.1 mmol/kg) contrast agent (Magnevist, Bayer, Wayne, NJ, USA). Axial and coronal T2-weighted single-shot fat spin-echo slices are derived (repetition time ms/echo time ms, 4500/92; field of view, 320 mm; matrix, 256 9 180; slice thickness, 6 mm, slice gap, 1.2 mm; receiver bandwidth, 543 Hz/pixel; flip angle, 150). For MRCP, T2-weighted fast relaxation fast spin-echo (FRFSE) sequence is obtained in a series of thin slices using respiratory triggering in coronal plane and reconstructed via the maximal intensity projection (MIP) algorithm. Axial T1 fat-suppressed spoiled gradient-echo imaging of the abdomen is performed with and without IV contrast (repetition time/echo time (milliseconds), 5.77/2.77; field of view, 320–400 mm; matrix, 192 9 160; section thickness, 2.5 mm; receiver bandwidth, 496 Hz/pixel; flip angle, 10). Images are obtained at the 20 s, 70 s, and 3 min after the contrast administration in the arterial, portal venous, and delayed phases, respectively.

Pre-operative imaging

Diagnosis of CP is made on clinical grounds and imaging evaluations. CP managements require a multidisciplinary approach to tailor various options based on individual patient's need [22]. However, CT and MRI have a significant role in initial diagnosis [7] and pre-operative assessment of CP patients [13, 14]. Pre-operative imaging findings are critical in the choice of optimum procedure for CP patients [13, 14]. Transabdominal ultrasonography has a lower accuracy when compared to CT, due to its operator dependence and technical limitations such as overlying bowel gas [23]. Endoscopic ultrasonography may have superior sensitivity in comparison with CT as it provides valuable information about changes associated with CP such as pancreatic duct dilation, small pancreatic cysts, and heterogeneous parenchymal echogenicities (Fig. 2) [24]. MDCT is the most widely used modality for pancreatic imaging. MRI is more prone to issues related to motion artifacts and the presence of stents as well as decreased sensitivity for calcification, as opposed to MDCT [25].

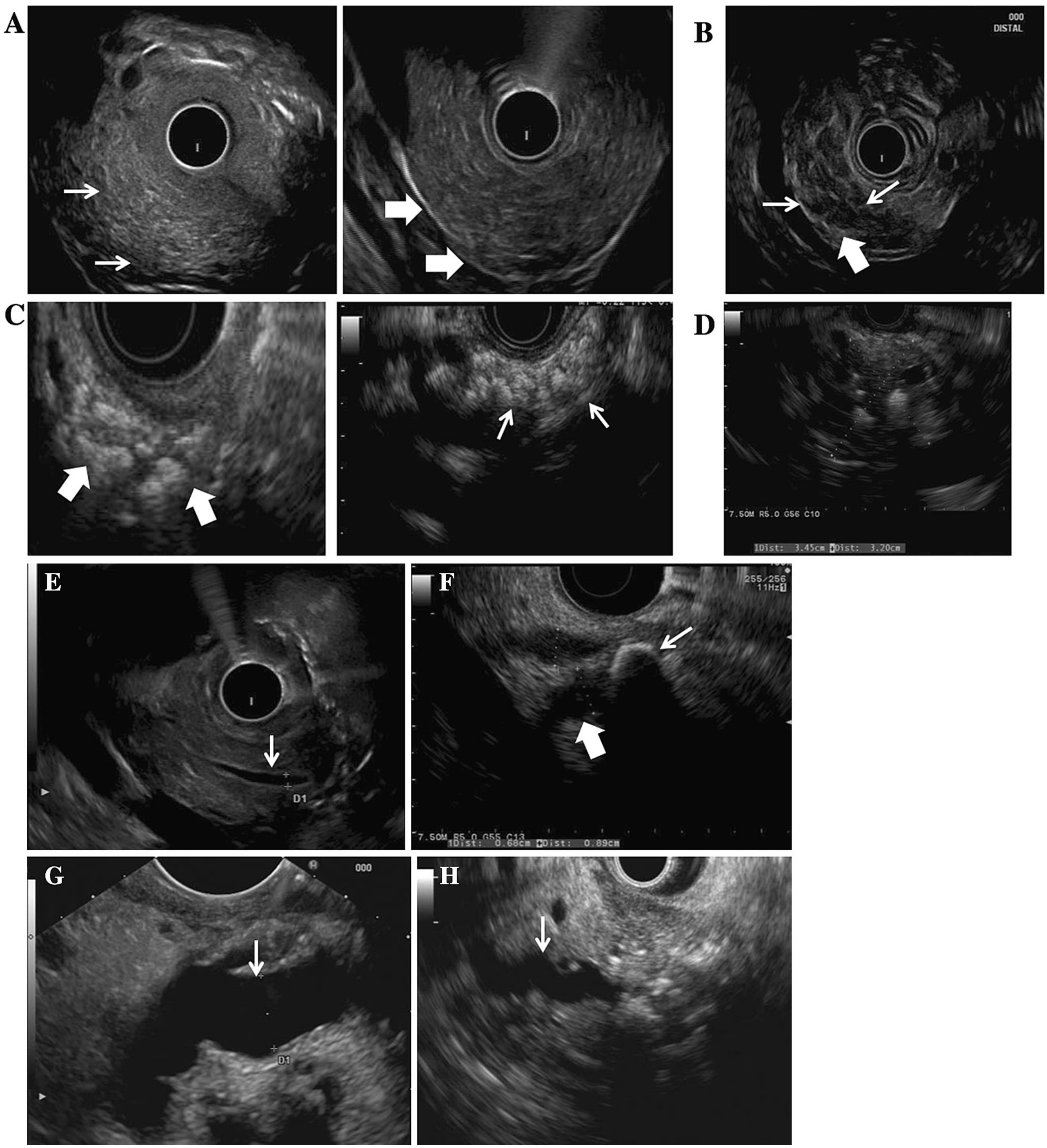

Fig. 2. Endoscopic ultrasound (EUS): Parenchymal features in chronic pancreatitis. **A** normal head (*thin arrows*) and body (*thick arrows*); **B** honeycomb lobularity (*thin arrows*), Major B criteria, and stranding (*thick arrow*), Minor criteria; **C** parenchymal shadowing calcifications in the head (*thick arrows*) and body (*thin arrows*), Major A criteria; **D** pseudo-mass (with measuring calipers) from chronic inflammation. Ductal features in chronic pancreatitis. **E** hyperechoic main pancreatic duct margin (*thin arrow*), Minor criteria; **F** intraductal stone (*thin arrow*) and upstream dilatation of the main pancreatic duct (*thick arrow*), Major A criteria; **G** dilated pancreatic duct (*thin arrow*), Minor criteria; **H** irregular main pancreatic duct (*thin arrow*), Minor criteria.

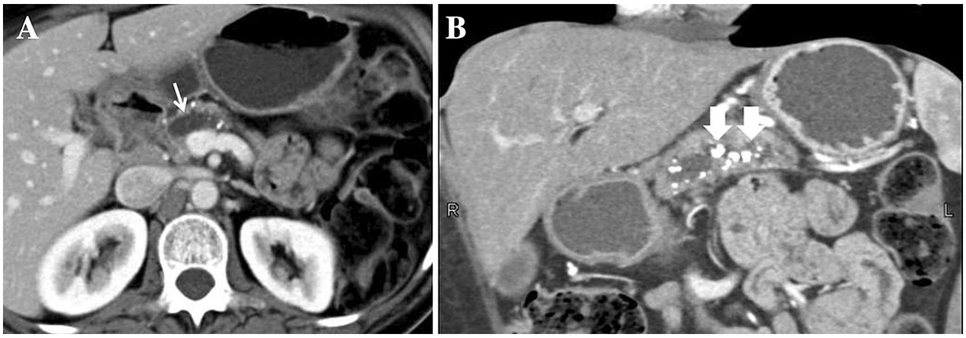

Fig. 3. 48-year-old woman with late-stage chronic pancreatitis. Contrast-enhanced venous phase CT shows a dilated main pancreatic duct (**A** *thin arrow*) and multiple intraductal calculi (**B** *thick arrows*).

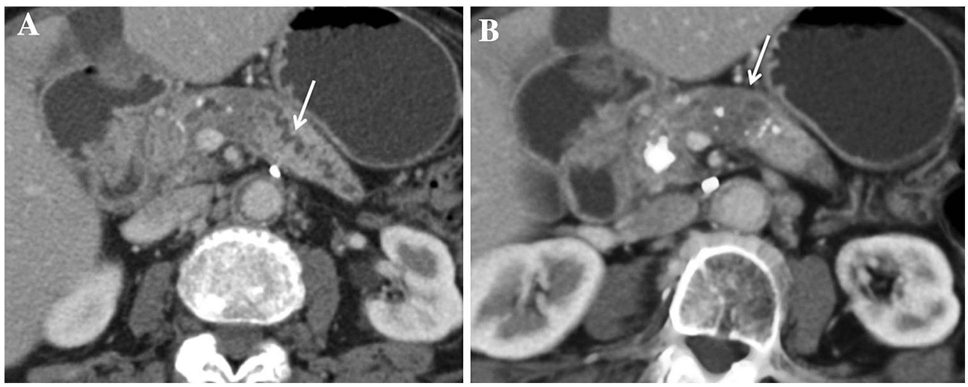

Fig. 4. 66-year-old woman with chronic pancreatitis. CT showed (**A**) a dilated main duct in the pancreatic tail (*thin arrow*) and (**B**) a hypoenhancing mass in the pancreatic body (*thin arrow*). Multiple foci of calcifications are also present. Biopsy of the identified mass was consistent with the diagnosis of pancreatic adenocarcinoma.

CT helps identify pancreatic atrophy, pancreatic duct dilatation, or parenchymal calcifications that are the hallmarks of CP (Fig. 3). It should be noted that CP can also present with normal size pancreas or with pancreatic enlargement [23, 26]. Newer studies have utilized CT perfusion (CTP) scans by using functional perfusion maps and time density curves to identify the changes in pancreatic perfusion (PF), peak enhancement intensity (PEI), time to peak (TTP), and blood volume (BV) [27, 28]. In comparison to control subjects, CP patients with and without exocrine pancreatic insufficiency have shown decreased PF, PEI, and BV while having increased TTP values. Other CTP parameters including TTP aortic enhancement and maximum aortic enhancement were not shown to be different among patients with and without CP or exocrine pancreatic insufficiency [28]. Differentiating pancreatic adenocarcinoma from mass-forming CP is also a diagnostic challenge (Fig. 4), knowing that CP patients may bear an increased risk of pancreatic adenocarcinoma as well [27]. With regard to studies of CTP parameters, pancreatic adenocarcinoma and mass-forming CP have both shown decreased blood flow, BV, and PEI and increased permeability and TTP values when compared to healthy controls. However, CTP of pancreatic adenocarcinoma may show further decreased blood flow, BV, permeability and PEI, and increased TTP values, in comparison with mass-forming CP [27]. Dual-phase CT scans may also provide additional information for evaluating CP and signs of pancreatic adenocarcinoma [29, 30]. The normal pancreas is expected to show peaked contrast enhancement in the pancreatic phase (approximately 40 s after the administration of IV contrast). Conversely, CP demonstrates delayed contrast enhancement. Pancreatic adenocarcinoma may also show a gradually increasing pattern of enhancement within a hypodense mass [29, 30].

CT also serves as an independent predictor of post-operative pain and treatment response. The number of parenchymal calcifications correlates with the degree of fibrosis, which, in turn, may be a significant predictor of pain relief after surgery [21].

Recently, MRI has gained an increased usage in the evaluation of CP [1]. Generally, MRI can be used to detect morphological changes (especially for early mild CP), similar to the characteristics that are detected on CT, though with a higher precision. MRI can also show signal intensity alteration in the parenchyma including loss of the high signal on the T1-weighted fat-saturated pre-contrast images [31]. With improved contrast resolution, MRI and MRCP can be used to demonstrate pancreatic duct stricture, pancreatic duct dilatation, and side branch irregularities as the hallmarks of CP (Fig. 5)

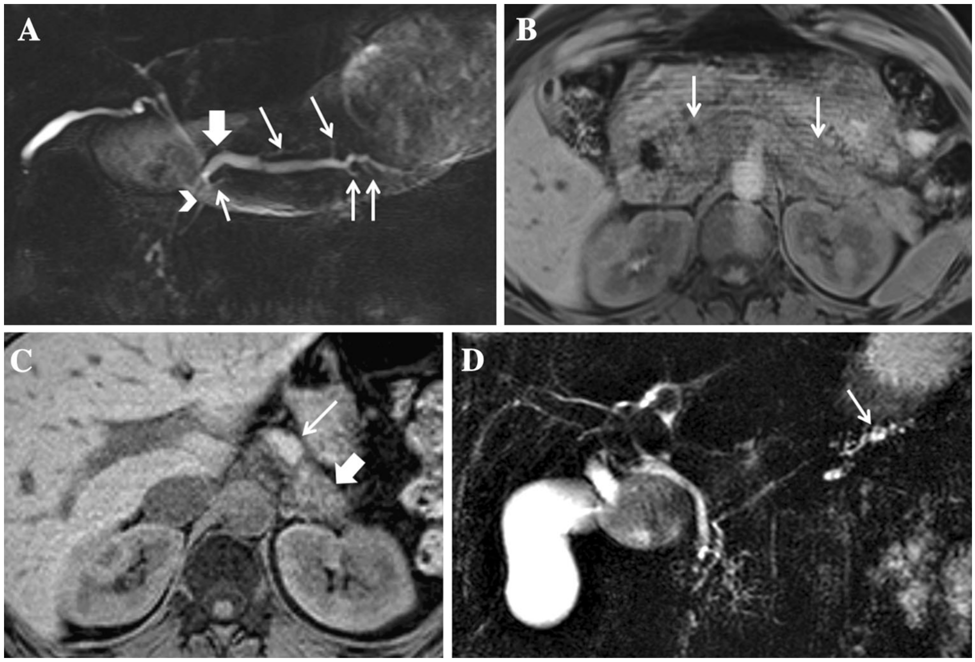

Fig. 5. **A**, **B** 27-year-old woman with late-stage chronic pancreatitis. **A** Magnetic resonance cholangiopancreatography shows greater than 3 dilated side branches (*thin arrows*), and a dilated main pancreatic duct (*thick arrow*) with a stricture in the pancreatic head due to chronic inflammation (*arrowhead*). **B** Decreased signal is shown in the pancreas on the T1 fat-saturated pre-contrast image (*thin arrows*). (**C**, **D**) 40-year-old woman with focal small duct chronic calcific pancreatitis. **C** Normal signal in the pancreatic body (*thin arrow*) and decreased signal in the pancreatic tail (*thick arrow*) on the T1 fat-saturated pre-contrast image. **D** Magnetic resonance cholangiopancreatography shows greater than three dilated side branches and focal dilated main pancreatic duct in the tail (*thin arrow*).

Table 1. Cambridge classification of chronic pancreatitis

Grade	Main pancreatic duct	Side branches
0: Normal	Normal	Normal
1: Equivocal	Normal	<3 Abnormal
2: Mild	Normal	≥3 Abnormal
3: Moderate	Abnormal	>3 Abnormal
4: Severe	Abnormal plus:	
	Duct obstruction	
	Large cavity (>10 mm)	
	Filling defect	
	Severe dilatation or irregularity	

[32]. CP is associated with loss of epithelial lining, alterations in the microvasculature and pancreatic outflow restriction [33]. Cambridge classification utilizes imaging tests to provide grading and severity of CP by demarcating the presence and severity of ductal strictures (Table 1; Fig. 6). In this regard, endoscopic retrograde cholangiopancreatography (ERCP) is a highly sensitive modality in visualizing the pancreatic ducts and can be used to detect even mild cases of CP [34]. Nevertheless, ERCP is an invasive procedure and is associated with post-ERCP pancreatitis [35].

MRCP can comparably detect moderate to severe stages of ductal strictures while avoiding the risk of pancreatitis associated with ERCP [36]. MRCP can also visualize the ducts distal to complete obstructions and reveal other associated findings including mass lesions, communicating or non-communicating pseudocysts (Fig. 7) and filling defects as a result of pancreatic stones and protein plugs (Fig. 8) [34]. MRCP sensitivity may be limited to the very early changes of CP as compared to ERCP. For instance, mild CP may be associated with changes only in the smaller side branches (Fig. 9) [32, 34]. Secretin-stimulated MRI may be able to identify the early changes by evaluating pancreas/spleen signal intensity ratio (SIR), arterial/venous enhancement ratio (A/V), and pancreatic duct caliber change (PDC) after secretin administration [37, 38]. Significantly decreased SIR, A/V, and PDC may be an indicator of diminished pancreatic exocrine function (HCO3 <80 mEq/L) and CP, even among patients with non-diagnostic MRCPs (Fig. 10) [37, 38].

A standard MRI examination, including T1-weighted imaging with fat suppression, demonstrates decreased parenchymal signal intensity and glandular atrophy in CP patients (Fig. 11) [39]. Gadolinium-enhanced MRI can also measure the pancreatic signal intensity, diagnosing early or mild CP before standard MRI changes are present [40]. In contrast-enhanced MRI, signal intensity is decreased and a pattern of delayed perfusion, due to fibrosis and chronic inflammation, is observed [39]. After gadolinium administration, normal pancreas shows the peak enhancement on the arterial phase.

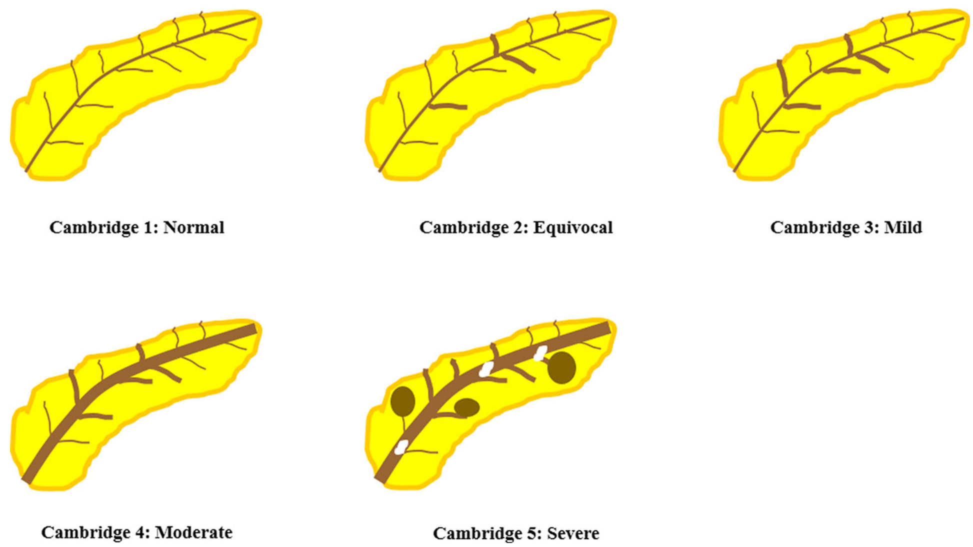

Fig. 6. Ductal changes and the Cambridge classification of chronic pancreatitis: Cambridge 1 is normal; Cambridge 2 shows equivocal features including dilatation or obstruction of less than three side branches; Cambridge 3 shows mild features including dilatation or obstruction of more than three side branches with normal main pancreatic duct; Cambridge 4 shows additional stenosis and dilatation of main pancreatic duct; and Cambridge 5 shows additional obstruction, cysts, and stenosis of main pancreatic duct and calculi.

However, CP shows the peak enhancement in the early venous phase [40]. Thus, compared to a normal pancreas, CP shows a lower enhancement in the early arterial phase and a higher enhancement in the later phases [40].

Diffusion-weighted imaging (DWI) parameters including diffusion constant, perfusion fraction (*f*), and apparent diffusion coefficients (ADC) may help differentiate pancreatic adenocarcinoma from mass-forming CP (Fig. 12) [41, 42]. Higher *f* and ADC values are in favor of the diagnosis of CP [43]. An *f* value of 11.05% was proposed as the optimal cut-off for differentiating pancreatic adenocarcinoma from mass-forming CP, with lower values indicating pancreatic adenocarcinoma [43]. Other cut-off values were proposed for ADC_{200}, ADC_{600}, and ADC_{800} parameters, as well. However, using the cut-off value (11.05%) for *f* was superior to the other cut-off values, having a sensitivity of 80.0% and a specificity of 89.9% [43]. While a recent meta-analysis has proposed a pooled sensitivity and specificity of 86% (80% to 91%) and 82% (72% to 89%) for DWI in differentiating pancreatic adenocarcinoma from mass-forming CP [41], some experts argue that DWI parameters provide no significant addition to the conventional MRI scores [42].

Surgical options

Surgical techniques that are used for the treatment of CP have undergone marked modifications and improvements, during the last decades [12]. More and more studies have advocated the use of early surgical interventions in the course of CP [44, 45]. It is suggested that early surgery in the course of CP may be superior in pain control and may reduce the risk of pancreatic insufficiency and need for further intervention [45]. However, given the complications, morbidity and mortality that are associated with CP surgeries, medical treatments, and less invasive interventions lead the mainstream of early treatment options in CP patients [7, 8, 17]. Since intractable pain is the major manifestation leading to surgery among CP patients [11, 14], pain control is the primary aim of the intervention [8, 15, 46]. Thus, different surgical options have been deployed depending upon the patient characteristics, complications, and morphology of the pancreatic ductal system and its drainage [11, 47].

Current CP surgery techniques consist of three main options including pancreaticoduodenectomy (PD), duodenum-preserving pancreatic head resection (DPPHR) and drainage procedures, and total pancreatectomy with islet autotransplantation (TPIAT) (Table 2) [7, 14, 15, 48–50]. PD is one of the most traditional surgeries which has been performed for a variety of pancreatic pathologies for decades [51]. Beger, Frey, and Puestow procedures are among the most commonly practiced DPPHR and drainage procedures which leave the duodenum unresected, focusing on a combined approach of drainage, and resection [52, 53]. TPIAT combines an old surgery with a novel treatment option, which has been argued, to provide an ultimate cure for CP [50, 54].

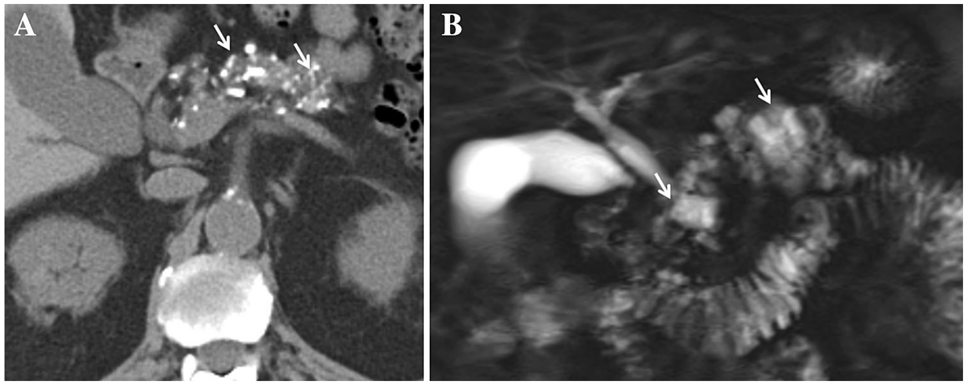

Fig. 7. 68-year-old man with chronic calcific pancreatitis. **A** Non-contrast CT showing multiple parenchymal calculi (*thin arrows*). **B** Magnetic resonance cholangiopancreatography showing multiple pseudocysts in the pancreas (*thin arrows*), demonstrating a "Chain of lake appearance" (diagnosis was confirmed using endoscopic ultrasound-guided fine needle aspiration in order to exclude multiple intraductal papillary mucinous neoplasms (IPMNs)).

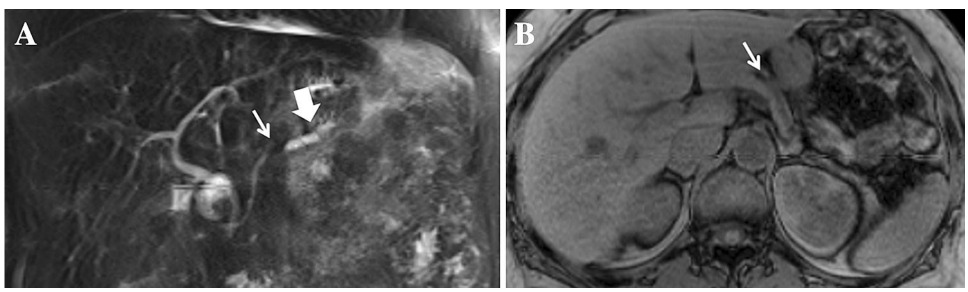

Fig. 8. 49-year-old woman with chronic pancreatitis. **A** Magnetic resonance cholangiopancreatography shows a filling defect in the main pancreatic duct (*thin arrow*) with upstream dilatation (*thick arrow*). **B** Susceptibility artifact within the main pancreatic duct in the pancreatic body (*thin arrow*) on the T1 fat-saturated pre-contrast image is consistent with an intraductal stone.

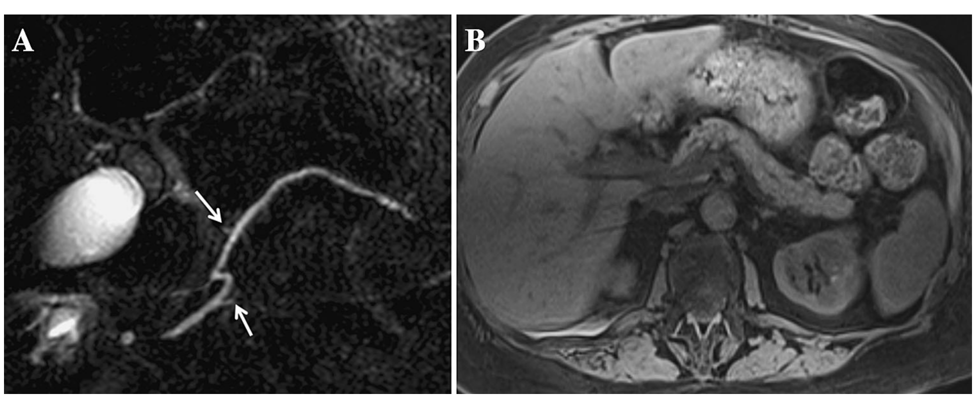

Fig. 9. 69-Year-old woman with mild chronic pancreatitis: **A** normal main pancreatic duct and two dilated side branches (*thin arrows*) and **B** normal signal in the pancreas on a T1 fat-saturated pre-contrast image.

Pancreaticoduodenectomy

Surgical indications

Classical PD is one of the first surgical operations which were used for the treatment of CP [51, 55]. In the classical procedure, pancreatic head, duodenum, proximal jejunum, and the distal portion of gastric pylorus and antrum are resected (Fig. 13). Several modifications increased its applicability and its potential usefulness for pain control in CP patients. Specifically, pylorus preservation had been introduced to the standard procedure to reduce the associated morbidity and mortality [56, 57]. PD had been classically used for the treatment of pancreatic malignancies [58]. It is still the method of

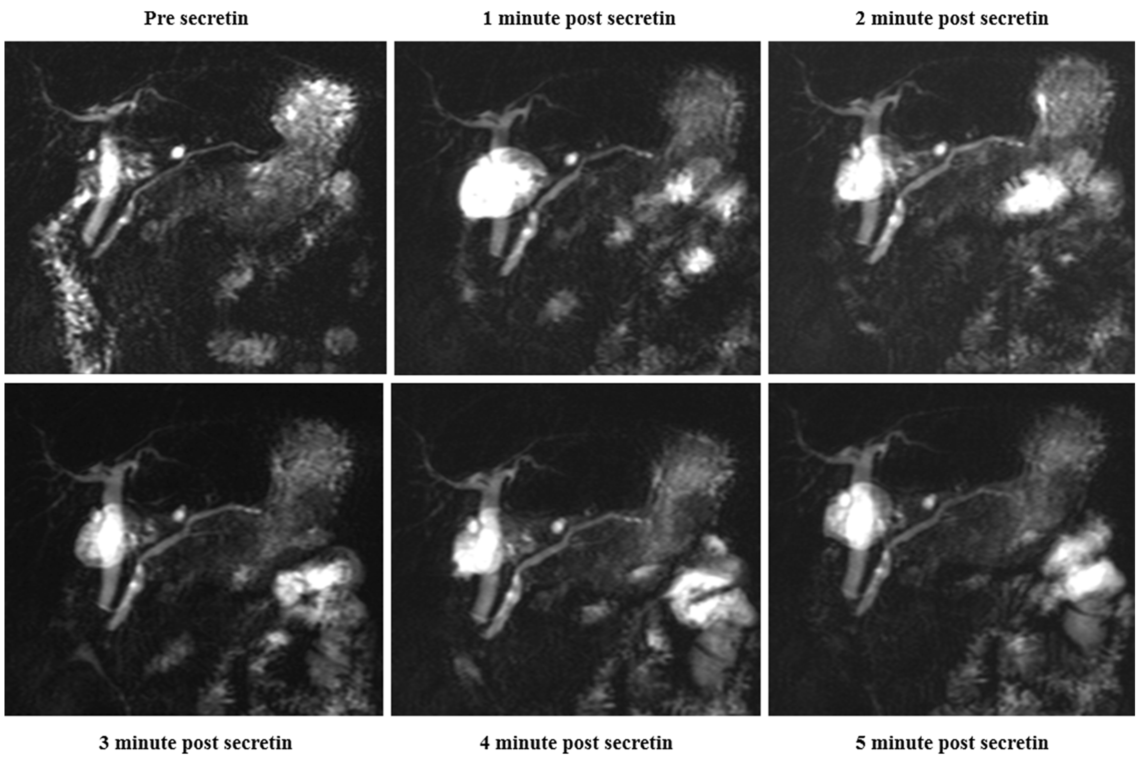

Fig. 10. 65-year-old woman with chronic pancreatitis. Secretin-enhanced magnetic resonance cholangiopancreatography showing mildly dilated and irregular main pancreatic duct in the pancreatic head with >3 pancreatic side branches (Cambridge 4) on the pre-secretin image. Grade 1 pancreatic exocrine function with lack of filling of the duodenum along with persistently dilated (>3 mm) duct at 5 min.

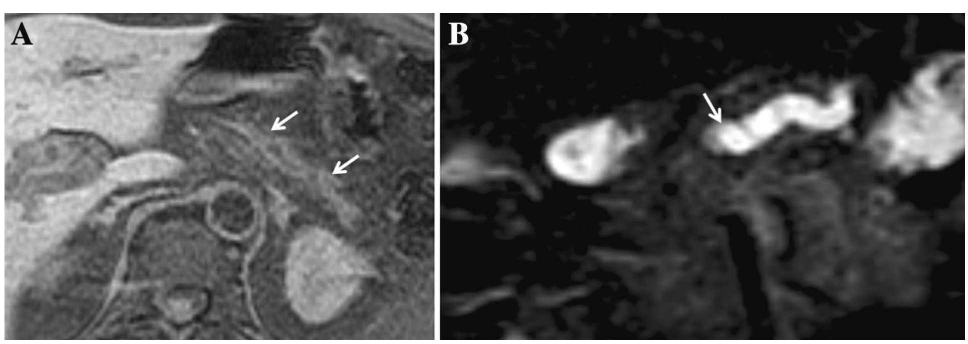

Fig. 11. 66-year-old woman with chronic obstructive pancreatitis. **A** Parenchymal atrophy and decreased signal intensity in the pancreas on the T1 fat-saturated pre-contrast image (*thin arrows*). **B** Magnetic resonance cholangiopancreatography showing main pancreatic duct's dilatation (*thin arrow*) due to an inflammatory stricture proximally.

choice when there is a high suspicion for pancreatic head malignancy in a CP patient [58, 59]. The results are more promising than pylorus preserving PD, and the pain relief is achieved in a greater number of patients when pancreatic pathology is disproportionately more severe in the head of the pancreas [57]. In summary, PD is still reserved for patients with severe CP and abnormally enlarged pancreatic head and distorted pancreatic ducts [51, 60], and in patients with small duct form of CP [61] and for duodenal stenosis due to calcific CP of the head [62]. In comparison with less invasive resections such as DPPHR, PD accompanies a higher rate of complications [63]. Despite continuous technical improvements [64], studies have demonstrated the superior quality of life, lower rates of long-term mortality, complications, and post-surgical pancreatic insufficiency, with organ sparing procedures and drainage procedures [65, 66].

Groove pancreatitis is another uncommon, yet challenging diagnosis that bears careful evaluation before CP surgery [19]. As the name implies, "Groove" refers to the

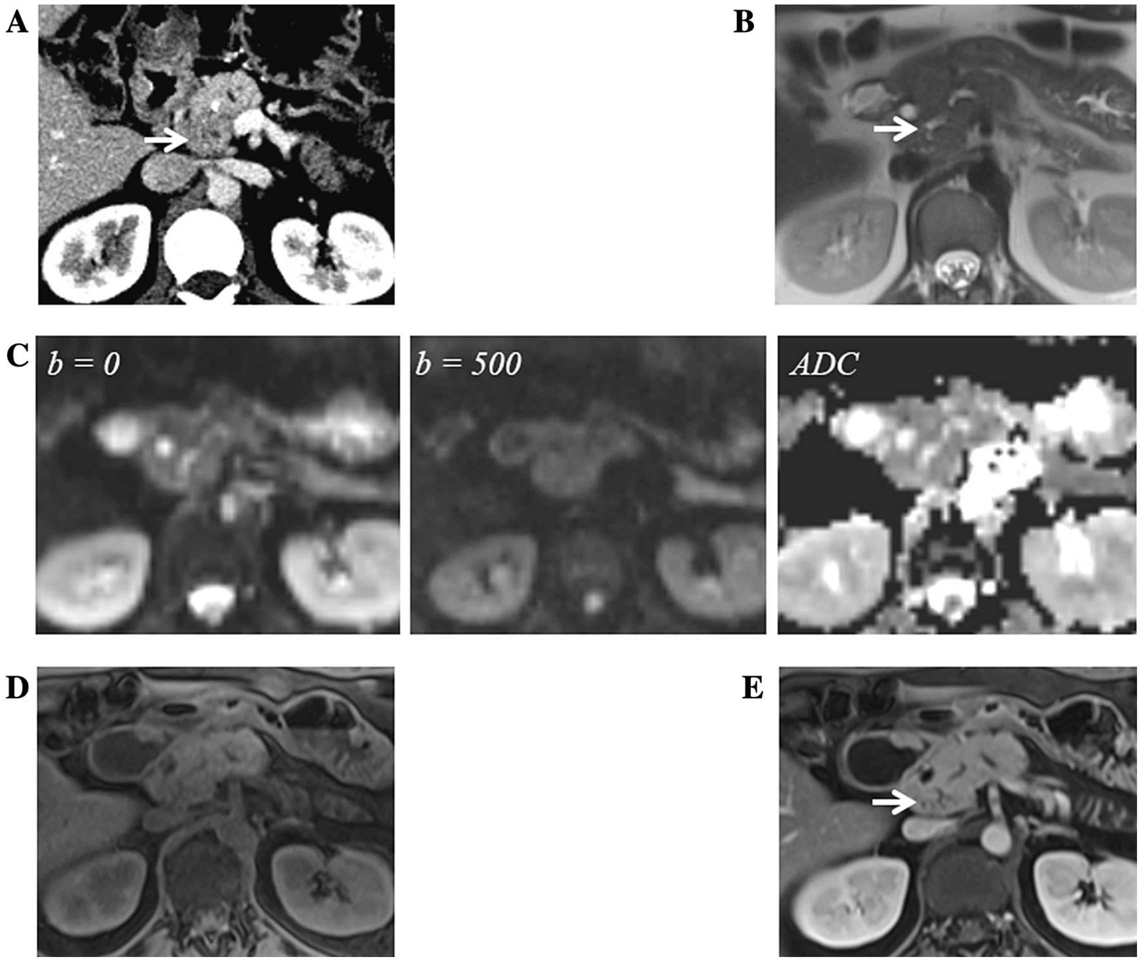

Fig. 12. 47-year-old woman with mass-forming chronic pancreatitis in the tail. **A** Venous phase CT showing a hypoenhancing area in the pancreatic head (*thin arrow*). **B** T2-weighted imaging showing main pancreatic duct being visible through the "mass like area" (*thin arrow*); duct-penetrating sign which is a typical finding for mass-forming pancreatitis. **C** No high signal on $b = 0$ and $b = 500$; signal intensity on ADC in the suspected region is same as the adjacent parenchyma. **D** Pre-contrast, venous phase T1-weighted imaging. No mass lesion is seen. **E** Post-contrast venous phase T1-weighted imaging. No hypoenhancing mass is seen. A homogeneous enhancement of the whole pancreatic parenchyma and presence of a few dilated side branches in the head (*thin arrows*) allowed an accurate diagnosis of mass-forming pancreatitis.

Table 2. Surgical options for chronic pancreatitis

Category	Surgical technique	Reviewed procedure	Indications
Resection procedures	Pancreaticoduodenectomy Pylorus-preserving pancreatico-duodenectomy	Whipple procedure (and its modifications)	Pancreatic mass suspicious for malignancy
Drainage procedures	Pure drainage (Pancreaticojejunostomy)	Puestow procedure	Diffuse dilation of the pancreatic ducts
Combined resection and drainage procedures	Duodenum-preserving pancreatic head resections	Berger and Berne procedures Frey procedure	Inflammatory mass in the pancreatic head Obstruction of the pancreatic ducts
Excision procedures	Total pancreatectomy Segmental pancreatectomy	Total pancreatectomy with islet autotransplantation	Selected genetic causes of CP Severe CP with no response to the other treatments

CP chronic pancreatitis

anatomical groove between the pancreatic head, duodenum, and common bile duct. On MRI, there is sheet-like, crescentic soft tissue within the groove that shows progressive enhancement on post-contrast imaging due to the presence of fibrosis [19, 67]. Dual-phase CT imaging can help diagnose groove pancreatitis by identifying soft tissue thickening in the pancreaticoduodenal groove and the presence of duodenal wall thickening [18]. However,

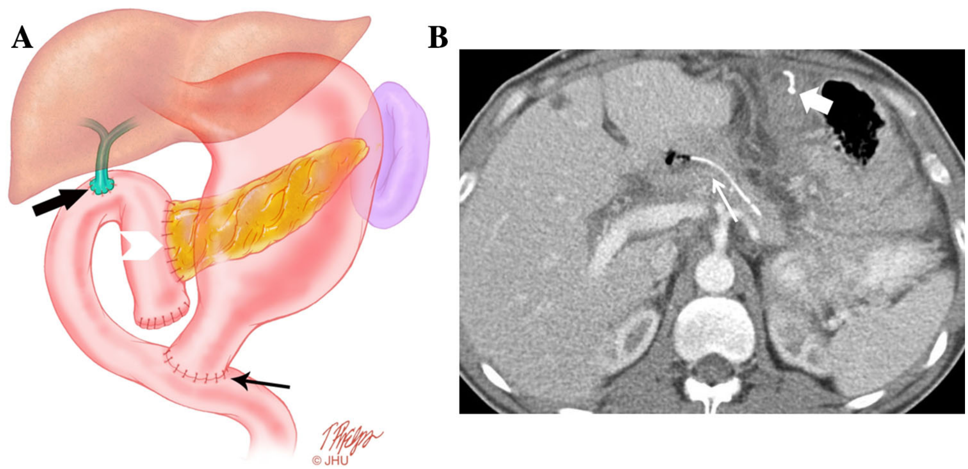

Fig. 13. **A** Schematic drawing of the Whipple procedure. Anastomoses include choledochojejunostomy (*thick arrow*), pancreaticojejunostomy (*arrowhead*), and gastrojejunostomy (*thin arrow*). **B** Post-operative imaging after pancreaticoduodenectomy showing the gastrojejunal anastomosis (*thick arrow*), pancreaticojejunal anastomosis (*thin arrow*), and the altered anatomy. Note that the pancreatic head, part of the duodenum, and the gall bladder are resected.

the majority of these patients will end up having PD procedure for suspicion of the pancreatic head malignancy and obstructive symptoms [19].

Post-operative imaging

PD surgeries, including the Whipple procedure, introduce a significant change to the anatomy of the alimentary tract. Hepaticojejunostomy, pancreaticojejunostomy, and gastrojejunostomy (or duodenojejunostomy in case of pylorus preservation) are the expected post-operative anastomoses. With the pancreatic head being removed, superior mesenteric vein and the splenomesenteric venous junction will be found closer to the inferior vena cava (IVC) [25]. Knowledge of this altered anatomy is crucial for having a precise imaging interpretation [68].

CT imaging is the most widely used modality for post-operative evaluation post-PD [69]. Periportal hepatic edema, pneumobilia, edematous afferent loops of the bowel, reactive lymphadenopathy, perivascular cuffing, and mild pancreatic duct dilation are of the most common post-surgical findings [68]. Stricture of the pancreatic duct may also develop (Fig. 14). Pneumobilia is the single most common post-operative finding. Air in the residual pancreatic duct is also considered a normal post-operative finding. However, air bubbles in the surrounding fluid may be a sign of a bowel fistula or a developing infection (Fig. 15). Reactive lymphadenopathies may also be seen. Perivascular cuffing has an inflammatory origin and presents as a soft tissue thickening of the mesenteric fat (Fig. 16) [25].

There is no indication for CT as a routine imaging for asymptomatic patients after PD [67]. It is suggested that CT should be obtained in the presence of clinical symptoms. CT is primarily obtained to assess complications associated with PD such as bowel ischemia, hemorrhage, and fluid collections [68]. Delayed gastric emptying and gastric outlet obstruction are two of the commonly associated complications. Post-operative imaging may reveal a distended stomach with a narrowed gastric outlet [70]. Anastomotic leaks are other important early post-operative complications that can be detected by the presence of fluid and gas in the surgical bed (Fig. 17) [25]. While pancreatic leaks and fistulas are some of the most important causes of mortality and morbidity after PD, leaks from the gastrojejunostomy are rare and are recognized when a fluid collection is detected in the vicinity of the gastrojejunostomy. Direct extravasation of the contrast material (in case of administrating positive oral contrast material) is strongly suggestive of anastomotic leakage [70]. Anastomotic stricture at the pancreaticojejunostomy site is a late complication [25].

CT scan can effectively identify the residual pancreas, signs of pancreatic atrophy, and the pancreatic duct. Additionally, comparison of the pre and post-operative CT can assess the progression of pancreatitis [69]. Finally, CT may detect uncommon, yet important, vascular complications. Post-operative vascular complications may develop in less than 10% of patients. Nevertheless, they are responsible for 11% to 38% of mortalities [71]. Early hemorrhage (within the first 24 h) is most commonly due to failure of the gastroduodenal artery (GDA) stump. Late hemorrhage (after the first 24 h) may be caused by vascular erosions from the pancreatic leak, fistula, infection, pseudoaneurysm, or anastomotic dehiscence [70]. Sentinel bleeding or herald bleeding from an abdominal drain may be the initial clue. MDCT angiography can show the cause and the site of the bleeding (Fig. 18) [71]. Active extravasation and arterial

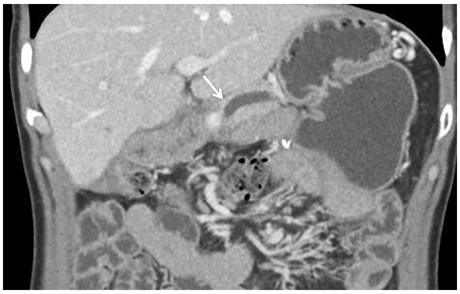

Fig. 14. 46-year-old woman with history of pancreatic divisum and chronic pancreatitis who underwent a pylorus-preserving Whipple procedure. Post-operative CT obtained 6 months later shows ductal dilation of the remnant pancreas indicative of a structure.

Fig. 15. 65-year-old man status post-operative (Whipple surgery) presented with fever, nausea, weight loss, and malaise. CT shows a 9 cm peripherally enhancing mass with multiple cystic areas (*arrow*) in the right lobe of the liver consistent with an abscess.

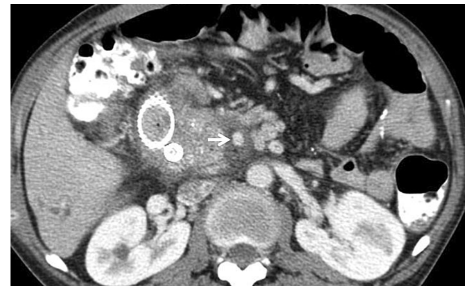

Fig. 16. 46-year-old man with history of alcohol abuse and severe chronic pancreatitis. Postsurgical CT shows the Roux-en-Y gastrojejunostomy and soft tissue thickening along the superior mesenteric artery (*arrow*), likely secondary to chronic fibrosis, as a feature of severe chronic pancreatitis.

Fig. 17. 61-year-old man status post-pancreaticoduodenectomy with pain at the surgical site. Axial contrast-enhanced CT shows a new fluid collection (*thin arrow*) at the pancreaticojejunostomy anastomotic site containing fluid and air (*thick arrow*) consistent with an anastomotic leak.

anatomy are visualized in the arterial phase while contrast pooling is best seen in the venous phase [71]. Portal vein and superior mesenteric vein (SMV) thrombosis may be overlooked when radiologists rely solely on the axial images. Short-segment filling defects, especially in the coronal plates, can help diagnose such thrombosis [70].

Duodenum-preserving pancreatic head resection and drainage procedures—Beger, Frey, and Puestow procedures

Surgical indications

Beger, Frey, and Puestow procedures are the main duodenum-preserving procedures that were introduced as alternatives to the classic PD procedure in CP [52, 72]. The Puestow procedure is mainly a drainage procedure that consists of a longitudinal pancreaticojejunostomy with or without distal pancreatectomy. It includes a side by side opening and anastomosis of both the pancreas (from the uncinate process to the tail) and the jejunum. Frey procedure includes pancreatic head resection with a longitudinal side-to-side anastomosis of the pancreas and the jejunum (Fig. 19). As a result, the anatomy of the bile duct is preserved. In Beger procedure, the pancreatic head is resected, and an anastomosis connects the remainder of the pancreatic duct to the jejunum (Fig. 20). Beger procedure does not have longitudinal anastomosis of the pancreatic ducts, as it is mainly a pancreatic head resection and is used in CP cases with enlarged pancreatic heads [68]. In general, the aforementioned procedures may be indicated in cases with ductal dilatation [52, 72]. Similar to all other CP surgeries, the most important indication for these procedures is the presence of persistent, intractable pain. Other classical indications embrace local complications related to CP such as pancreatic ductal obstruction and common bile duct stenosis [55]. Unlike endoscopic treatments (like endotherapy), these procedures are associated with complete pain relief [73] and higher quality of life [17, 74]. A direct comparison of DPPHR procedures with PD revealed shorter duration of procedure (246 vs. 360 min), less blood loss (214 vs. 535 mL), and shorter hospital

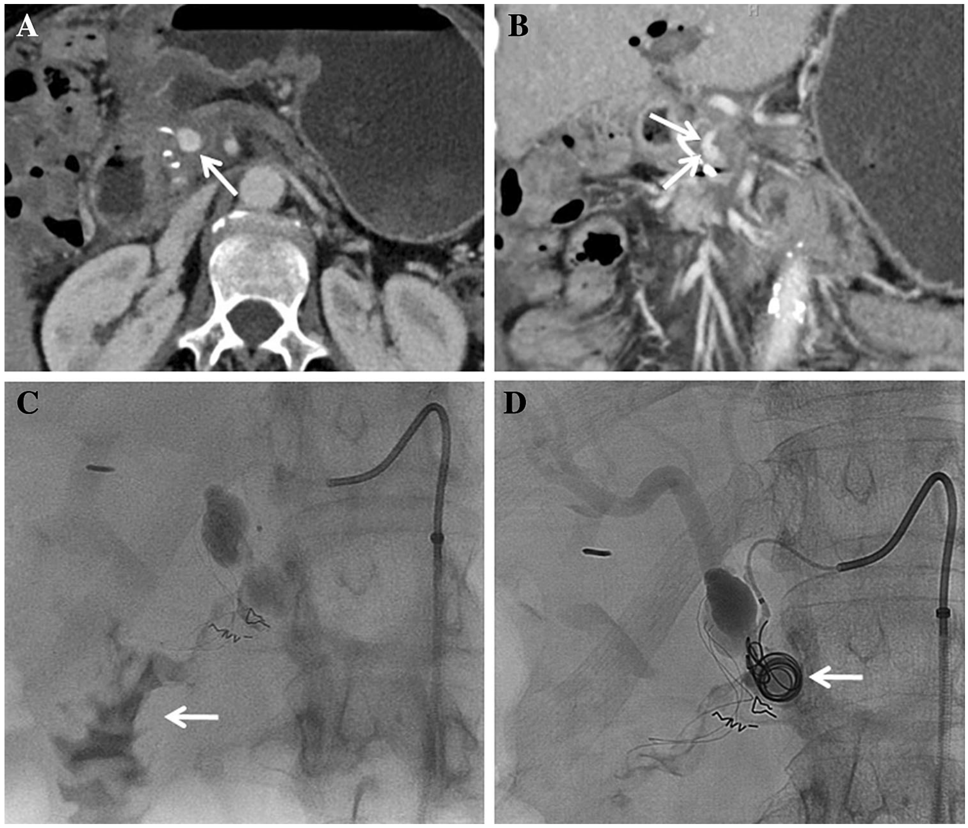

Fig. 18. A 69-year-old woman status post-pancreaticoduodenectomy arrived at the emergency department becoming hemodynamically unstable. CT showed a small pseudoaneurysm and contrast extravasation from the gastroduodenal artery stump into the patient's new pancreatic head resection site (*arrows* in **A**, **B**). The patient was presented to interventional radiology unit for mesenteric angiogram and embolization of the hemorrhage. Visceral arteriogram demonstrated active extravasation from the gastroduodenal artery stump near its takeoff from the common hepatic artery, with pooling of contrast and hemorrhage into the small bowel (*arrow* in **C**). Successful embolization of the gastroduodenal artery was performed using one coil and a microvascular plug (*arrow* in **D**).

stay (9.5 vs. 12.0 days) for the patients receiving DPPHR procedures [74].

More recent studies have focused on the comparison between these procedures [75–77]. Meanwhile, some experts have adopted combined approaches by mixing selected features of each procedure [73]. The combined procedures may be as equally effective while preserving the endocrine and exocrine function of patients (Fig. 21) [73]. Among the DPPHR and drainage procedures, studies suggest a similar overall effectiveness for Frey, Beger, and even modifications including the Berne procedure (Berne procedure is a technically simplified modification of the Beger procedure which spares the dissection of pancreatic body and avoids laying the pancreatic duct open) [64, 76, 78]. Some experts suggest the Frey procedure to be superior in pain control while subjects receiving the Beger procedure tend to have lower trends of endocrine and exocrine insufficiency [75]. Nevertheless, other studies have reported better pain control for the Beger, and lower trend of post-operative complications for the Frey procedure [15]. On the other hand, subjects with diffuse pancreatic duct dilations with less involvement of the head are better candidates for Puestow procedure [25].

Post-operative imaging

Changes in the post-operative imaging findings follow a similar principle and are closely related to the anatomic alterations [68]. The longitudinal anastomosis of the jejunal loop may be apparent on the anterior surface of the pancreas (as in the post-operative imaging of Puestow procedure). As with any similar jejunal loop, the anastomosis may appear as a bulging bowel lumen filled with fluid. However, unlike in post-pancreaticoduodenectomy, pneumobilia is not a common finding. In the immediate post-operative period, peripancreatic soft tissue stranding has a presentation similar to acute pancreatitis [25]. The presence of a fluid-filled area in the pancreatic head that corresponds to the resected section of the gland, and biliary dilations particularly after the Frey procedure, is one of the important considerations

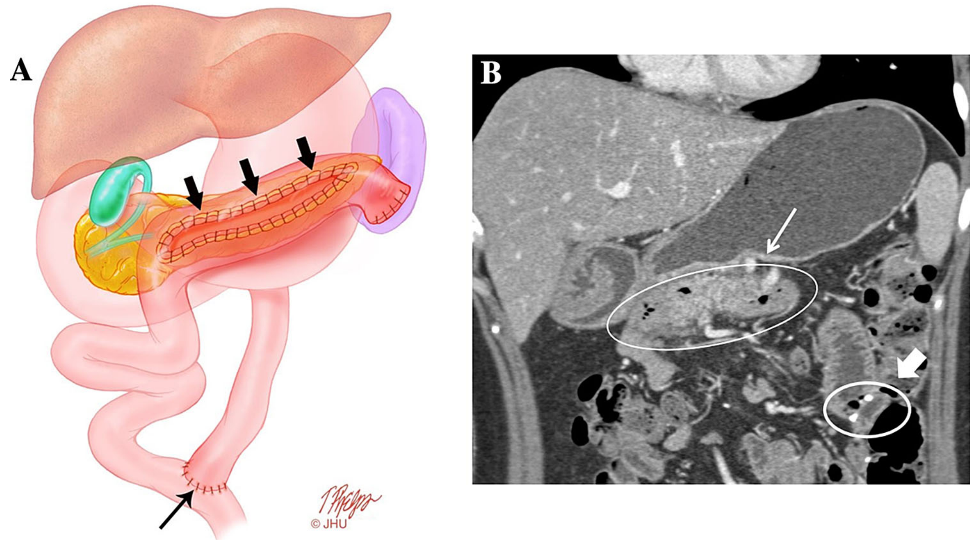

Fig. 19. **A** Schematic drawing of the Frey procedure. Anastomoses include pancreaticojejunostomy (*thick arrows*) and jejunojejunostomy (*thin arrow*). **B** Post-operative imaging after the Frey procedure showing the lateral pancreaticojejunostomy (*encircled* and *thin arrow*), distal jejunal anastomosis (*encircled* and *thick arrow*), and the altered anatomy. Note that the pancreatic duct is opened and anastomosed laterally, and the pancreatic head has undergone a wedge resection.

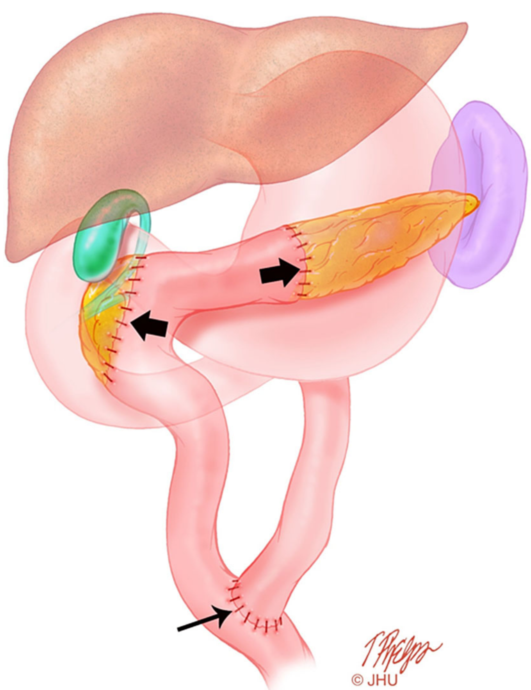

Fig. 20. Schematic drawing of the Beger procedure. Anastomoses include pancreaticojejunostomy (*thick arrows*) and jejunojejunostomy (*thin arrow*).

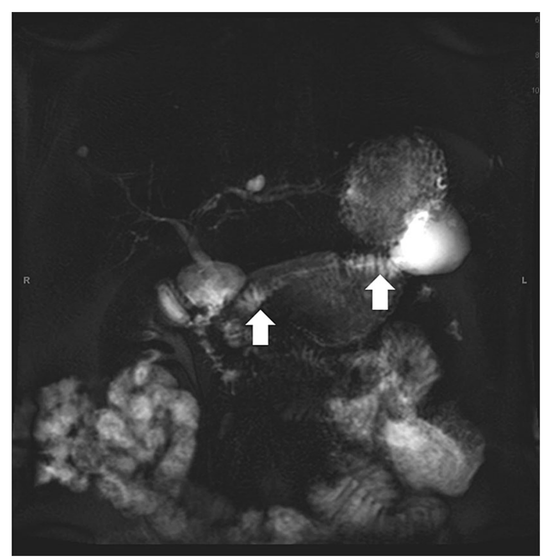

Fig. 21. 65-year-old woman status post Frey procedure for chronic pancreatitis. Post-operative secretin-enhanced magnetic resonance cholangiopancreatography shows filling of the jejunal loops with pancreatic fluid (*arrows*).

during interpretation of post-operative CT or MRI imaging [68]. Differentiation of a fluid-filled loop from fluid collections may be performed by administration of positive oral contrasts. Particular attention should be given to the vessels, including arterial and portal venous branches, for early detection and secondary prevention of associated hemorrhage, thrombosis, or aneurysms [79]. MDCT remains as a critical evaluation when transient fluid collections, hematomas, obstructions, and adhesions are suspected [25, 80]. Residual small pancreatic ductal stones, recurring pancreatitis, and abscess are other complications that are associated with Puestow procedure. Bleeding from the splenic artery and stump of the gastroduodenal artery may occur after Frey procedure and may require surgical intervention. On the other hand, fluid collections (as a result of large pancreatic head removals) and gastroenteric fistulas are usually managed conservatively.

Large pancreatic head removals may lead to common bile duct (CBD) and duodenal ischemia due to sacrificed pancreaticoduodenal arteries. In these cases, the second portion of the duodenum and the distal bile duct may be resected to prevent complications resulting from ischemia to these organs. To prevent the ischemia in the first and third portions of the duodenum, the gastroduodenal and the anterior inferior pancreaticoduodenal arteries should be reserved [81]. Duodenal or CBD ischemia may present as bowel obstruction or CBD dilation and can be seen in the post-Beger procedure [25]. Not surprisingly, the large size of the pancreatic head is associated with a superior outcome when Beger procedure is performed [82]. In fact, patients with localized inflammatory mass in the pancreatic head may be at increased risk of bile duct obstruction even before presenting with cholestasis or jaundice [83].

Total pancreatectomy with islet autotransplantation (TPIAT)

Surgical indications

Despite numerous modifications, both PD and DPPHR procedures are associated with high readmission rates after the CP surgery [84]. Failure of the aforementioned surgeries led the investigators to design disease-specific treatments. While TP was introduced decades ago, islet autotransplantation and TPIAT are of the most recently investigated issues for surgery in CP [50, 54, 85]. Given the high cost of CP, recent studies have declared TPIAT as a cost-effective treatment for patients with minimal change CP (MCCP) [86, 87]. Although there is no agreement on how it is diagnosed, MCCP is characterized by chronic inflammation and destruction of the pancreas without main duct dilation. While the entire gland is affected, MCCP patients frequently present without conventional imaging findings of CP [87]. Patients suffer from disease progression and intractable pain that is not amenable to drainage procedures. With classical resections and PD, the pancreatic remnant remains as the source of pain. Experts argue that islet autotransplantation has rejuvenated the choice of total pancreatectomy in MCCP patients [86, 87].

In spite of the extensive need for further research to unveil the actual effectiveness, target population, and clinical recommendations regarding the use of TPIAT, primary studies had promising results in the treatment of CP patients [50, 54, 85]. Recent recommendations suggest intractable pain and impaired quality of life as the main indication for TPIAT, while active alcoholism, active illicit substance use, uncontrolled psychiatric illness, and poor support network (due to the cost issues) were suggested as contraindications [54]. TPIAT is one of the treatment choices in cases of CP due to genetic mutations [87]. Effective harvest and autotransplantation of the pancreatic tissue are the critical steps for successful TPIAT [88]. History of previous CP surgeries, the extent of pancreatic fibrosis, and islet yield are determinants of insulin requirements after TPIAT [88]. Thus, subjects with prior pancreatic surgery [89] and/or concurrent diabetes [90] should undergo a careful evaluation before being considered as suitable candidates for TPIAT. In fact, TPIAT may be the best option for patients who risk CP pain for insulin-dependent diabetes mellitus [91]. More researchers are expanding the target population for TPIAT to the pediatric patients with CP, arguing for its favorable outcome in terms of pain control and improved quality of life [85, 92]. TPIAT is a promising focus for an increasing number of studies investigating a targeted, practical, cost-effective treatment for CP [48, 50].

Post-operative imaging

As mentioned earlier, knowledge of modified anatomy related to a particular surgical intervention is crucial to avoid misdiagnosing the complications [68]. Total pancreatectomy includes resection of the pancreas, along with the spleen and parts of the duodenum, CBD, and even the gall bladder. Duodenojejunostomy and hepaticojejunostomy are the formed anastomoses. In the post-operative imaging, edema and the transient fluid collection may be visible, due to the high extent of this surgery [25]. Other post-operative complications may include hemorrhage, bowel obstruction, and biliary leak. In addition, TPIAT has its own unique set of complications like portal vein thrombosis and peculiar hepatic steatosis [93]. Knowledge of the unique alterations of the surgical bed, and the complications that are associated with islet autotransplantation, including arteriovenous fistula formation, biliary tree trauma, and graft rejection, is crucial for having a correct diagnosis [93].

The role of imaging in TPIAT goes beyond the conventional pre-operative and post-operative image acquisitions that are performed (either for diagnosis of CP or for detection of its complications) for other CP surgeries [7, 94]. In fact, imaging examinations may be useful in characterizing the islet yield, as a key step in TPIAT. Different imaging modalities have been utilized in this regard. It has been shown that CT volumetric assessments can accurately assess the total islet yield (per pancreas weight and per patient body weight) that, in turn, predicts the islet graft function, insulin dependency, and glycated hemoglobin levels after transplantation [95]. More recent investigations have explored the same role using MRI acquisitions. Delayed interstitial phase MRI sequences in pre-operative assessments are also associated with a diminished islet yield [96]. Positron

Emission Tomography (PET) of the 18 F-fluorodeoxyglucose-labeled islet cells have also been used to track the number of successfully implanted islets [97]. However, the limited half-life of 18 F-fluorodeoxyglucose marker has restricted its applicability in later assessments of the implanted islets. Experimental studies have focused on using MRI labels that appear as low-intensity markers in the consecutive T2 weighted images (including superparamagnetic iron oxides, lanthanides, or manganese) [93, 98]. Considering the high cost of CP and complicated multidisciplinary, medical and surgical care of TPIAP, and imaging examinations are regarded as an inseparable part of the diagnosis, treatment, and cost evaluation in TPIAP [2, 86, 99].

Conclusion

Imaging modalities, including CT and MRI, have an important role in the current multidisciplinary management of CP. Although the ultimate diagnosis of CP is made with a combination of imaging and clinical findings, pre-operative decision making is largely based upon the imaging data in choosing the best procedure for CP patients. Knowledge of surgical options, their indications, and post-operative changes associated with each option is necessary for a precise interpretation of the imaging findings.

Compliance with ethical standards

Conflict of interests The authors have no relevant conflict of interest.

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