European Journal of Radiology Open 12 (2024) 100544

Contents lists available at ScienceDirect

European Journal of Radiology Open

journal homepage: www.elsevier.com/locate/ejro

Cross-sectional imaging after pancreatic surgery: The dialogue between the radiologist and the surgeon

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HIGHLIGHTS

- The dialogue between the surgeon and the radiologist is fundamental after pancreatic surgery.
- Contrast-enhanced computed tomography is the modality of choice after pancreatic surgery.
- Magnetic resonance imaging should be used to detect biliary and anastomotic complications.

ARTICLE INFO

Keywords:
Pancreas
Pancreatectomy
Pancreaticojejunostomy
Pancreaticoduodenectomy
Postoperative complications

ABSTRACT

Pancreatic surgery is nowadays considered one of the most complex surgical approaches and not unscathed from complications. After the surgical procedure, cross-sectional imaging is considered the non-invasive reference standard to detect early and late compilations, and consequently to address patients to the best management possible. Contras-enhanced computed tomography (CECT) should be considered the most important and useful imaging technique to evaluate the surgical site. Thanks to its speed, contrast, and spatial resolution, it can help reach the final diagnosis with high accuracy. On the other hand, magnetic resonance imaging (MRI) should be considered as a second-line imaging approach, especially for the evaluation of biliary findings and late complications. In both cases, the radiologist should be aware of protocols and what to look at, to create a robust dialogue with the surgeon and outline a fitted treatment for each patient.

1. Introduction

Pancreatic surgery includes major procedures to treat several pancreatic and peri-pancreatic entities, ranging from chronic pancreatitis to benign cystic tumors and malignant neoplasms, above all pancreatic ductal adenocarcinomas (PDACs). These procedures unavoidably change patients' gastrointestinal anatomy and require highly experienced surgeons. Even at high-volume centers, pancreatic surgery is frequently burdened with postoperative complications, as well as with significant morbidity and mortality [1,2].

Pancreatectomy encompasses different interventions, including pancreaticoduodenectomy (PD), as well as distal pancreatectomy (DP), central pancreatectomy (CP), and total pancreatectomy (TP) [3].

PD, also defined as the Whipple procedure, is the technique of choice in case of resectable PDAC of the pancreatic head and other peri-ampullary cancers, such as distal bile duct cholangiocarcinoma, adenocarcinoma of the ampulla of Vater, and duodenal neoplasms. Less common indications for PD are pancreatic neuroendocrine tumors (NETs), gastrointestinal stromal tumors (GISTs), mucinous cystic neoplasms, isolated metastatic lesions, chronic pancreatitis with an inflammatory head mass, and severe pancreatic traumas [4]. The classic PD technique consists of removing the head of the pancreas, distal bile

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https://doi.org/10.1016/j.ejro.2023.100544
Received 5 November 2023; Received in revised form 29 December 2023; Accepted 29 December 2023

duct, gallbladder, duodenum, the first tract of the jejunum, and distal stomach. Intestinal continuity is reestablished by creating an anastomosis between the resected stomach and jejunum (gastrojejunostomy). A pancreaticojejunostomy and a choledochojejunostomy are also performed to allow the excretion of bile and pancreatic enzymes into the small bowel [5]. Over the years, a few variations of the PD conventional approach have been developed. The most common one is the pylorus-preserving pancreaticoduodenectomy (PPPD), in which the duodenum is transected immediately distally to the pylorus and a duodenojejunostomy is performed [6].

Nowadays, TP is indicated in case of malignant tumors growing from the pancreatic head into the left pancreas, recurrent malignancies in the pancreatic remnant, pancreatic head cancers where it is not possible to secure a tumor-free resection margin, multifocal intraductal papillary mucinous neoplasms with potentially malignant foci present in all parts of the gland, multiple pancreatic metastases, multifocal NETs, and in case of a leaking pancreatojejunostomy with sepsis or bleeding after PD [7].

DP is indicated for tumors located in the pancreatic body and tail, but also for chronic pancreatitis, pancreatic injury, and arteriovenous malformation located in the body and tail of the pancreas [8]. This procedure may be performed by open laparotomy or with a laparoscopic approach [9]. DP entails the removal of a portion of the pancreas extending to the left of the superior mesenteric vein/portal vein trunk, with the exact line of transection depending on the location of the lesion, while the duodenum and distal bile duct are not resected. Typically, DP is associated with splenectomy, even if, depending on the extent of the lesion, spleen-preserving techniques are also used [10].

CP generally represents an alternative approach to DP in the management of benign or low-grade malignant lesions located in the pancreatic neck and body, intending to reduce the loss of parenchyma and therefore postoperative endocrine and exocrine pancreatic failure [11]. Fig. 1 summarizes the most important surgical approaches in pancreatic surgery.

In patients with severe acute necrotic pancreatitis and infected necrosis, pancreatic necrosectomy (PN) is a treatment option, usually performed after the failure of less invasive techniques, such as percutaneous drainage of pancreatic necrosis [12]. PN can be realized through a conventional open approach or with minimally invasive techniques, including percutaneous, laparoscopic, or endoscopic ones [13,14].

All these surgical procedures are associated with several post-operative complications, including post-surgical bleeding, pancreatic fistula (POPF), delayed gastric emptying, pancreatitis, abscesses, biliary leaks, anastomotic strictures, hepatic complications, and splenic complications. The intervention that is most frequently associated with severe complications is PD and, even if its mortality rate has continuously decreased in recent years (nowadays approximately 1% in high-volume centers), the morbidity rates remain high (about 50%) [1,2,15].

Cross-sectional imaging has a central role in the management of patients with suspected postoperative pancreatic complications, providing surgeons with pivotal information about complications' occurrence, severity, and precise location. Practical knowledge of these possible complications and post-surgical anatomy allows an accurate interpretation of imaging findings, that may have a great impact on patients' outcomes.

On these bases, this review aims to describe the most frequent pancreatic surgery complications and their key imaging findings, focusing on the practical information that should be reported to provide the best support to surgeons in the management of these critical conditions.

2. Imaging modalities and appearance after resection

2.1. Computed tomography

The first and most common and widely used imaging technique to evaluate patients after pancreatic surgery is contrast-enhanced computed tomography (CECT).

CECT should be considered the modality of choice in post-operative patients thanks to its acquisition speed, high spatial and contrast resolutions, and overall good diagnostic values in the detection of the most common acute, subacute, and chronic complications of pancreatic

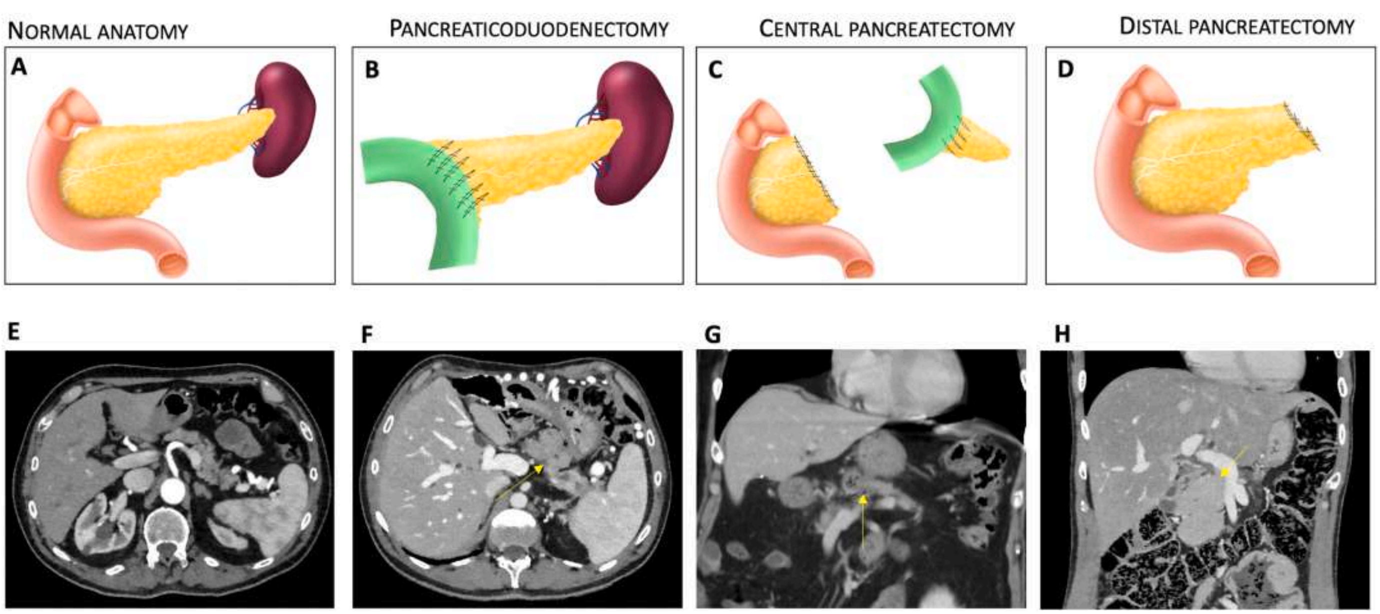

Fig. 1. Schematic representation of regular anatomy (A) and its appearance on axial CECT (E). In the case of pancreaticoduodenectomy (B), the surgeon removes the distal segment of the stomach, the first and second portions of the duodenum, the head of the pancreas, the common bile duct, and the gallbladder. After resection, three anastomoses should be completed: 1) Pancreatic anastomosis, to connect the remnant pancreas to the jejunum (green bowel loop in B, yellow arrow in F) or the posterior wall of the stomach; 2) Biliary anastomosis between the common hepatic duct and the jejunum; 3) Enteric anastomosis between the stomach and the jejunum In the case of central pancreatectomy (C), the surgeon removes the central part of the pancreas. After resection, the anastomosis between the remnant distal pancreas to the jejunum (green bowel loop in C, yellow arrow in G) or the posterior wall of the stomach should be completed. In the case of distal pancreatectomy (D), the surgeon removes the distal part of the pancreas. After resection, no anastomoses are needed (yellow arrow in H).

surgery.

Moreover, CECT is the first imaging modality of choice because it's able to clearly define the postoperative anatomy, allowing identification of the anastomoses [16].

CECT should include an unenhanced acquisition, to help detect hyperattenuating components in the abdominal cavity, especially blood products and surgical clips or devices, and to increase the detection of different alterations that can manifest a contrast enhancement in the following dynamic phases [17]. After acquiring the unenhanced phase, the pancreatic arterial phase is mandatory. The correct acquisition can be obtained by using a bolus-triggering (BT) technique, with a delay of about 18 s after reaching the threshold of 120 HU in the abdominal aorta. The pancreatic arterial phase can help obtain the correct enhancement of the remnant pancreatic parenchyma and depict early complications. Moreover, thanks to the vascular phase, it's possible to delineate the presence of active bleeding near the surgical margins [18].

After completing the pancreatic arterial phase, the portal-venous phase is mandatory. This phase should be acquired about 70 s later reaching the threshold by using BT techniques. During the portal-venous phase, all abdominal organs show their typical enhancement. On these bases, the diagnostic accuracy in the detection of pancreatic and extra-pancreatic complications can increase. The portal-venous phase is particularly useful to better delineate peri-pancreatic complications, especially abscess or wall-of-necrosis, other-than-pancreatic alterations, such as splenic or hepatic ones, and finally evaluate the patency of the most important venous structures of the abdomen [19].

The delayed phase can add important data if bleeding is suspected: by waiting for more time it's possible to better delineate low-flow bleeding near the surgical site. However, this phase should be carefully considered, especially according to the ALARA principle. In these settings, no important studies were published in the literature, and consequently, its usefulness should be considered case by case [20].

To help and increase the dialogue between the surgeon and the radiologist, multiplanar reconstructions (MPRs), especially in the coronal and sagittal planes, are recommended. This aspect should be carefully known, in particular for the surgeon, of whom the line of vision is typically oriented in non-axial planes [21].

2.2. Magnetic resonance imaging

Magnetic resonance imaging (MRI) is still considered an important imaging technique to evaluate post-operative pancreatic patients, especially thanks to its intrinsic contrast resolution and high diagnostic accuracy. However, MRI has some important limitations that should be considered before suggesting it to the surgeon. The first one is related to the requirement of breath-hold during the examination, and this aspect should be carefully considered, especially during the first days after surgery, when patients can suffer from pulmonary or pleural alterations. In fact, breathing-related motion artifacts can degrade images and reduce diagnostic accuracy [22].

Secondly, MRI suffers from high costs in terms of money [23] and time, even if abbreviated protocols have been proposed [24].

On these bases, MRI should be considered as the reference standard radiological technique for the study of biliary and pancreatic ductal systems and anastomoses. Its superior diagnostic accuracy is mainly guaranteed by cholangiopancreatography sequences (MRCP), specific heavily T2-weighted imaging (T2WI) acquired with different technical approaches. With MRCP it's possible to study the biliary system, pancreatic duct(s), and surgical anastomosis. The typical protocol to evaluate post-operative pancreatic patients should include multiplanar T1- and T2WI with and without fat saturation, diffusion-weighted imaging (DWI), and at least 3D MRCP acquisitions. According to the clinical suspicion, as mentioned in the below specific sections, it's possible to administer contrast media. In this setting, extracellular contrast agents (ECA) can be useful to evaluate pancreatic and peri-pancreatic complications. Dynamic phases can be acquired as above-mentioned for CECT [25]. In case of suspected biliary or liver complications, hepatobiliary contrast agents (HBA) can be useful, especially in detecting biliary leaks. According to the HBA injected (Gd-BOPTA or Gd-EOB-DTPA), the hepatobiliary phase can be performed to better study the biliary system and choledochojejunostomy (at least 90 or 20 min after Gd-BOPTA or Gd-EOB-DTPA, respectively) [26–28].

3. Post-surgical bleeding

3.1. Surgeon's point of view

Postoperative hemorrhage (PPH) is one of the most severe complications after pancreatic resections, with an incidence between 2% to 8% and it is responsible for 10–38% of mortality [29].

The International Study Group for Pancreatic Surgery (ISGPS) proposed a classification based on bleeding severity (mild/severe), onset (early/delayed), and location (intraluminal or extraluminal) [30,31].

The distinction between early and delayed post-pancreatectomy hemorrhage is crucial because of their different frequencies, etiologies, and treatment strategies.

Early post-pancreatectomy hemorrhage (EPH) occurs in the first 24 h postoperatively. It is most likely due to technical failure of appropriate hemostasis during the operation.

Delayed post-pancreatectomy hemorrhage (DPH) represents the majority of cases of PPH with an incidence of 3.9% after pancreatic resection and a high mortality (between 30% and 50%) [32,33].

DPH occurs typically from complications of the operation, with a usual delay of several days or even weeks, and is widely associated with vessel erosion caused by anastomotic leakage including pancreatic fistula, infection, or intra-abdominal abscess. Particularly, the pancreatic fistula may directly expose skeletonized or divided vessels, especially gastroduodenal artery stump, to active pancreatic juice, forming a region that may result in vessel erosion or even DPH.

The severity of bleeding may be either: (1) mild, characterized by light clinical impairment and low blood loss (hemoglobin level decrease <3 g/dl); (2) severe, with clinically significant impairment and severe blood loss (hemoglobin level decrease ≥ 3 g/dl) [30].

The majority of DPH arises from arterial structures, the so-called "sentinel bleeding": a small amount of blood loss via abdominal drainages or nasogastric tube several hours before massive hemorrhage may be present [33]. An immediate imaging approach after a sentinel bleeding is helpful to address the patient to an endovascular or surgical procedure.

3.2. Radiologist's point of view

The most frequently involved peripancreatic vascular structures are the gastroduodenal artery stump, followed by the splenic artery, the inferior pancreaticoduodenal artery, the splenic vein stump, or the intrapancreatic arteries [33–36]. Other common sites of PPH include the anastomoses suture lines (i.e., gastro-enteric, duodenal-enteric, jejunal-jejunal, or pancreatic-enteric anastomoses), the resection area (i.e., pancreas stump, retroperitoneum), or a ruptured pseudoaneurysm that has developed [37–39].

PPHs can be classified into (1) intraluminal (i.e., from anastomotic suture line at stomach or duodenum, pancreatic surface at anastomosis, stress ulcer, haemobilia from biliary stents placed preoperatively) and (2) extraluminal, within the abdominal cavity (i.e., from vascular structures vessels, diffuse bleeding from the resection area, anastomosis suture lines, ruptured pseudoaneurysm).

In hemodynamically unstable patients, direct angiography is considered the most appropriate method for identifying the site of bleeding, with the advantage of sparing time for a subsequent immediate intra-arterial treatment [40,41]. Conversely, in the case of hemodynamically stable patients with suspected DPH, CECT is recommended to confirm the presence of active bleeding [42,43]. CECT is a highly accurate technique for detecting the bleeding source (close to 100%), providing information on vascular anatomy (anatomical variants, vessel occlusions, etc.), and indicating the need for a selective endovascular treatment [42]. Moreover, CECT is extremely useful before angiography to avoid - if the suspicion is excluded - or guide - if the bleeding is confirmed – the interventional procedure.

The CECT protocol includes an unenhanced phase on the whole abdomen to identify hyperattenuating intraabdominal fluid consistent with hemoperitoneum or any pre-existing material, particularly surgical clips or suture material, that can be misinterpreted. For contrast-enhanced phases, high concentrations of iodinated contrast medium are mandatory, according to patient weight, administered at high flow (3.5–4 mL/s) into the antecubital vein and followed by a bolus of 40 mL of saline solution. The arterial phase is extremely useful for detecting active blushing, investigating vascular anatomy, and detecting post-operative pseudoaneurysms. Then, the portal-venous phase with a delay of 70 to 90 s from the injection, is obtained to demonstrate any possible increase of arterial extravasation or venous bleeding (Fig. 2). The delayed phase, usually obtained between 140 s and 5 min after the injection, should be also considered to confirm the extravasation, particularly in the case of patients with reduced cardiac function [44–46].

The crucial CT sign of post-operative bleeding is the contrast media extravasation outside vascular structures, which is observed as an irregular area of high attenuation (about 90 HU) during the arterial phase not detectable in the non-contrast-enhanced images. This hyper-attenuating focus presents a changing inter-phasic appearance since during portal-venous and delayed phases it tends to increase in size and change in morphology, which unequivocally confirms the diagnosis of active bleeding. Moreover, in the case of intraluminal hemorrhages, the extravasation may assume a declivous position in the intestinal lumen or a more irregular shape due to the peristalsis. The so-called "sentinel clot sign", defined as a hyperdense clot observable near the postoperative bleeding source, may be documented when recent bleeding has occurred but has stopped at the time of CECT [47] (Fig. 3).

4. Post-operative pancreatic fistula

4.1. Surgeon's point of view

Postoperative pancreatic fistula (POPF) is the leading complication after pancreatic surgery and is still considered the main source of major morbidity and mortality after pancreatic resection, affecting between 13% and 41% of patients [48,49].

It is defined as "drain output of any measurable volume of fluid on or after postoperative day 3 with an amylase content greater than 3 times the serum amylase activity" [50]. POPF develops as a consequence of pancreatic juice leakage from a surgically exfoliated surface and/or anastomotic stump, which sometimes causes intraperitoneal abscesses and subsequent hemorrhage [51].

Small pancreatic duct, soft pancreas, high-risk pathology, and excessive blood loss are the most widely recognized risk factors for pancreatic fistula [52].

A clinical grading system for postoperative pancreatic fistula has been proposed, by the International Study Group of Pancreatic Fistula (ISGPF). Grade A is defined as a biochemical leak in which there is fluid drainage with an amylase level greater than 3 times the normal limit; Grade B, with persistent drainage for more than three weeks, the need for drainage or occurrence of complications including bleeding and infections; Grade C if the POPF leads to reoperation, organ failure or patient death [53].

4.2. Radiologist's point of view

CECT is the main modality of the imaging diagnosis of POPF. However, timing and indication for CT scans during the postoperative period

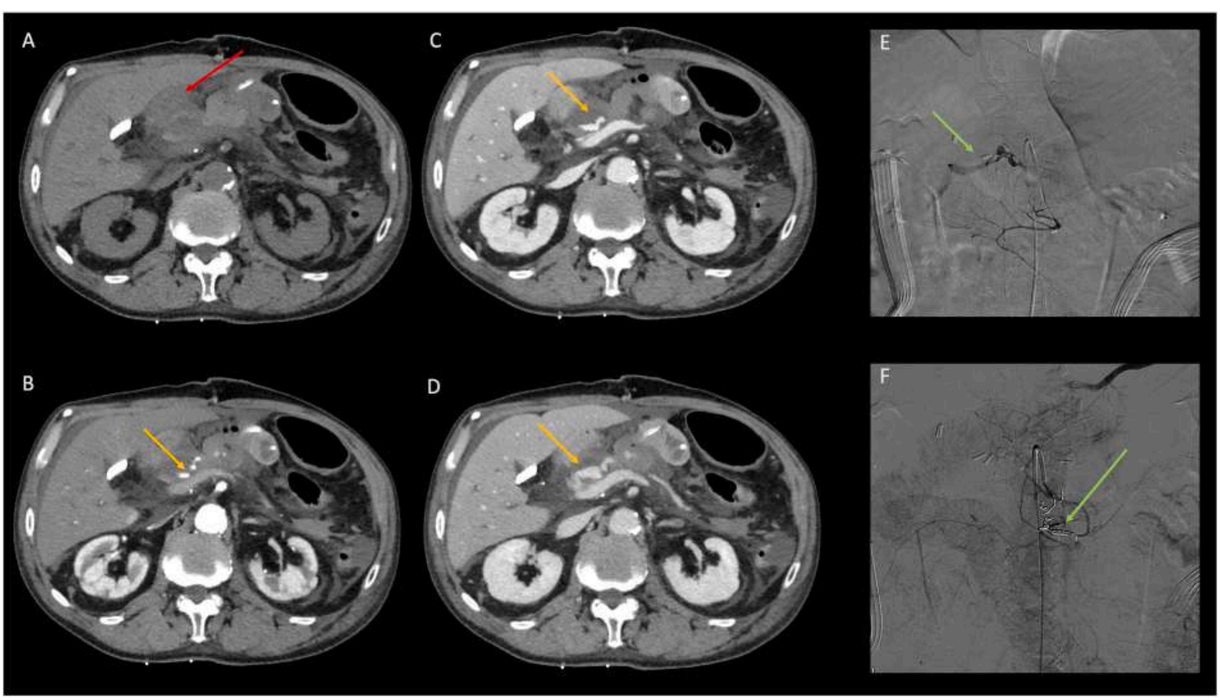

Fig. 2. 68-year-old patient underwent pancreaticoduodenectomy two days before. The abdominal drainage showed an increase of blood products and the patient was referred for a CECT. In the unenhanced phase (A) a blood clot is appreciable near the duodenum and the medial portions of the liver (red arrow). It's possible to evaluate the presence of an irregular area of hyperenhancement during the arterial phase (B) near the blood clot (yellow arrow). During the portal-venous (C) and delayed phase (D), this irregular area showed an increase in dimension. The final diagnosis an active arterial blushing. The patient was referred to the angiography team and underwent digital subtraction angiography (DSA). DSA confirmed the presence of active bleeding (E – green arrow). Finally metal coils were placed into the feeding vessel (green arrow) and the blushing resolved (F).

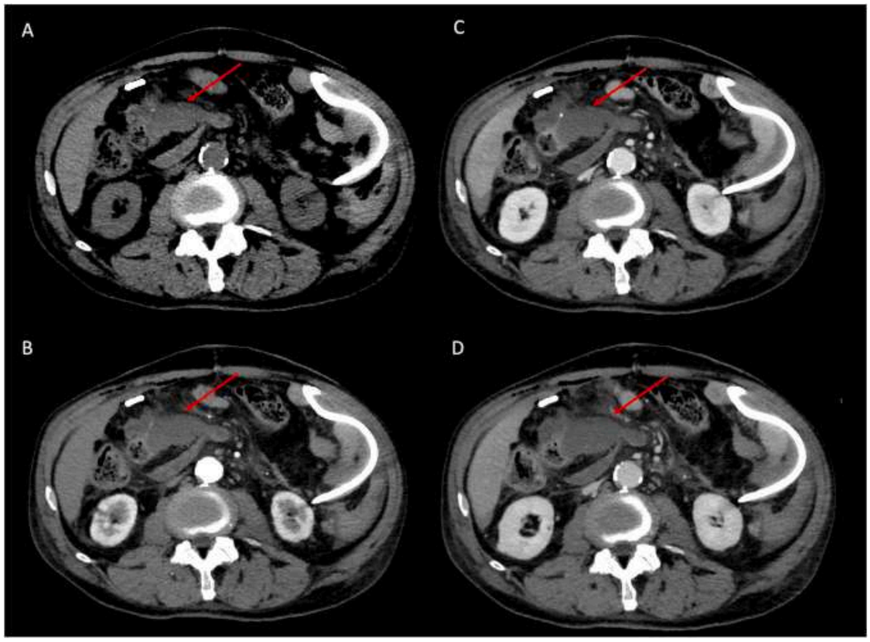

Fig. 3. 61-year-old patient underwent pancreaticoduodenectomy five days before. CECT was requested before removing the abdominal drainage. On the inferior part of the surgical area, an oval-shaped hyperattenuating on the unenhanced phase (A) was depictable (red arrow). After the contrast media injection, no active blushing was present in it (B – arterial phase, C – portal-venous phase, D – delayed phase, red arrows). The reported findings are compatible with a blood clot.

lack standardization. Systematic CT exams during the first week seem to it seems not to be effective in preventing severe postoperative complications [54]. A recent nationwide trial (PORSCH trial) proposed an algorithm for early recognition of complications and standardization for the CT scan indication based on clinical and laboratory parameters, including physical examination, drain dropout, blood test findings, and clinical examination [55]. In a retrospective study, CECT acquired at the seventh postoperative day demonstrated a sensitivity of 63% and a

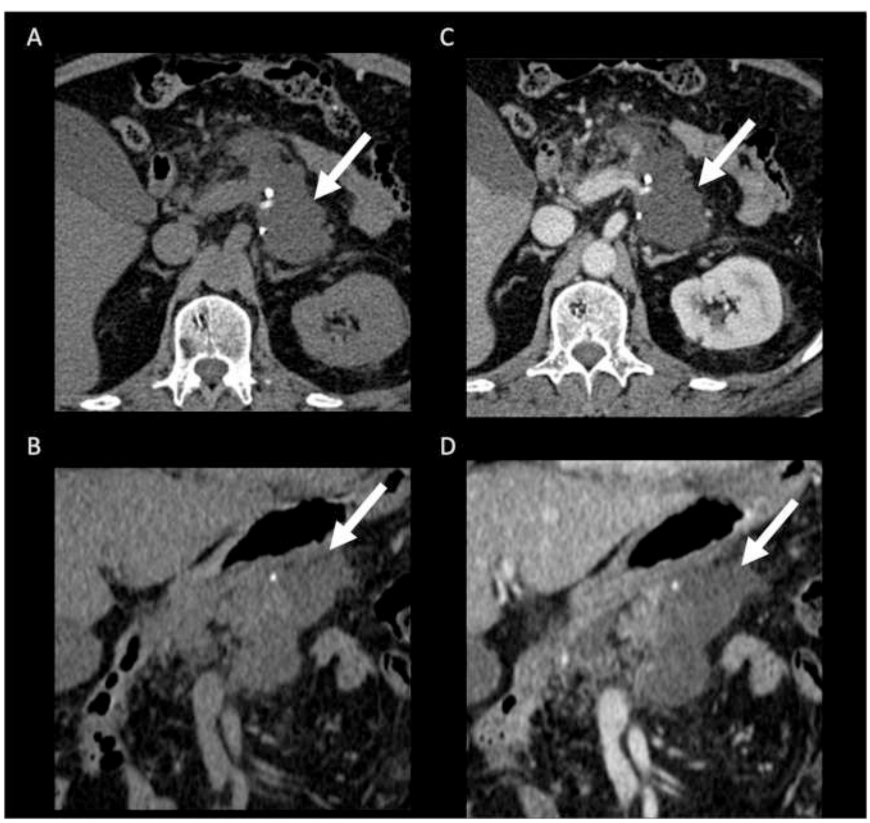

Fig. 4. 63-year-old man with pancreatic ductal adenocarcinoma who underwent distal pancreatectomy. Axial and coronal pre-contrast (A and B), axial and coronal postal-venous phase (C and D) CT images on the fifth postoperative day show a fluid collection at the resection margins (arrows) consistent with postoperative pancreatic fistula.

specificity of 83% for the diagnosis of POPF [56]. On contrast-enhanced CT, imaging findings of grade B/C POPF include the presence of a fluid collection adjacent to the pancreaticojejunostomy or at the resection margin (Fig. 4) and disruption of the anastomosis [16]. Communication between the main pancreatic duct can also be observed [19]. A retrospective study by Lee et al. on 235 postoperative patients reported that pancreaticojejunostomy dehiscence (defined by a distance >2 mm between the pancreatic duct and jejunal mucosa), pancreaticojejunostomy defect, and acute necrotic collection were more frequently observed in patients with grade C POPF compared to grade A/B POPF on contrast-enhanced CT [57]. Other complications can be associated with POPF, including hemorrhage, pancreatitis, and development of abscess or sepsis and they need to be carefully evaluated on post-contrast CT images [19].

Several risk factors have been associated with the development of POPF, which may be related to the type of surgical procedure, type of pancreatic lesion, postoperative course, and patient characteristics [58, 59]. Recent studies attempted to correlate imaging findings observed on preoperative contrast-enhanced CT with the occurrence of POPF, based on either pancreatic parenchymal findings or the patient body composition. On preoperative contrast-enhanced CT, pancreatic findings such as increased diameter of the main pancreatic duct, increased pancreatic gland thickness, pancreatic glad texture, pancreatic margins, and attenuation values have been associated with the risk of clinically relevant POPF [60–63]. Furthermore, visceral obesity and sarcopenia have also been correlated with an increased risk of POPF [64].

5. Delayed gastric emptying

5.1. Surgeon's point of view

Delayed gastric emptying (DGE) represents the inability to return to a standard diet by the end of the first postoperative week and includes prolonged nasogastric intubation, vomiting, and use of prokinetic drugs. DGE is one of the most common complications after pancreatic resection, especially after PD and its incidence ranges between 19% and 57% [65].

Three different grades (A, B, and C) were defined based on the impact on the clinical course and postoperative management, and even if DGE is a rarely life-threatening condition is usually associated with significant patient discomfort, prolonged hospital stay, and higher cost [66].

Causes for delayed gastric emptying are still unclear and are probably multifactorial, involving disruption of pylorus innervation, motility deficiency, and technical aspects. DGE usually occurs with the development of other complications including POPF, biliary leak, or abdominal collections in contact with the gastric walls [67].

5.2. Radiologist's point of view

Although not a diagnosis based primarily on imaging, the presence of a severely distended stomach filled with fluids from the upper digestive tract can be very revealing in an appropriate clinical setting [68] (Fig. 5). To help the surgeon depict this post-surgical complication is of utmost importance excluding other causes of gastric dilation, otherwise mechanical obstruction. Secondly, considering the major surgical procedure with a high risk of hypovolemic shock, it's important to evaluate gastric walls: focal ulcerations, gastric wall thickening, or the presence of intramural gas should be considered as risk factors for gastric ischemia [69].

6. Pancreatitis

6.1. Surgeon's point of view

The occurrence of an acute inflammatory process of the pancreatic parenchyma after pancreatic resections has been reported in the literature [70,71]. The ISGPS defines Postpancreatectomy Acute Pancreatitis (PPAP) as an acute inflammatory condition of the pancreatic remnant occurring in the setting of a partial pancreatic resection within the first 3 postoperative days. Its clinical impact and sequelae have been partially investigated and shown to contribute to the development of other complications, especially POPF [71–73].

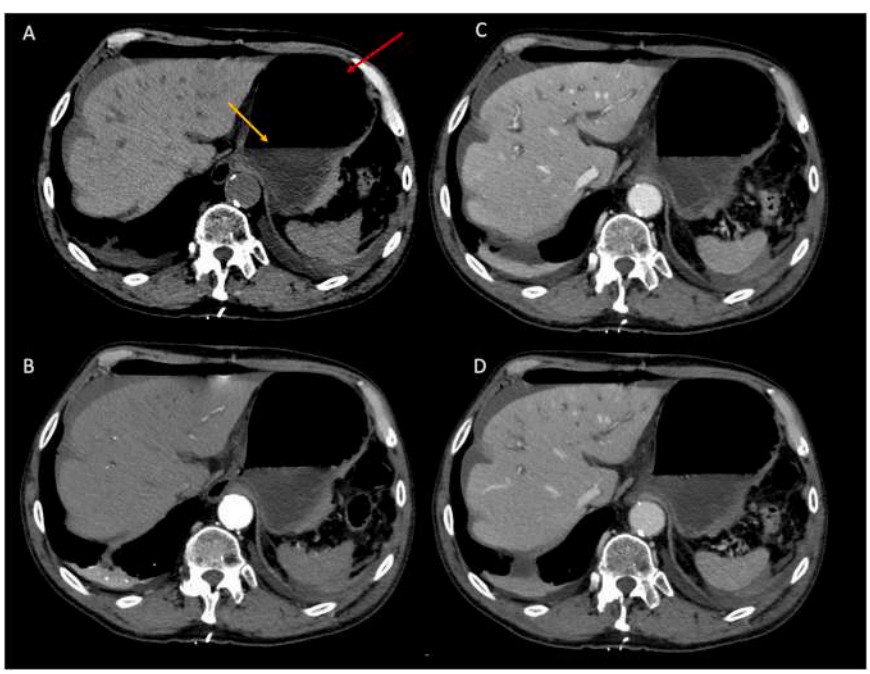

Fig. 5. 55-year-old patient underwent pancreaticoduodenectomy one day before. The patients reported vomiting and abdominal pain. The CECT showed a typical example of delayed gastric emptying. The stomach is filled with fluid, with a large air-fluid level. In similar cases, it's important to evaluate the stomach's walls, which should be homogenous in all dynamic phases (B – arterial phase, C – portal-venous phase, D – delayed phase, red arrows). A small amount of free fluid in the peri-hepatic and peri-splenic spaces was present, in line with the recent surgical approach.

Its diagnosis is based on the fulfillment of three criteria: (1) a sustained postoperative hyperamylasemia, namely a sustained increase in serum amylase activity greater than the institutional upper limit of normal persisting for at least the first 48 h postoperatively, (2) the association with a clinically relevant downturn in the patient's condition, and (3) radiologic findings consistent with PPAP [73].

6.2. Radiologist's point of view

The diagnosis of PPAP can be challenging, considering that its appearance can mimic post-operative inflammation [16]. In case of clinical suspicion, both CT and MRI can show the presence of fat stranding near the surgical site.

Other signs to be checked are focal or diffuse pancreatic enlargement, and inhomogeneous enhancement due to edema [74] (Fig. 6). Moreover, hemorrhagic components can be depictable as hyperattenuating during the unenhanced CT or hyperintense on T1WI before contrast media injection.

MRI can increase the diagnostic accuracy of pancreatitis, especially thanks to DWI: a hyperintense signal of the involved portion of the pancreas with decreased ADC values should be considered as suspected for inflammation [75].

7. Fluid collections and abscesses

7.1. Surgeon's point of view

Fluid collection and abscess formation in the upper abdomen are frequent complications after pancreatic surgery [76–78]. Postoperative pancreatic leaks and consecutive abscess formation represent a challenge in clinical management [79,80]. They occur in up to 30% of patients undergoing pancreatic resections [81].

Fluid collections and abscess following pancreaticoduodenctomy is most likely the consequence of pancreatic fistulae or leakage from the pancreaticojejunostomy or choledochojejunostomy. They are often associated with increased morbidity secondary to sepsis and are a common cause of readmission to the hospital following discharge [82].

Intraabdominal fluid collections are common in the early postoperative period and should not be confused with the more serious finding of an abscess, which manifests with signs of sepsis.

The treatment of choice for larger is drainage by percutaneous catheter techniques.

7.2. Radiologist's point of view

The natural course of acute fluid collections is variable: they can either enlarge and evolve into pancreatic abscesses or they can disappear completely. The most important variable to consider is time: the earliest are acute fluid collections and pancreatic necrosis (1st week), followed by infected necrosis (2nd to 3rd week), and finally pseudocysts and pancreatic abscesses (4th week) [83].

Peri-pancreatic fluid collections can be easily diagnosed thanks to cross-sectional imaging techniques. Acute fluid collection can be depictable as hypoattenuating fluid components near the surgical site. Fluid can be arranged in an irregular way near the remnant parenchyma, anastomosis, and vascular structures. Normally its borders are delimited by abdominal fascia and no walls should be appreciable (Fig. 7). A similar morphological appearance can be depictable on T2WI, especially with fat saturation. If proteins or hematic components are present within the fluid collection, the signal on T2 can be slightly inhomogeneous or within hypointense components due to blood degradation products [84].

In the case of pancreatic necrosis, the collection of heterogeneous attenuation components can be seen on CECT. On T2WI the signal is inhomogeneous, especially due to fat and hematic components. The pancreatic necrosis is partially or surrounded by walls, well depictable both on CT and MRI as a peripheral rim associated with contrast enhancement [85]. If the collection undergoes superinfection (infected necrosis), air components can be evident. Air bubbles are easily detected on CT, acquired in any phase. On MRI, air components can be seen as signal voids in all sequences.

Finally, late complications are easily recognizable. The presence of a fluid collection with a thickened and enhancing wall is the typical aspect of a pancreatic abscess and the presence of an air component inside is pathognomonic (Fig. 8). On the other hand, pseudocyst can be diagnosed in the case of a well-circumscribed round fluid collection, with homogenous hypoattenuating appearance and enhancing walls. On MRI, the pseudocyst contents are hypointense on T1WI and homogenously hyperintense on T2WI. Sometimes debris can be depictable as hypointense and irregular declivous components [86] (Fig. 9).

8. Biliary leakage

8.1. Surgeon's point of view

Biliary leakage after PD is reported with an incidence of up to 8% [87]. According to the International Study Group of Liver Surgery (ISGLS), biliary leakage is defined as a measured bilirubin level in drain fluid three times above bilirubin levels in plasma, on or after the third postoperative day [88]. BF occurs less frequently than postoperative pancreatic fistulas and has a lower rate of complications and mortality [89]. However, the development of biliary leakage increases the risk of sequelae such as intraabdominal abscesses [90]. Excessive skeletonization of the hepatic duct, a small duct diameter, as well as anastomosis to the common bile duct, are among the known risk factors [91]. Reconstruction techniques, percutaneous biliary drainage, and intraoperative T-tube placement are among many attempted protective measures [92, 93].

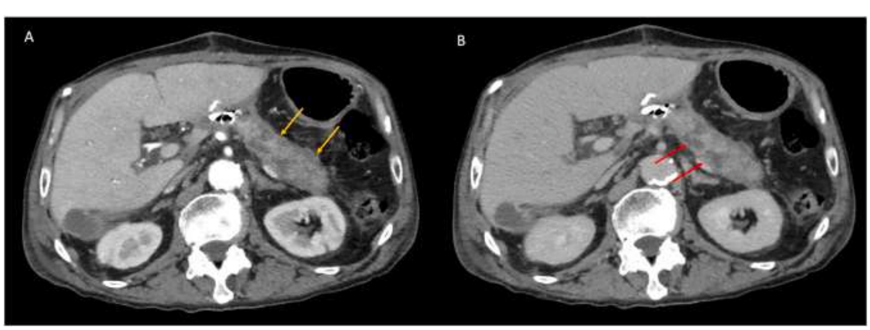

Fig. 6. 44-year-old patients underwent pancreaticoduodenectomy two weeks before. Inflammatory indexes (C reactive protein and white blood cells) showed a continuous increase during days and a CECT was required to exclude septic foci. The arterial phase (A) showed a swollen appearance of the pancreatic remnant (yellow arrows) within inhomogeneous and irregular components. The portal-venous phase (B) confirmed the presence of small and irregular hypoattenuating foci, in line with PPAP. Peri-pancreatic fat stranding was also present.

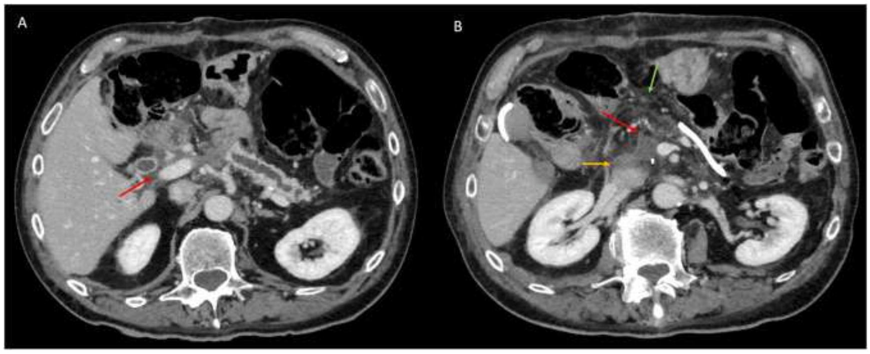

Fig. 7. 50-year-old patients underwent pancreaticoduodenectomy one week before. CECT acquired on the portal-venous phase showed a typical example of peri-pancreatic fluid collection. Fluid components are located in the hepatoduodenal ligament (A, red arrow), in the anterior paracaval space (B, yellow arrow), and in the pancreatic bed (B, red arrow). Moreover, fat stranding near the surgical site is appreciable (B, green arrow). All the fluid components are not encircled by walls and no air bubbles were detectable.

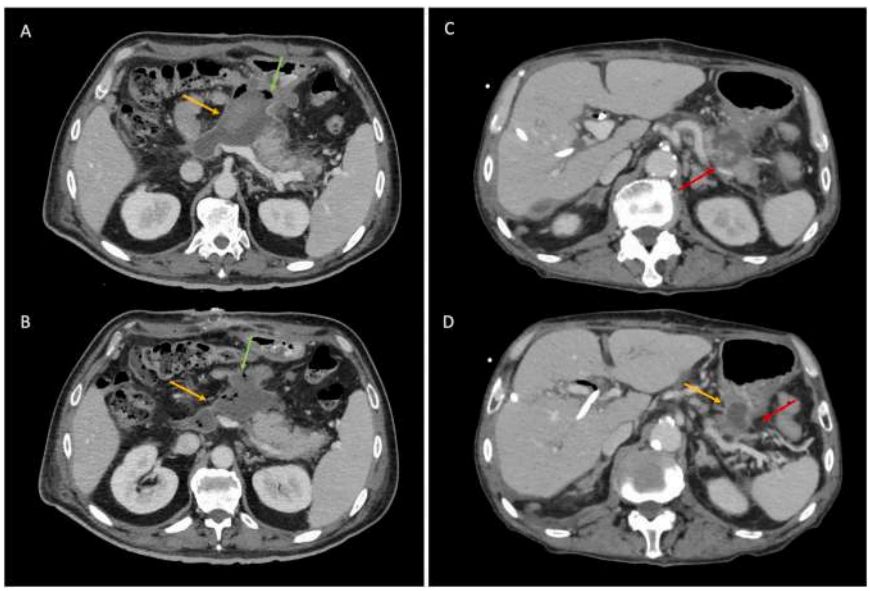

Fig. 8. 64-year-old patients underwent pancreaticoduodenectomy 13 days before (A and B). Inflammatory indexes (C reactive protein and white blood cells) showed a continuous increase during days and a CECT was required to exclude septic foci. A serpiginous fluid collection with thickened walls (yellow arrow) was depictable in the pancreatic bed. This inflammatory process was fulfilled with hyperattenuating materials and air bubbles (green arrows), near the pancreatic remnant. A similar case was reported in C and D. In this case the peri-pancreatic abscess was located near the splenic artery (C, red arrow) without an adipous clivage pain from the stomach walls (D, yellow and red arrows).

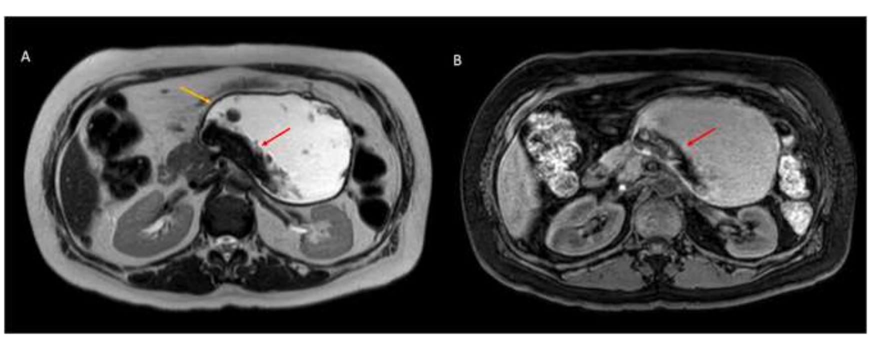

Fig. 9. 49-year-old patients underwent pancreaticoduodenectomy 6 months before (A and B). T2WI (A) and T1W1 (B) showed a cystic component in the transpyloric plane. The lesion was filled with fluid components, hyperintense on T2WI and hypointense on T1WI, encircled by thin walls (A, yellow arrow). Moreover, debris was present within it (red arrows), representing proteins and necrotic components. This is an example of the pseudocyst.

8.2. Radiologist's point of view

In case of biliary leakage, it's possible to appreciate an irregularly shaped fluid collection near the choledochojejunostomy. On CECT the fluid collection appears as homogenously hypoattenuating on all sequences, without walls (Fig. 10). A similar appearance can be depictable on MRI, with a hypointense signal on T1WI and a hyperintense signal on T2WI. The most common pitfall is solving the differential diagnosis only based on imaging between a biliary leak and a pancreatic fistula, considering the proximity of the pancreaticojejunostomy [16].

However, by administering HBA and acquiring a late HBP, it's possible to detect the biliary leak, helping the differential diagnosis with a pancreatic fistula, considering that the pancreatic duct is not fulfilled with HBA. During HBP it's possible to detect the active bile leakage with contrast medium extravasation into fluid collections [94]. To endorse its usefulness, some Authors demonstrated that HBP acquired with Gd-EOB-DTPA can significantly increase the accuracy if associated with MRCP in comparison with MRCP alone (84% accuracy, 100% specificity, $p < 0.05$) [95].

9. Anastomotic strictures

9.1. Surgeon's point of view

Postoperative biliary anastomotic stricture is an uncommon complication after PD and the pathogenesis is likely to be multifactorial. This complication occurs later in the postoperative course and is often diagnosed during the patient's oncological follow-up for the development of recurrent cholangitis [96].

Small bile duct size, tension at anastomosis, and ischemia may be the most important contributing factor. Relflux of gastric end enteric contents with secondary cholangitis may contribute to the development of anastomotic stricture [97].

Non-operative management of biliary strictures by percutaneous transhepatic cholangiography or endoscopic balloon dilatation may produce satisfactory short-term results, while a surgical treatment with a Roux-en-Y hepaticojejunostomy is the preferred management when non-operative management has failed [98,99].

9.2. Radiologist's point of view

Biliary narrowing is more commonly the result of fibrotic tissue formation at the anastomotic site of the biliary system and bowel loop [43], although it may also be due to tumor recurrence. Both ultrasound and CT can show a dilatation of the biliary tree, but MRI with MRCP is more commonly used for the assessment of the biliary system and anastomotic region. Patients undergoing pancreatic surgery may have mild duct dilatation despite a patent anastomosis; the presence of pneumonia should be considered an indirect sign of anastomosis patency. Stenosis should be considered only when duct dilatation is associated with narrowing, thickening, and sometimes periductal enhancement of the anastomotic site [100] (Figs. 11 and 12). Although the distinction between obstructive and non-obstructive dilatation of the bile ducts is often difficult on MRCP, contrast-enhanced MR cholangiography with intravenous administration of hepatobiliary contrast agents such as Gd-BOPTA and Gd-EOB-DTPA [101] is a recently developed technique that may provide a combination of anatomic and functional information on the biliary tract.

Contrast material filling of the biliary tree and the jejunal loop at contrast-enhanced MR cholangiography provides direct evidence of the patency of the anastomosis; on the other hand, biliary obstruction or diminished hepatobiliary function can be suspected in patients with reduced or no visualization of the biliary tree and the missed filling of the anastomotic loop on the hepatobiliary phase [27]. In cases of biliary-enteric stricture, delayed imaging on hepatobiliary phase images is required to differentiate between complete and partial obstruction of the bile duct [102].

Pancreaticojejunostomy strictures are also a late complication that can be present in up to 30% of patients after pancreatic surgery [103]. Both on CT and MRI with MRCP it's possible to observe a progressive dilation of the main pancreatic duct with evidence of secondary ducts. A stenotic appearance of the main pancreatic duct at the anastomotic site can also be appreciable and it is usually associated with a progressive hypotrophy of the remnant parenchyma.

10. Hepatic complications

10.1. Clinical and Surgeon's point of view

10.1.1. Steatosis

About 2.2% of patients who undergo pancreatic resection may have a postoperative increase in liver enzymes, which is considered a normal postoperative finding if serum aminotransferases show only a mild increase and a peak in levels on the first day after surgery followed by a slow decrease until normal values are reached usually within 5 days [104]. De novo development of non-alcoholic fatty liver disease

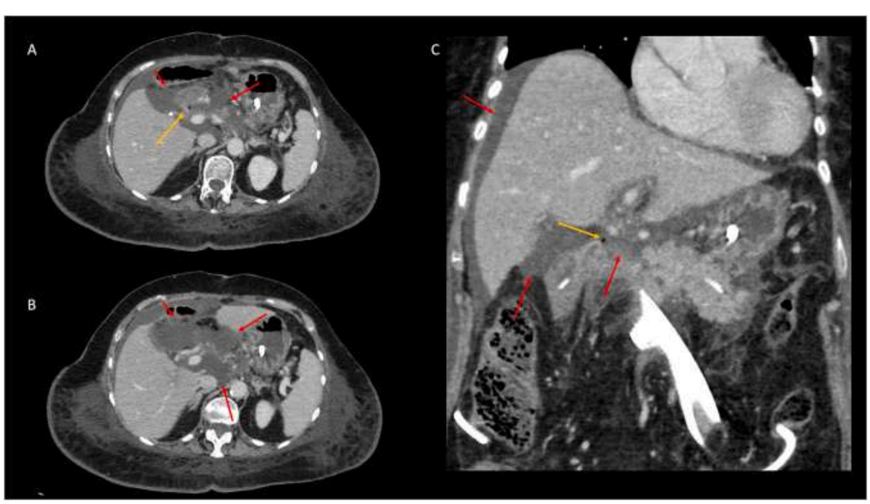

Fig. 10. 77-year-old patients underwent pancreaticoduodenectomy 18 days before. The abdominal drainage reported an increase of biliary enzymes and a CECT was required for the suspicion of a biliary leak. CECT acquired in the portal-venous phase reported an inhomogeneous fluid collection near the common bile duct and the peri-hepatic spaces (red arrow). A small air bubble (yellow arrow) was present near the bilioenteric anastomosis, in line with a biliary leakage.

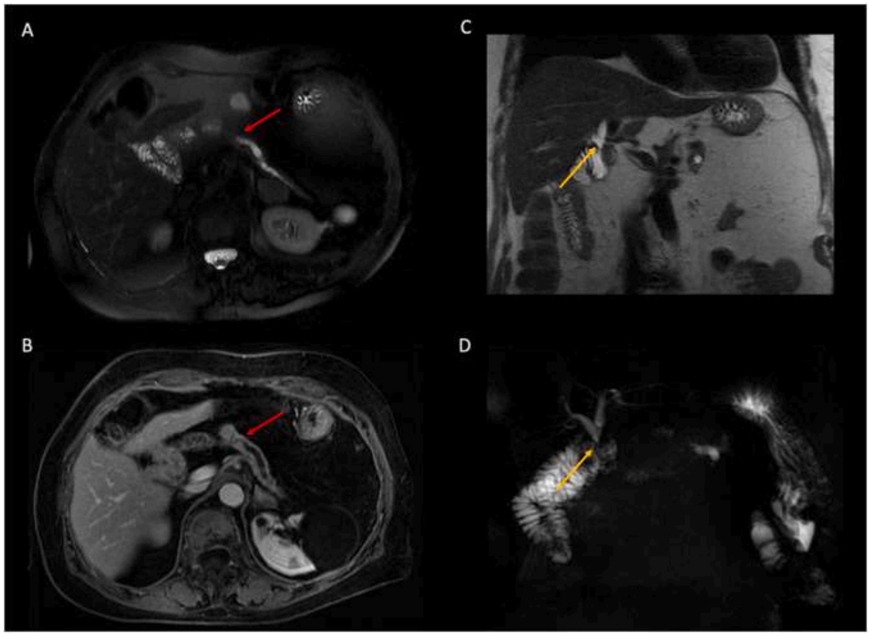

Fig. 11. 70-year-old patients underwent pancreaticoduodenectomy 12 weeks before. Lab tests showed an increase in serum biliary enzymes. An MRI was requested for the study of the anastomosis. The pancreatic anastomosis was regular, as appreciable on axial T2WI (A, red arrow). Moreover, the remnant pancreas showed homogeneous enhancement on the T1WI acquired during the portal venous phase (B, red arrow). However, coronal T2WI showed a focal stricture near the bilioenteric anastomosis (C, yellow arrow), confirmed by the MRCP sequence (D, yellow arrow). The stricture determined a dilation of the hepatic bile ducts.

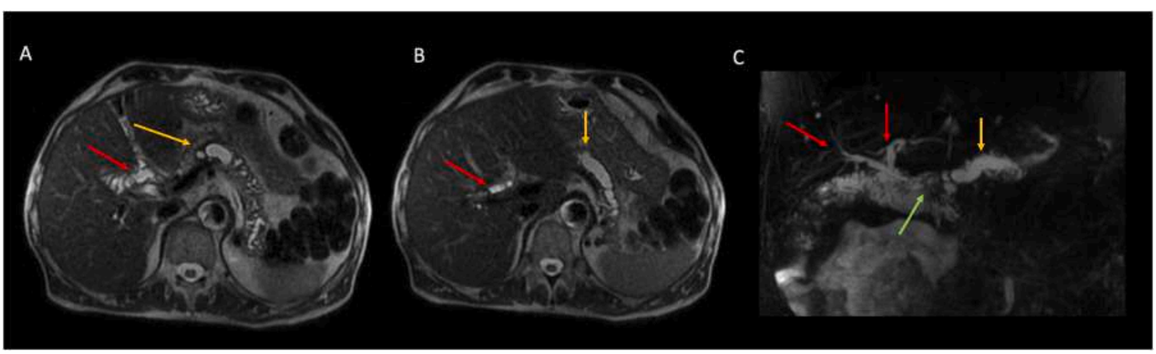

Fig. 12. 61-year-old patients underwent pancreaticoduodenectomy 13 weeks before. Lab tests showed an increase in serum biliary and pancreatic enzymes. An MRI was requested for the study of the anastomosis. Axial T2WI showed diffuse dilation of biliary (A and B, red arrows) and main pancreatic (A and B, yellow arrows) ducts. These findings were confirmed by the MRCP sequence (C, yellow, and red arrows). On MRCP it's possible to detect the presence of strictures located both at the bilioenteric and pancreatic anastomosis (C, green arrow).

(NAFLD) after pancreatic surgery has been increasingly observed, with a reported incidence of up to 37% occurring 4 to 12 months postoperatively [105–111]. The two main possible causative mechanisms for the development of hepatic steatosis after pancreatic surgery include metabolic syndrome and insulin resistance leading to increased circulating free fatty acid in the blood, liver uptake of free fatty acid, and lipogenesis in the liver and malnutrition, malabsorption of amino acids, decreased insulin secretion, decreased carnitine, and choline levels, and upregulated levels of peroxisome proliferator-activated receptors. Other potential factors that may contribute include the inflammatory status that occurs after surgery and chemotherapy [112]. Tanaka et al. [113] found out that patients who underwent PD and developed nonalcoholic steatohepatitis (NASH) had significantly lower body mass index and lower levels of serum albumin, cholesterol, apolipoprotein B, and homeostasis model assessment for insulin resistance compared with the patients who had conventional NASH. As such, the authors concluded that pancreatic exocrine insufficiency could be the main etiology for de novo NAFLD/NASH after pancreatic surgery. These results are corroborated by Nakagawa et al. [108] who demonstrated that postoperative pancreatic exocrine insufficiency was the only independent risk factor for NAFLD. Conversely, although it is a potentially causative mechanism for hepatic steatosis, obesity, hyperlipidemia, insulin resistance, or chemotherapy, it does not seem to be associated with de-novo NAFLD after pancreatic surgery [113].

10.1.2. *Infarction*

Postoperative hepatic infarction can be caused by different conditions such as intraoperative systemic hypotension leading to global hepatic hypoperfusion or occlusion of hepatic vessels; however, while the former is usually reversible, the latter may be irreversible and lead to hepatic ischemia, and, eventually, (partial) hepatic necrosis. In a study by Gaujoux et al. [114], among 545 patients who underwent pancreaticoduodenectomy, only six developed ischemic complications, but only in four cases it was related to intraoperative hepatic artery injury. In patients with liver perfusion failure, transaminase increases 24 h after surgery with maximum levels that depend on the severity of liver damage, and then they return to preoperative levels within the second postoperative week in reversible mild or moderate failure or remain stable increased over 10 days in case of severe liver damage [104]. Concerning the therapeutic consequences, an early diagnosis of hepatic perfusion failure is important to choose the most appropriate and timely treatment, including revascularization by the interventional radiologist or by the surgeon as appropriate [40,104,115].

10.2. Radiologist's point of view

10.2.1. Steatosis

The detection and quantification of steatosis at imaging is clinically relevant and needs to be reported [107,108,113].

Cross-sectional imaging assessment of hepatic steatosis includes the adoption of US, CT, and MRI [116]. Among them, the use of MRI for the calculation of proton density fat fraction (MRI-PDFF) is the most accurate method for the detection and quantification of hepatic steatosis [117]. However, the use of MRI-PDFF has drawbacks that limit its use as a screening tool, such as high cost and limited availability.

On CT, the diagnosis of moderate hepatic steatosis can be suggested on pre-contrast images when the liver attenuation value is at least 10 HU lower than that of the spleen or absolute attenuation of liver parenchyma is equal or lower than 40 HU, with the former being less reliable compared to the latter [118–121] (Fig. 13). In particular, based on the previously noted formula describing a linear relationship between pre-contrast CT attenuation and MRI-PDFF, mild-moderate steatosis can be defined as a pre-contrast liver attenuation in the range of 40.0 to 48.6 HU (corresponding with an estimated fat fraction of $>$10% to 15%), mild steatosis can be defined as a pre-contrast liver attenuation in the range of 48.6 to 57.2 HU (corresponding with an estimated fat fraction of $>$5 to 10%), and normal liver can be defined as a pre-contrast liver attenuation $\geq$ 57.2 HU (corresponding with an estimated fat fraction of $\leq$5%). On CECT, at least moderate steatosis may be diagnosed with sensitivity and specificity respectively of 77.8% and 93.2% if post-contrast liver attenuation is below 80 HU and 90.5% and 78.4% if below 90 HU [120]. However, CT is burdened by ionizing radiation exposure, and cannot be considered a screening tool for hepatic steatosis, but assessment of hepatic steatosis on CT should be taken into account whenever CT is performed for other reasons after pancreatic surgery.

In addition to the qualitative and quantitative assessment of the liver parenchyma, other imaging features that may be associated with the development of hepatic steatosis after pancreatic surgery and should be reported are development of atrophy of the pancreas remnant [110], with de-novo NAFLD being more common in patients with small-volume remnant pancreas (less than 10 mL) at 1 month after surgery measured on CT [122].

10.2.2. Infarction

Contrast-enhanced CT and MRI with arterial and portal venous phase imaging are of utmost importance for evaluating perfusion disturbances and vessel pathology. Hepatic infarction is usually identified on post-contrast CT and MRI as a wedge-shaped area with reduced enhancement compared to the non-ischemic liver, with sharp margins and without mass effect [43]. At MRI these areas are slightly hyperintense on T2-weighted images. At the same time, CT and MRI may allow for the identification of the cause of hepatic infarction in some cases, including hepatic artery or celiac artery injury/dissection, hepatic artery thrombosis, or portal vein thrombosis. The role of imaging, however, is not only limited to the post-operative assessment of hepatic infarction; indeed, some underlying vascular abnormalities in the arterial vasculature, including severe atherosclerotic disease (particularly at the origin of the celiac artery), median arcuate ligament syndrome, fibromuscular dysplasia, or mesenteric vasculitis may make patients vulnerable to postoperative variations, such as hypotension or sepsis [123]. Therefore, radiologists should look for and indicate the presence of any of these conditions on the preoperative imaging examinations.

11. Splenic complications

11.1. Surgeon's point of view

The main splenic complications from spleen-preserving distal pancreatectomy that may be identified at imaging include splenic infarction, which may result in reduced splenic volume, and perigastric collaterals due to left-sided portal hypertension [124,125]. The clinical diagnosis is challenging, sometimes characterized by slight abdominal pain [124]. However, it is important to note that splenic infarction occurring after spleen-preserving distal pancreatectomy usually does not require any re-intervention and usually patients recover with a spleen volume greater than 40% after a minimum of 6 months and that perigastric vessels developing after surgery are usually asymptomatic without any episodes of intraluminal hemorrhage, as also reported in the literature [125,126].

11.2. Radiologist's point of view

Splenic infarction appears as a pyramidal wedge area of affected splenic tissue with the apex pointing towards the hilum, and the base on the splenic capsule, with reduced or lack of enhancement on post-contrast images (Fig. 14). In the long term, splenic infarcts may disappear completely, or less commonly may reveal progressive volume loss caused by fibrotic contraction of the infarct [16].

12. Vascular complications

12.1. Surgeon's point of view

Vascular erosions and pseudoaneurysm may occur after pancreatic surgery and involve usually the hepatic artery, celiac artery, or splenic artery [127]; these complications can lead to hemorrhage, which is best discussed in the post-surgical bleeding paragraph, and interventional radiology is usually indicated.

Fig. 13. 61-year-old patients underwent pancreaticoduodenectomy 5 weeks before. The patient was referred to CECT for the follow-up. A typical hepatic complication is the onset of steatosis, as confirmed by the unenhanced CT (A, red circle). The hypoattenuating appearance of the whole liver is also present in the arterial (B) and portal-venous (C) phases. Aerobilia was also present (B, red arrows) suggesting the patency of the bilioenteric anastomosis.

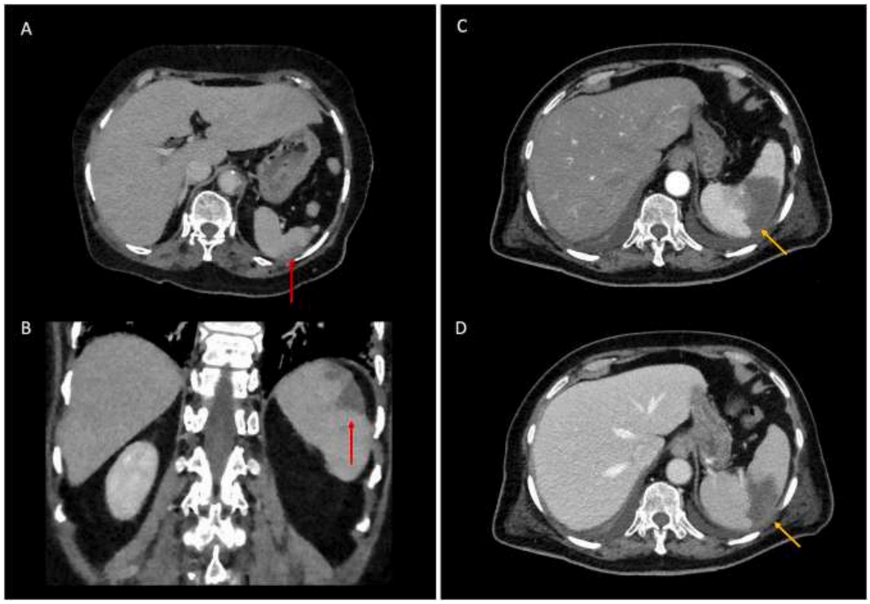

Fig. 14. Two different patients underwent pancreaticoduodenectomy a few days before. All findings are in line with splenic infarction, reporting the presence of wedge-shaped hypoattenuating areas on the portal venous phase in axial (A, C, and D) and coronal plane (B) in the spleen parenchyma (red and yellow arrows).

12.2. Radiologist's point of view

Pseudoaneurysm will appear on contrast-enhanced CT angiography as saccular focal contrast-filled outpouching budding from the wall of the involved artery; it may be rounded by a spontaneous hyperdense area on pre-contrast image scans which may indicate local thrombus or hematoma. Knowledge of this complication is relevant, considering that a retrospective series of 77 visceral pseudoaneurysms showed that about 42% of visceral pseudoaneurysms were overlooked on CT scans and that in 6% of cases, they were falsely interpreted [127].

13. Disease recurrence

Considering the main aim of the present paper, only the most important findings are reported below for the sake of completeness. We invite readers following specific references to examine in-depth surgical and radiological information regarding disease recurrence.

13.1. Surgeon's point of view

Local recurrence after resection with curative intent is frequently observed within 2 years for the majority of patients [128]. The median survival in resectable pancreatic cancer is reported to range from 11 mo for surgery alone to 20 months for surgery in combination with adjuvant chemotherapy [129,130].

Postoperative surveillance is mainly based on expert opinion guidelines, currently provided by the National Comprehensive Cancer Network (NCCN) and the European Society of Medical Oncology (ESMO). The most recent NCCN guidelines recommend every 3–6 months for 2 years a follow-up with history and physical examination; determination of serum CA 19.9 levels and CT of the abdomen and pelvis have lower evidence (NCCN guidelines pancreatic carcinoma v.2 2023). The most recent ESMO guidelines suggest regular follow-up after resection, even though there is insufficient evidence of an impact on overall survival; however, no indications are provided on how to perform this follow-up [131]. It is worth noticing that an analysis of the SEER-Medicare database has demonstrated no significant survival benefit for patients who received regular postoperative CT surveillance [132].

Pancreatic adenocarcinoma can recur locoregionally or with metastatic disease. Patients with isolated local recurrence have been demonstrated to have a longer median survival if the recurrence is resected [133].

A meta-analysis published in 2019 showed weighted median rates of initial recurrence of 20.8% for local recurrence, 26.5% for liver, 11.4% for lung, and 13.5% for peritoneal disease [134]. Imaging surveillance after pancreatic cancer resection can detect both locally recurrent and metastatic disease.

13.2. Radiologist's point of view

Locoregional recurrence is defined as a recurrence within the resection site; it occurs most often after pancreaticoduodenectomy, with soft tissue along the common hepatic artery or near the superior mesenteric artery and vein. Careful comparison with prior imaging can be fundamental in the differential diagnosis with expected postoperative findings such as perivascular soft tissue thickening. Local recurrence usually appears as infiltrating soft tissue with perineural invasion and encasement of the mesenteric vessels, while perivascular cuffing is stable or decreases over time. Hence the importance of obtaining a new postoperative "baseline" 6–8 weeks after surgery, to use for comparison in the follow-up [135].

Distant recurrence occurs most often in the liver and peritoneum. The liver is the most common site of metastases; for the diagnosis of small metastases, careful comparison with prior, early imaging is fundamental. MR can be used as a problem-solving technique, especially using DWI sequences and liver-specific contrast agents. Lung metastases are less common, and when isolated they are associated with longer survival as compared to liver metastases. Skeletal and brain metastases are rare [135].

14. Conclusions

Cross-sectional imaging plays a fundamental role in the post-operative evaluation of patients with pancreatic cancer who underwent surgical approaches. Thanks to its high spatial and contrast resolution, CECT can create a robust dialogue between the surgeon and the radiologist. On the other hand, MRI, even if expensive and time-consuming, can help depict the most important distant sequelae after pancreatic surgery. Finally, a crosstalk between the radiologist and the surgeon is fundamental to correctly address patients to the best management possible.

Disclosures

Support for attending meetings from Bracco and Bayer; research collaboration with Siemens Healthineers.

Funding

Roberto Cannella receives co-funding by the European Union - FESR or FSE, PON Research and Innovation 2014-2020 - DM 1062/2021.

CRediT authorship contribution statement

Vernuccio Federica: Writing – original draft. **Zamboni Giulia:** Writing – original draft. **Gianotti Luca Vittorio:** Validation, Supervision. **Cannella Roberto:** Writing – original draft. **Maino Cesare:** Writing – original draft, Project administration. **Ippolito Davide:** Validation, Supervision. **Franco Paolo Niccolò:** Writing – original draft. **Cereda Marco:** Writing – original draft. **Boraschi Piero:** Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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