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HOW-I-DO-IT ARTICLE

Surgical strategies for restoring liver arterial perfusion in pancreatic resections

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Abstract
Background Hepatic perfusion failure represents an important risk factor for severe complications and death after pancreatic resections. Arterial reconstruction could be required during pancreatic surgery because of tumor infiltration, benign strictures, or as a consequence of accidental arterial injury during dissection. All these situations can be faced with a certain frequency in high-volume pancreatic centers, where surgeons must be aware of the different alternatives to deal with these intricate scenarios.
Purpose We herein describe the preoperative surgical planning as well as different surgical strategies for the restoration of arterial perfusion of the liver in pancreatic resections.
Conclusion A thorough preoperative evaluation is essential for planning pancreatic surgery and preparing the surgeon and patient for potentially high complex procedures. The various therapeutic alternatives presented in this technical report might represent a good solution for selected patients with no other potentially curative option than surgery.

Keywords Pancreatic cancer · Hepatic artery reconstruction · Pancreatectomy · Vascular resection · Liver ischemia · Postoperative complications

Introduction

A proper liver function represents a crucial factor to successfully overcome and recover from major abdominal surgery. Whenever liver sufficiency is compromised, it might either determine or worsen postoperative complications. Hepatic perfusion failure may represent an important risk factor for severe complications and death after pancreatic resections [1–3]. According to current guidelines, arterial involvement of the common hepatic artery (CHA) or celiac trunk (CT) defines local irresectability in patients with pancreatic cancer [4, 5]. Arterial resection in patients undergoing pancreatectomy for pancreatic cancer is associated with poor short- and long-term outcomes. Nevertheless, it can be justified in highly selected patients owing to the potential survival benefit compared with patients without resection [6]. Arterial infiltration requiring reconstruction can occur either at the CT, CHA, or at vascular anomalies such as a right hepatic artery originating from the superior mesenteric artery. On the other hand, arterial reconstruction can be essential for purposes other than tumor infiltration, such as benign stenosis of the CT (atherosclerosis or compression by the median arcuate ligament) or accidental arterial injury during dissection. Since the development of liver transplantation, surgeons have established new techniques of arterial reconstruction to ensure adequate hepatic perfusion. These strategies can be used as valuable alternatives for certain occasions during pancreatic surgery. We aim to describe the preoperative surgical planning as well as the different surgical strategies possible for the restoration of arterial perfusion of the liver during pancreatic resections.

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Preoperative surgical planning

The study of preoperative risk factors in major abdominal surgery can improve patient selection and predict adverse postoperative events [7]. Patient selection should be done taking into account patient age, comorbidities, performance status, and feasibility of the procedure [6]. With the advent of multidetector computed tomography (MDCT), the pancreas can be studied with high temporal and spatial resolution. The MDCT with pancreatic phase protocol is an excellent method for preoperative staging and surgical planning. Recent evidence indicated a positive predictive value for tumor resectability of 91 % and a negative predictive value for detection of vascular invasion of 99 % (286 of 288 vessels) [8]. Furthermore, it can predict the invasion of adjacent organs to the pancreas (colon, stomach, adrenal gland, etc.), anticipating the possibility of multivisceral resections and even determine anatomical variations of the hepatic artery. Through three-dimensional views and arterial reconstructions, extrinsic compressions (median ligament arcuate) or intrinsic stenosis by atherosclerosis can be diagnosed (Fig. 1). Whenever an atherosclerotic stenosis is diagnosed, a selective arteriography should be performed. The stenosis is considered as hemodynamically significant when superior mesenteric contrast injection results in retrograde opacification of the gastroduodenal artery and hepatic artery through dilated pancreaticoduodenal arcades [3].

Surgical alternatives

Extrinsic compression of the celiac trunk

During a Whipple procedure, it is highly recommended to perform a gastroduodenal artery (GDA) clamping test before the division of this vascular structure. This maneuver is performed through palpation of the hepatic artery after clamping the GDA and can be confirmed assessing the arterial flow in liver parenchyma using intraoperative Doppler ultrasound. A

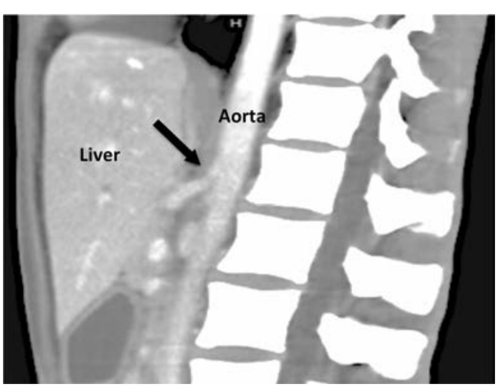

Fig. 1 CT-scan sagittal section in a patient with extrinsic compression of the celiac trunk (*black arrow*)

positive GDA clamping test (absence of flow in the hepatic artery) represents an indication for median arcuate ligament division. The surgical technique requires a complete dissection of the CHA and splenic artery, releasing the anterior aspect and both sides of the CT from dense fibrous tissue until the level of the aorta.

Intrinsic stenosis of the celiac trunk

The intrinsic stenosis of the celiac trunk is associated most often with atherosclerosis and can be treated either preoperatively with interventional radiology or intraoperatively with an aortohepatic vein bypass as the first stage of a Whipple procedure. Recently, Gaujoux et al. [3] recommend the endovascular stenting strategy, because it not only avoids an additional surgical procedure but also eliminates the risk of arterial anastomotic blow out in case of postoperative pancreatic fistula. In cases where it is required to perform a bypass, it is highly recommended to perform it before the pancreatic resection to ensure adequate hepatic perfusion. This technique needs the removal of a saphenous vein graft or whenever possible (due to the size and length), of the inferior mesenteric vein. The proximal anastomosis is performed at the anterior surface of the aorta below the origin of the superior mesenteric artery. The venous graft is then carried through the mesentery root and the distal anastomosis can be done with the GDA or the hepatic artery (Fig. 2). This strategy for liver revascularization may also be useful when arterial lesion of the CT or CHA occurs during pancreatic surgery. From the lessons learned by our group in liver transplant and from the experience published by many other high-volume liver transplant centers, we would like to clarify that when we use graft interposition, the aorta is a simple and safe place for anastomosis.

Tumor involving the common hepatic artery and/or the celiac trunk

In 1953, Appleby described the resection of the CT to achieve curative resection of gastric cancer [9]. This procedure was then adopted for the resection of malignant tumors of the body/tail of the pancreas involving the CT and/or the CHA. The key to perform a CT resection without arterial reconstruction is the indemnity of the pancreaticoduodenal vascular arcades that communicate the superior mesenteric artery with the gastroduodenal artery. This must be certified with preoperative imaging methods. Preoperative embolization of the CHA can be used to enlarge the collateral pathways and prevent ischemia-related complications (Fig. 3) [10, 11]. It is recommended that surgeons identify the origin of the inferior pancreatoduodenal artery from the superior mesenteric artery by MDCT and/or arteriography, both preoperatively and at the start of the surgical procedure, to avoid an accidental injury of this key vessel [11]. Other groups performed reconstruction of

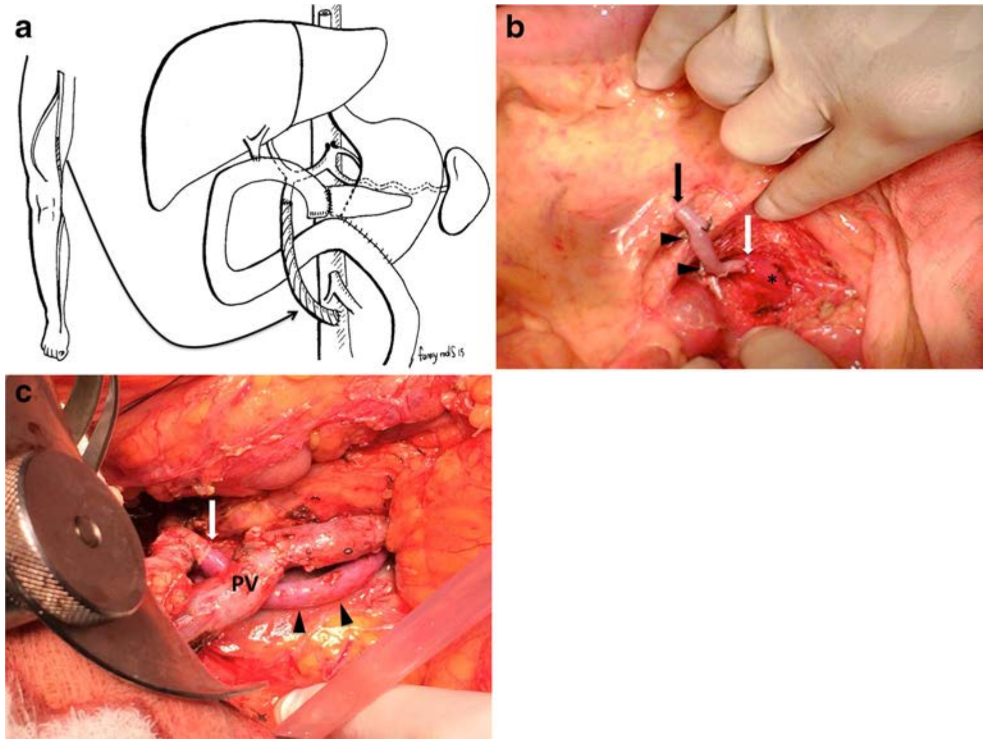

Fig. 2 **a** Aorto-hepatic bypass using a saphenous graft interposition for the treatment of an intrinsic stenosis of the celiac trunk. **b** The proximal anastomosis (*white arrow*) is performed on the anterior surface of the aorta (*asterisk*), at a level below the origin of the superior mesenteric artery. The saphenous vein graft (*arrow heads*) is then carried through the mesentery root (*black arrow*). **c** Distal saphenous vein graft (*arrow heads*) is located behind the portal vein (PV) and anastomosed with the gastroduodenal artery (*white arrow*)

the hepatic artery using the splenic artery which had been taken beforehand from the resected pancreatic specimen [12, 13] or using a reversed saphenous vein graft to augment flow through the pancreaticoduodenal arcade [14] and avoid complications produced by a reduction in hepatic arterial flow. Although the comparison of different arterial reconstruction techniques in pancreatic surgery has not yet been performed, the use of a homologous artery seems reasonable. Especially, the splenic artery is suitable in this setting and allows a reconstruction in a large variety of locations of the distal hepatic artery stump, including anastomoses on retroportal aberrant hepatic arteries [13].

Right hepatic artery compromise

A replaced or accessory right hepatic artery originating from the superior mesenteric artery can be identified in 10.6 % of patients [15]. Preoperative identification of this vascular variation is important to rule out tumor involvement or to avoid an injury during resection of a tumor located in the pancreatic head. One alternative is the anastomosis of the distal stump of the aberrant right hepatic artery with the GDA (Fig. 4). Arterial reconstruction should be performed before the pancreaticoduodenectomy is complete, to reduce the time of liver ischemia. Another strategy may be the transposition of the splenic artery into a replaced right hepatic artery. The distal stump of the splenic artery can then be anastomosed either with the GDA or the proper hepatic artery. The advantage of this surgical strategy is the length of the graft [13].

Proper hepatic artery compromise

Tumor involvement of the proper hepatic artery is less common. However, certain tumors with invasion of the GDA, may extend into the hepatic artery and require vascular resection. Additionally, the CHA may arise from the superior mesenteric artery, which is found in 2–5 % of the population [16]. These conditions can be resolved either by resection with end-to-end anastomosis or with a graft interposition if the vascular segment is large (Fig. 5).

Results

Between January 2011 and July 2015, 436 pancreatic resections were performed at the Hospital Italiano de Buenos Aires Hepatopancreatobiliary (HPB) Surgery Section. In 11 patients, it was necessary to restore arterial perfusion of the liver due to either tumor involvement ($n = 5$), benign stenosis ($n = 5$), or injury during dissection ($n = 1$) at the Hospital Italiano de Buenos Aires HPB Surgery Section. Patient general characteristics and operative data are provided in Table 1. Eight patients (72 %) experienced postoperative complications. According to the Dindo–Clavien classification of surgical complications [17], severe morbidity (≥IIIb) occured in four patients (36 %). Three patients died during the late postoperative period. One patient was readmitted 53 days after surgery and died of massive pulmonary embolism. The other two patients died at 46 and 61 days respectively. The first died

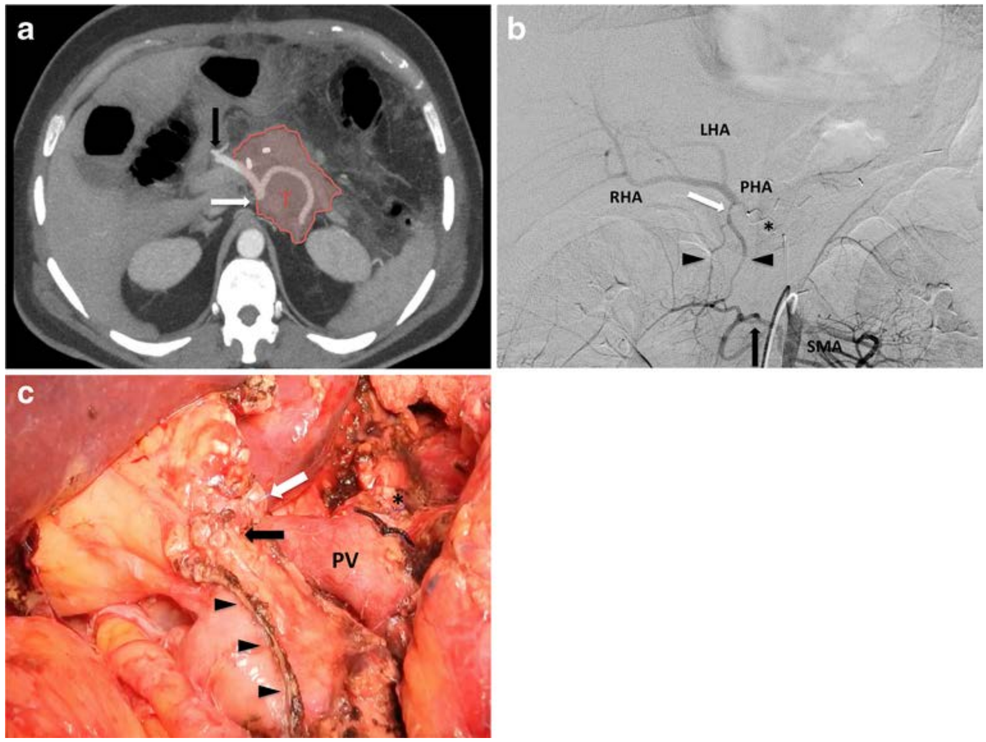

Fig. 3 **a** CT scan in a 42-year-old patient with a pancreatic tumor (*T*) compromising the celiac trunk (*white arrow*) and the origin of the common hepatic artery (*black arrow*). **b** Preoperative embolization of the common hepatic artery using a vascular plug (Amplatzer type 2–10 mm, *asterisk*). Hepatic perfusion is guaranteed through the pancreaticoduodenal arcades (*arrow heads*) between the gastroduodenal artery (*white arrow*) and the inferior pancreaticoduodenal arteries (*black arrow*). Distal perfusion of the proper hepatic artery (*PHA*), right hepatic artery (*RHA*) and left hepatic artery (*LHA*) is evidenced after injecting contrast in the superior mesenteric artery (*SMA*). **c** Surgical field of an Appleby operation. The celiac trunk is resected en block with the stomach and distal part of the pancreas while hepatic perfusion is guaranteed through the pancreaticoduodenal arcades into the gastroduodenal artery (*black arrow*). The pancreatic head is preserved with the collateral circulation and the duodenum is closed (*arrow heads*). The *white arrow* indicates the stump of the common hepatic artery and the *asterisk* marks the stump of the celiac trunk

due to arterial thrombosis after endovascular stenting for an arterial pseudoaneurism and the last, due to multiorgan failure after recurrent septic complications.

Discussion

Recently, the influence of liver perfusion on hepatic function and postoperative outcomes has been assessed. Occlusion of hepatic vessels may cause irreversible damage with hypoxia, ischemia, and finally, hepatic necrosis, with an underestimated impact as a cause of death during pancreatic resections [1–3].

According to the consensus statement of the AHPBA/SSO/SSAT [4] and the ISGPS [5], tumor-induced encasement of the CT or CHA is defined as a tumor-vessel interface of >180^0, and represents an unresectable pancreatic cancer [18]. A recent systematic literature search provides evidence that pancreatectomy with concomitant arterial resection for pancreatic cancer is associated with poor perioperative outcomes and long-term survival [6]. This population of patients with locally advanced primarily irresectable pancreatic carcinomas should be treated with neoadjuvant treatment to down-stage or even down-size the tumor to obtain the chance of secondary resection [19]. Apart from these circumstances, arterial reconstruction can be essential for purposes other than resecting an infiltrated vessel, such as the stenosis of the CT or vascular anomalies of the hepatic artery that can be injured during dissection. All these situations are frequently seen in high-volume pancreatic centers. Therefore, surgeons must be aware of their existence and prepared to deal with these complex situations.

Modern cross-sectional imaging studies can distinguish moderately well between different tumor stages, confirm adjacent tumor invasion, and diagnose anatomical variations of the hepatic artery. Moreover, a study of 545 patients evaluated by MDCT, showed arterial stenosis in 62 (11 %) of all patients undergoing pancreaticoduodenectomy, including 27 (5 %) hemodynamically significant ones. Most of these arterial stenoses were CT compression by median arcuate ligament diagnosed with 96 % sensitivity and 92 % accuracy [3]. After the development of high-quality noninvasive imaging methods with the possibility of three-dimensional vascular reconstructions, the indication for a selective arteriography has been limited to patients with high suspicion of intrinsic stenosis of

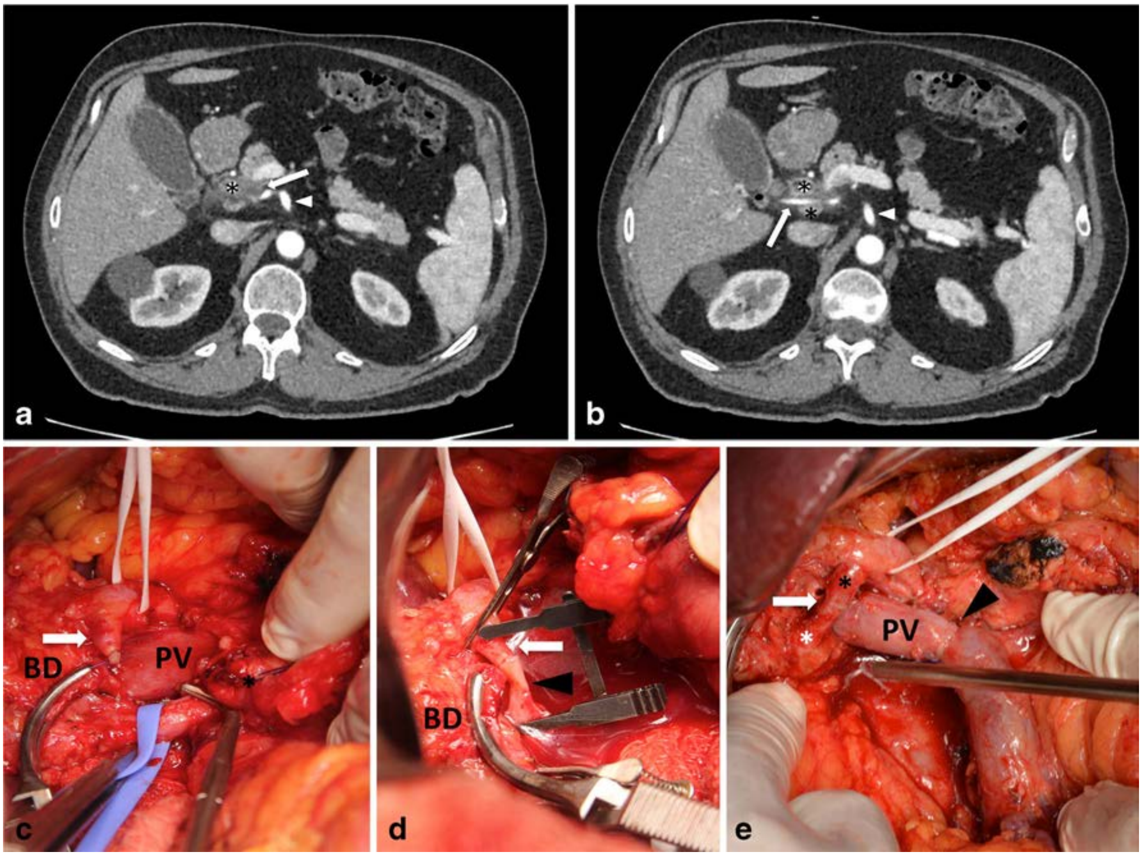

Fig. 4 **a**,**b** Multislice CT scan showing circumferential tumor involvement (*asterisk*) of a replaced right hepatic artery (*white arrow*) originating from the superior mesenteric artery (*white arrowhead*). **c** Intraoperative confirmation of aberrant right hepatic artery (encircled with a blue vessel loop) with tumor involvement (*asterisk*). The *white arrow* shows the gastroduodenal artery stump. **d** Microvascular end-to-end anastomosis between the gastroduodenal artery stump (*white arrow*) and the right hepatic artery (*black arrow head*). **e** Surgical field after a Whipple procedure with combined arterial and portal reconstruction. *White arrow* marks the anastomosis between the gastroduodenal artery (*black asterisk*) and right hepatic artery (*white asterisk*). The *black arrowhead* marks an end-to-end portal vein (PV) anastomosis. *BD* bile duct

the CT. This offers the possibility of arterial stenting if it is diagnosed during preoperative surgical planning.

It is important to emphasize the GDA clamping test during a Whipple procedure. A positive GDA clamping test (absence of flow in the hepatic artery) requires the measurement of the intrahepatic arterial flows with a Doppler ultrasound. Most of these situations can be successfully treated by median arcuate ligament division [3]. However, intrinsic compression of the CT may require the revascularization using an aortohepatic vein bypass. We highlight the use of autologous saphenous

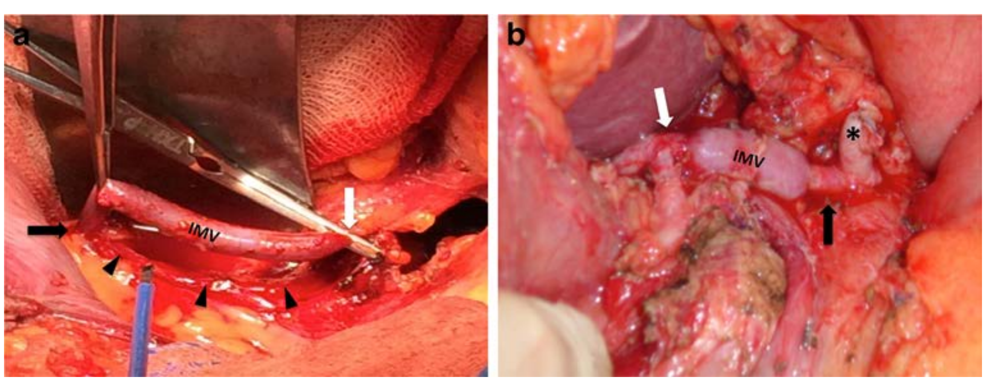

Fig. 5 **a** Inferior mesenteric vein (*IMV*) graft preparation in a patient with an intraoperative lesion and endothelial dissection of the proper hepatic artery during a Whipple procedure. *Black arrowheads* show the mesentery. The *white arrow* indicates the proximal limit and the *black arrow* the distal limit of the graft. **b** Hepatic perfusion was restored with the interposition of the IMV graft between the distal hepatic artery (*asterisk*) and the gastroduodenal artery (*black arrow*). The proper hepatic artery with endoterial dissection was ligated (*asterisk*)

Table 1 Patient's general characteristics, operative data, and outcomes

Patient	Age	ASA score	Disease type	Pancreatic resection	Arterial issue	Treatment	Portal vein resection	Complication	Follow-up	Recurrence	Alive
1	55	3	Ductal adenocarcinoma	Whipple	Arcuate ligament	–	–	Wound infection	36 months	No	Yes
2	74	2	Neuroendocrine tumor	Whipple	Arcuate ligament	–	–	–	45 months	No	Yes
3	67	3	Ductal adenocarcinoma	Whipple	Intrinsic stenosis of CT	SV interposition between the aorta and GDA	–	Pleural effusion + abdominal collection	22 months	No	Yes
4	57	3	Ductal adenocarcinoma	Whipple	Intrinsic stenosis of CT	SV interposition between the aorta and CHA	–	Abdominal collection	17 months	No	Yes
5	63	2	Ductal adenocarcinoma	Total pancreatectomy	Intrinsic stenosis of CT	IMV interposition between the GDA and inferior PDA	–	Pancreatic fistula (C), arterial pseudoaneurism	3 months	–	No
6	46	2	Ductal adenocarcinoma	Appleby	Tumor invasion of CT	[a]	–	Pancreatic Fistula (C)	61 days	–	No
7	72	2	Ductal adenocarcinoma	Whipple	Tumor invasion of aberrant RHA	End-to-end anastomosis between RHA and GDA	Type 3[b]	Biliary Fistula, arterial pseudoaneurism	46 days	–	No
8	59	2	Ductal adenocarcinoma	Whipple	Tumor invasion of aberrant RHA	End-to-end anastomosis between RHA and GDA	–	–	20 months	No	Yes
9	44	2	Ductal adenocarcinoma	Whipple	Tumor invasion of aberrant RHA	End-to-end anastomosis between RHA and GDA	Type 2[b]	Pancreatic Fistula (A)	19 months	Yes	Yes
10	47	2	Main duct IPMN	Whipple	Tumor invasion of CHA from SMA	End-to-end anastomosis between CHA and GDA	–	Pleural effusion + delayed gastric emptying	25 months	No	Yes
11	68	3	Ductal adenocarcinoma	Whipple	Intraoperative lesion of the PHA	IMV interposition	–	–	32 months	Yes	Yes

ASA operative risk according to American Society of Anesthesiologists, *IPMN* intraductal papillary mucinous neoplasms, *CT* celiac trunk, *RHA* right hepatic artery, *SMA* superior mesenteric artery, *PHA* proper hepatic artery, *SV* saphenous vein, *GDA* gastroduodenal artery, *CHA* common hepatic artery, *IMV* inferior mesenteric vein, *PDA* pancreaticoduodenal artery

[a] Preoperative common hepatic artery embolization

[b] Resection of the portomesenteric vein, according to the ISGPS definition

vein graft for artery reconstruction. Visceral vein grafts have a completely different structure, with a theoretical risk of aneurysm after reconstruction. However, it can be used as another option. Other alternative is the use of cadaveric vascular graft. However, this alternative is not always available and depends on precise country legislations and the disposal of a human tissue bank for the preservation of cadaveric vascular graft.

Embryologically, the hepatic artery develops late in the gestational period, and, thus, variations are found in a large proportion of the population (33–45 %) [16]. Preoperative imaging planning therefore represents an important opportunity to detect anatomical variations of the hepatic artery, to prevent an arterial lesion during surgery, and in selected cases when the tumor infiltrates the artery (according to patient comorbidities), to perform a vascular resection with restoration of hepatic arterial perfusion. Arterial reconstruction should be performed before the pancreaticoduodenectomy is complete, to avoid liver ischemia and prevent biliary complications in the postoperative course. The need to perform arterial anastomosis of very small diameter (<3 mm) carries a high risk of hepatic artery thrombosis. The clinical improvements achieved by microvascular surgery in living-donor liver transplantation [20] indicate that this alternative can be safely extrapolated to deal with problematic reconstructions of the hepatic artery during pancreatic resections.

Arterial resection during a pancreatectomy for pancreatic adecocarcinoma may be accompanied by a vein resection (inferior mesenteric vein or portal vein), which carries an increased morbidity. Pancreatic fistula is the most feared complication, since it can be related to arterial erosion and severe postoperative vascular bleeding. In order to prevent the risk of late hemorrhage at the site of the arterial reconstruction, total pancreatectomy is proposed by some authors. In a recent report by Hartwig et al. [21], among 434 patients who underwent a total pancreatectomy, in 9 % of the cases, it was indicated due to a concomitant arterial resection and reconstruction with or without graft interposition.

Conclusion

Hepatic perfusion failure represents an important risk factor for severe complications and death after pancreatic resections. Arterial reconstruction could be required during pancreatic surgery because of tumor infiltration, benign strictures, or as consequence of accidental arterial injury during dissection. All these situations can be faced with certain frequency in high-volume pancreatic centers. Given their important potential impact on outcomes, surgeons must be aware of the different alternatives to deal with these intricate scenarios, which unfortunately are many times encountered intraoperatively. In order to avoid such difficult situation, preoperative evaluation should be exhaustive enough to allow planning the best possible surgical strategy, preparing both the surgeon and the patient for potentially high complex procedures. Despite a not surprising higher rate of complications, the various therapeutic alternatives presented here were feasible and safe in experienced hands, representing a good solution for selected patients with no other potentially curative option than surgery.

Compliance with ethical standards

Conflicts of interest None of the authors of this manuscript has any direct or indirect commercial financial incentive associated with the publication of this paper.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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Informed consent Informed consent was obtained from all individual participants included in the study.

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