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ORIGINAL ARTICLE

Classification and techniques of en bloc venous reconstruction for pancreaticoduodenectomy

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Abstract

Background: Surgical resection is the only cure for hepato-pancreato-biliary (HPB) malignancy. In the era of multidisciplinary approaches and neoadjuvant therapies for locally advanced, borderline resectable tumors, the feasibility and efficacy of en bloc vascular resection has been validated across multiple studies. However, the variability of venous anatomy within the perihepatic and peri-portal regions necessitates familiarity with alternative resection and reconstruction techniques appropriate to the specific region of tumor invasion.

Methods: To organize these paradigms, the venous system has been divided into five zones: 1) hepatic hilum; 2) hepatoduodenal ligament; 3) portal vein/splenic vein confluence, which is further subdivided into right (3a) and left (3b); 4) infra-confluence; and 5) splenic vein.

Results: This study systematically analyzes the anatomic considerations and clinical scenarios specific to each zone to organize the necessary preparative maneuvers, surgical procedures, and vascular reconstruction techniques to achieve an R0 resection. The anatomic and tumor-specific factors which deem a specimen unresectable are also explored. Surgical videos demonstrating these techniques are presented.

Discussion: Preparation and familiarity with venous reconstruction maneuvers is essential for an oncologically effective operation, and can be safely achieved by utilizing this logical anatomic and procedural framework.

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Introduction

Surgical resection offers the only potential for cure for hepato-pancreato-biliary (HPB) cancers. Unfortunately, patients often present with locally advanced disease involving the mesenteric vasculature, particularly along the superior mesenteric vein (SMV), portal vein (PV), splenic vein (SV), superior mesenteric artery (SMA), or hepatic artery (HA). Vascular invasion as a surrogate for incurable disease was justified by historically poor outcomes after vascular resection.[1] With the advent of multidisciplinary management, neoadjuvant chemotherapy and radiation are being increasingly utilized to select for patients who may later benefit from en bloc vascular resection. The outcomes of surgical approaches to treat these advanced malignancies are mixed. While some studies demonstrate poorer survival, increased R1 resection rates, and increased perioperative mortality after an en bloc venous resection,[2] others report similar perioperative morbidity, R0 resection rates, and survival when compared to pancreatectomies which did not require venous resection.[3–7] Moreover, some studies have suggested the length of venous invasion has prognostic significance. Pan and colleagues demonstrated that segmental venous resection greater than 3 cm resulted in poorer survival.[8] Despite these conflicting data, because surgical resection still remains the only hope for a viable cure, en bloc venous resection has become standard of care at many high volume centers, occurring in approximately 20–40% of cases with the ability to achieve R0 resection as high as 98%.[9]

It becomes imperative for the HPB surgeon to have a systematic approach to identify and treat vascular involvement. Given that each operative situation is unique, the surgeon must be cognizant of different surgical options to address each particular scenario. This paper aims to classify the peripancreatic venous anatomy and describe the resection and reconstruction techniques most appropriate to each anatomic zone in order to provide a logical framework for vascular resection in HPB malignancy.

Preoperative preparation

Anatomic considerations

Successful venous resection and reconstruction requires intimate knowledge of the portal venous system and its tributaries, especially because the venous system harbors many variations which surgeons should be familiar with.[10] The small intestine, ascending and transverse colon all drain into the superior mesenteric vein via its first order branches, the ileal and jejunal branches. The ileal branch, generally the larger of the two vessels, carries more of the intestinal venous return and usually lies vertically in a cranio-caudal conformation. The jejunal branch typically courses posteriorly to the SMA and merges posteromedially with the ileal branch to form the common trunk of the SMV. Although most patients demonstrate standard anatomy, variations are observed. One common anomaly occurs when the two branches fail to form a common SMV trunk but rather merge together with the splenic vein. In 20–40% of patients, the first jejunal branch courses anteriorly to the SMV with concomitant anomalous insertion of the inferior mesenteric vein (IMV) into the first jejunal branch.[11–13]

Cephalad along the SMV, anteriorly-inserting venous tributaries from the middle colic vein, gastroepiploic vein, and pancreaticoduodenal veins insert in a variety of configurations. Frequently, the middle colic vein joins the gastroepiploic vein to form a common trunk (Trunk of Henle).[14] Alternatively these veins can individually insert on the anterior surface of the SMV. Drainage of the right gastroepiploic vein and pancreaticoduodenal veins occurs either individually or through a common channel in about 50% of patients. These veins can generally be ligated without consequence.[14]

The SMV typically joins the splenic vein behind the neck of the pancreas and forms the portal vein. The inferior mesenteric vein drains into the SV in 50–70% of patients, into the SMV in 20–30%, into the splenoportal confluence in 5–10%, and rarely into the first jejunal branch.[13,15] These variations are important to recognize preoperatively so that the IMV is not mistaken for the first jejunal branch. The portal vein extends cranially where it bifurcates prior to entering the liver. Along the way, the left gastric vein (or coronary vein) inserts posteromedially, though this vein too is highly variable and can insert into the portal vein, splenic vein, or at their confluence.

For the sake of anatomic considerations for resection and reconstruction, the entirety of the hepato-pancreato-biliary venous system can be divided into five zones: 1) hepatic hilum; 2) hepatoduodenal ligament; 3) SV/PV confluence, which is further divided into the right (3a) and left (3b); 4) infrapancreatic SMV and confluence, and 5) splenic vein (Fig. 1). Dissection and reconstruction strategies can be anticipated depending on zone of involvement (Table 1).

Preoperative planning

Preparation for vascular resection should ideally be performed preoperatively. When anticipated preoperatively, concomitant en bloc vascular resection has been shown to result in lower rates of

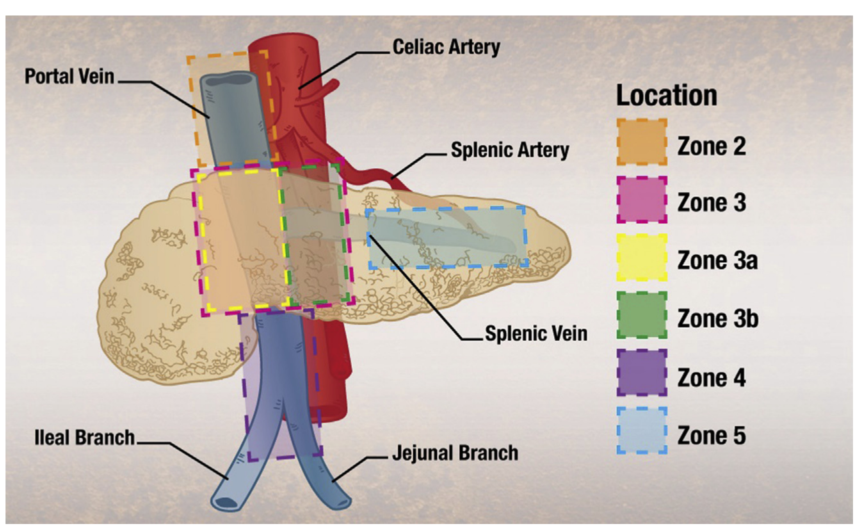

Figure 1 Zones of Venous Involvement. Zone 1 (not shown) extends from hepatic hilum onto the hepatoduodenal ligament (Zone 2). Zone 3 marks the splenic vein/portal vein confluence and is subdivided into right (3a) and left (3b). Zone 4 extends inferiorly from the confluence and includes the ileal and jejunal branches. Zone 5 extends along the splenic vein

positive margins in comparison to unplanned resections.[16] Cross-sectional imaging with computed tomography has a sensitivity of 80% in predicting vascular involvement, but falls to about 50% after neoadjuvant treatment.[17,18] Endoscopic ultrasound is also useful, with a sensitivity of 73% and a specificity of 90%.[19] Regardless, preoperative imaging may fail to detect venous invasion and the need for vascular resection becomes evident at the time of definitive resection in up to 40% of cases.[9]

Preoperative recognition of vascular involvement allows for procurement of appropriate personnel and materials. For instance, if a tissue patch or other venous conduit is anticipated, it is important to confirm its availability. If autologous vein harvest is planned, consideration for venous mapping should be made in patients with vasculopathy or prior cardiac or vascular surgery. The decision to use an autologous graft versus a synthetic graft such as polytetrafluoroethylene (PTFE) depends on many factors, including the length of conduit needed. Typically, autologous vein grafts using greater saphenous vein, internal jugular, or left renal vein are thought to be superior given their increased durability and decreased risk of infection.[20] Moreover, the use of prosthetic grafts is associated with longer operative times and blood loss.[21] However, recent series have demonstrated equivalent outcomes between using synthetic grafts and autologous grafts with respect to perioperative morbidity, mortality, graft infection, and patency.[21] The ultimate decision regarding the type of conduit to use is multifactorial, with the key determinant being the creation of a tension-free anastomosis.

Most importantly, the surgeon should ensure the availability of appropriate consultants, such as other HPB surgeons or vascular surgeons, depending on their comfort level. Many centers routinely employ two surgeons at the time of vascular reconstruction, while some exclusively utilize vascular surgeons to achieve improved patency rates.[22] Potential advantages of utilizing expert assistance includes decreased ischemia time leading to less bowel edema, postoperative ileus and anastomotic leak. The utilization of consultants or other surgeons is ultimately dependent on the comfort level and experience of the primary surgeon and complexity of vascular reconstruction required.

Intraoperative principles

The primary objective for vascular reconstruction is safety. Anticipation of potential pitfalls before they occur is of utmost importance. Operative strategies should not encompass a "one-size-fits-all" approach, but rather retain surgical decision making to properly react to unanticipated challenges. The sections below aim to prepare and optimize the surgeon for the various scenarios encountered during resection of HPB cancers with mesenteric and portal venous involvement.

Operating room setup and communication

Except when the reconstruction is in Zone 3a, the surgeon should stand on the right side of the table with the patient rotated to the left. If possible, the anesthetist should have access to both upper extremities for monitoring. Prior to vascular resection, staff should be informed of dosing and timing of heparin (if needed), vascular exclusion start and stop times, preparation of grafts and prosthetics, and equipment such as ultrasound and sutures. If an autologous homograft is anticipated, the harvest site should be prepped and draped in the operative field. If needed, homograft should be harvested, sized, and prepared prior to vascular exclusion and specimen extraction.

Specimen preparation

Prior to vascular excision, the only attachment keeping the specimen adherent to the patient should be the involved segment of vein. To achieve this, specialized dissection techniques may be needed, including the SMA first approach for Zone 3 involvement, or isolation of the jejunal and ileal branches for Zone 4 involvement.[23] Although there are up to six different ways to perform the SMA first technique,[23] most typically it is defined by early dissection along the adventitia of the artery at its aortic origin during a pancreatic head resection. A common way to achieve this is to open the peritoneum along the duodenojejunal flexure after flipping the small bowel to the patient's right and incising just to the left of the proximal jejunum and duodenojejunal flexure. Next, the SMA origin is identified at the aorta and dissection continues along its adventitial plane. Care must be taken to clear the SMA posterolaterally on the right side for a few centimeters to expose any aberrant hepatic arteries. Further mobilization of the gastroduodenal ligament, division of the jejunum, stomach and neck of the pancreas will allow for venous involvement to be the remaining point of attachment.

The rationale for the SMA first approach is based on pathologic review of tumor specimens showing that the areas most involved with tumor were at the SMA margin.[24] The most beneficial aspect of employing this technique is the ability to determine whether there is unresectable disease (i.e., arterial involvement) present, thereby allowing the surgeon to halt the operation before transection of critical structures occurs. Regardless which SMA first technique is used, it is preferable to keep the left-sided adventitia, nerves, and lymphatics intact to minimize complications such as diarrhea.

Vascular preparation

It may be tempting to simply "shave" the gland from the vein, especially if the plane between tumor and vein appears conducive. However, without adequate vascular control prior to attempting such a maneuver, an inadvertent venotomy can lead to substantial hemorrhage and compromise the repair. Therefore it is critical that inflow and outflow to the involved zone be totally controlled. This requires an adequate length of vein be cleared proximally and distally to the involved segment. Vascular clamps should be applied and sufficiently out of the way to allow for anastomosis. Similarly, all venous tributaries

Table 1 Zones of venous involvement

Zone	Venous involvement	Clinical scenario	Preparation	Procedure to perform with en bloc resection	Vascular reconstruction	Backup reconstruction
1	Hepatic Hilum	Hilar cholangioCa	1) Transect liver parenchyma; 2) Lower hilar plate	Liver Resection	1) End-to-end[g] 2) Patch repair[f]	Interposition graft
2	Hepatoduodenal Ligament	Distal cholangioCa Pancreas Head Tumors	1) Mobilize liver 2) Ligate coronary vein	Whipple	End-to-end[g]	Interposition graft
3	SV[a]/PV[b] confluence	1) Pancreas head tumors 2) Pancreas neck tumors 3) Pancreatitis	SMA first approach	WATSA[c]	End-to-end[g]	Interposition graft
3a	Right SV[a]/PV[b]			Whipple	Transverse plication[e]	1) Vein patch[f] 2) End-to-end[g]
3b	Left SV[a]/PV[b]			RAMPS[d]	Vein Patch[f]	
4	Infra-confluence	Pancreas head tumors	1) SMA first 2) Isolate jejunal/ileal branches 3) Liver mobilization	Whipple	1) End-to-end[g] 2) Interposition graft 3) Patch repair[f]	Ligating splenic vein → end-end repair
5	Splenic vein	Pancreas Body and Tail tumors		RAMPS[d]	None	

[a] SV: Splenic vein.
[b] PV: Portal vein.
[c] WATSA: Whipple at the splenic artery.
[d] RAMPS: Radical antegrade modular pancreaticosplenectomy
[e] See Video 1.
[f] See Video 2.
[g] See Video 3.

adjacent to or within the zone of involvement should be isolated and clamped. Some surgeons employ vessel loops given their low-profile in the operative field and to minimize trauma to the vessel. However, it is the authors' experience that vessel loops increase outward tension on the vessel. Instead, pediatric vascular clamps are preferentially employed given that adult clamps are too large for this area, except in obese and deep patients.

A durable, tension-free vascular repair should be achieved in every case. To facilitate this, the retractors holding the liver cephalad and the bowel caudad should be released, which can provide extra vessel length and relieve undue tension during repair. Mobilizing the liver from its diaphragmatic attachments and packing above it to displace the liver caudally can sometimes facilitate reconstruction. A transverse incision in the peritoneum at the base of the transverse colon can also be made to release the mesenteric root and allow cephalad migration. In combination with these maneuvers, if sufficient length of PV and SMV are mobilized it may be possible to perform a primary, end-to-end repair even after excision of up to four to 5 cm of vein.

Venous transection and reconstruction (see Videos 1–3)

Once critical factors are confirmed—the specimen is widely free except for the area of involvement; all inflow and outflow to the area is controlled; operating room staff is aware of venous reconstruction; the appropriate materials are present; adequate mobilization of bowel and liver is achieved—then venous resection can commence. Three to 5 min before vascular clamping, some advocate for administration of intravenous heparin (3000 units), but this can be avoided if clamping does not completely inhibit flow to the liver, for example with Zone 4 involvement where the SV-PV flow is not impeded.

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The venous reconstruction should be of adequate caliber to eliminate flow-limiting stenosis which could lead to acute thrombosis. Moreover, it should lie without kink or twist, therefore we recommend inking the proximal and distal vein prior to transection. If a graft will be used, that too should be marked to avoid twisting (Video 1). Upon completion of the anastomosis, clamps should be sequentially released to test for anastomotic integrity and prevent "blow out." Gross extravasation of blood should also be addressed. A "growth factor" should be incorporated during venous anastomosis, as usually the reconstructed vein will expand to 125–150% of its devascularized caliber after blood flow is restored. If the suture is tied flush with the vein, this will result in waisting and ultimately increase risk of thrombosis. On the other hand, if an air knot is incorporated when the suture is tied, it will allow for the reconstructed vein to expand without waisting. This may result in extravasation of blood initially, but usually resolves after a few minutes. For this reason, we recommend placing a topical hemostatic agent around the anastomosis with application of gentle pressure to allow for hemostasis. Patency and adequate flow are then proven using Doppler ultrasound.

The total time of vascular exclusion and re-anastomosis should ideally be less than 20 min. If portal venous clamp time is anticipated to be longer than 25 min, preemptive isolation and temporary occlusion of the SMA should be considered. This is typically performed by doubly encircling the SMA with a vessel loop and clamping it flush with the vessel or by applying a pediatric straight vascular clamp directly to the vessel. Clamping is typically performed just superior and anterior to the left renal vein. While rarely necessary, even in complex reconstructions, this maneuver will minimize bowel edema and prevent mismatched perfusion complications.

Surgical techniques

Pancreaticoduodenectomy

As the definitive operation for pancreatic head malignancies, this procedure entails the creation of a tunnel overlying the SMV under the neck of the pancreas. The en bloc specimen consists of the distal stomach (standard Whipple), duodenum, common bile duct, and the head and uncinate process of the pancreas as well as the peripancreatic lymph node basin.

Whipple at the splenic artery (WATSA)

Tumors with venous involvement along the traditional subpancreatic SMV tunnel can present a challenge. Attempting to tunnel in this scenario may be dangerous and result in positive margins. As described by Strasberg, the Whipple at the splenic artery (WATSA) divides the pancreas left of the SMV, allowing the specimen to be rolled anterolaterally for en bloc resection of the pancreatic head, neck, and the SMV-SV-PV confluence (Fig. 2).[25] The splenic vein is ligated where it contacts the superior border of the pancreas. If the IMV inserts into the SMV or within 2 cm of the SMV/SV confluence, it too must be ligated. This maneuver allows for visualization and clearance of the anterior and right aspects of the SMA. At this point the specimen is tethered only by its attachments to the vein. Venous transection then occurs en bloc with the specimen at the SMV and PV, and reconstruction can occur either by end-to-end repair or interposition graft.

Radical antegrade modular pancreatosplenectomy (RAMPS)

While the lymphatic drainage of the left half of the pancreatic body and tail is typically to the lymph nodes in the splenic hilum, tumors in the superior and inferior borders of the right half of the pancreatic body typically drain to the infrapancreatic and gastroduodenal nodes, and are not addressed in a standard distal or subtotal pancreatectomy. To address lymphatic spread and improve margins, the RAMPS procedure has evolved for tumors arising at the neck or body of the gland (Fig. 3).[26] The procedure entails creation of a tunnel overlying the SMV inferiorly to meet the superior pancreatic dissection. The right gastric artery and coronary vein are ligated and the gastroduodenal artery is retracted to the right facilitate the exposure. The pancreas is divided at this point which allows for dissection onto the celiac trunk and identification of the splenic artery, which is ligated at its takeoff. The splenic vein is likewise encircled and ligated at the SMV junction. If there is tumor invasion (Zone 3b), the portion of the vein can be excised and reconstructed. Next, the pancreas and the peripancreatic lymphatic tissue is freed along the sagittal plane toward the SMA, clearing its left side down to the aorta. Depending on the plane required for tumor excision—anterior

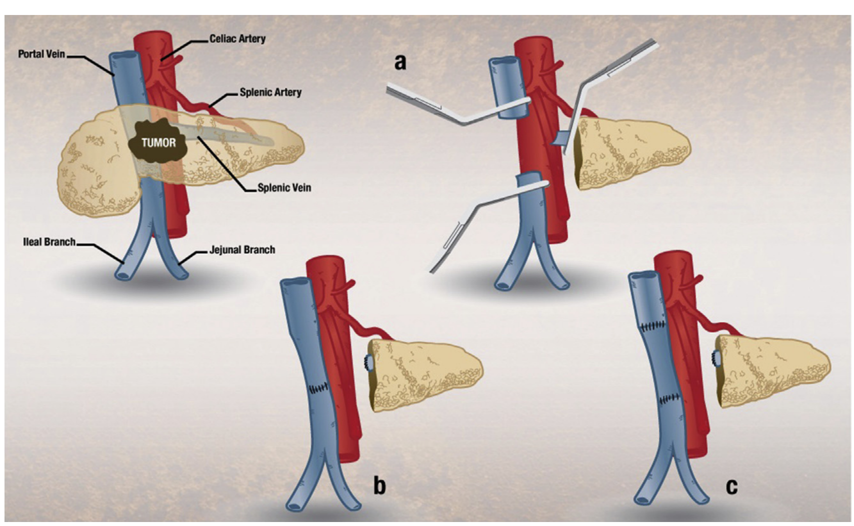

Figure 2 Tumors involving the left portion of the splenic vein/portal vein confluence (Zone 3b) must be treated with complete en bloc venous excision, typically achieved using a WATSA procedure. The pancreas is divided at the level of the splenic artery (A) after the splenic vein is sacrificed. The vein is reconstructed either end-to-end (B) if there is sufficient reach, or via interposition graft (C)

or posterior to the adrenal gland—the remainder of the specimen is resected en bloc toward the spleen. Whether to proceed with an anterior or posterior approach depends on the posterior penetration of the tumor. While rare, to ensure proper posterior margins and local tumor control sometimes it may be necessary to perform adjunctive resections of the celiac axis during pancreatosplenectomy (Appleby procedure).

Zonal assessment of venous involvement (Table 1)

Zone 1

Tumors at the hepatic hilum derive from the biliary bifurcation and typically necessitate concomitant hepatectomy. Vascular reconstruction is rarely indicated, although some series have reported good outcomes.[27] For right-sided tumors, it is necessary to dissect the left portal vein at its origin at the base of the falciform ligament. For left-sided tumors requiring a left trisegmentectomy, the Segment 6/7 pedicle takeoff should be assessed for involvement after lowering the hilar plate. If involvement of the right or left portal vein is identified, then assessment of the length of vein involved, whether proximal and distal control can be achieved, and the type of reconstruction required can be performed. In some cases, the involved segment of portal vein can be dissected and reconstructed prior to hepatic transection. Arterial inflow should be maintained to the remnant liver during venous reconstruction.

Zone 2

Venous involvement in Zone 2 occurs along the hepatoduodenal ligament, extending from the bifurcation of the right and left portal veins to just above the PV/SMV/SV confluence. Typically, vascular involvement occurs with extrahepatic cholangiocarcinoma and pancreatic head tumors. In these scenarios, successful resection involves mobilization of the liver to achieve maximal venous length. Ligation of the coronary vein can help achieve this. There is usually sufficient reach to achieve primary end-to-end anastomosis, though sometimes interposition grafts are necessary.

Zone 3

Zone 3 venous involvement is the most common location of tumor invasion, and is subdivided into right and left sides. This region is anatomically defined by the confluence of the SMV/PV/SV and extends up to 2 cm proximally and distally for up to 270 degrees of involvement. For tumors which invade the entirety of the confluence, an en bloc resection entails a WATSA procedure with an end-to-end reconstruction or interposition graft (Fig. 2).

Tumors involving the right side (Zone 3a) are best addressed by meticulous dissection, usually employing an artery-first approach (Fig. 4). When there is minimal or short-segment venous involvement, it may be tempting to perform a primary longitudinal repair and simply "oversew" the vessel. In our experience this is ill-advised, as inevitably a flow-limiting indentation will occur which can lead to venous thrombosis. For these short-segment occlusions, the preferred reconstruction involves a transverse repair with incorporation of a growth factor (Video 1, Supplemental Digital Content, transverse repair).[28] At the completion of reconstruction, the repaired vessel will have the same caliber as prior to resection, and sometimes even becoming larger caliber once the impinging tumor is removed. The overwhelming majority of reconstructions performed in this manner have rare postoperative thrombotic complications.

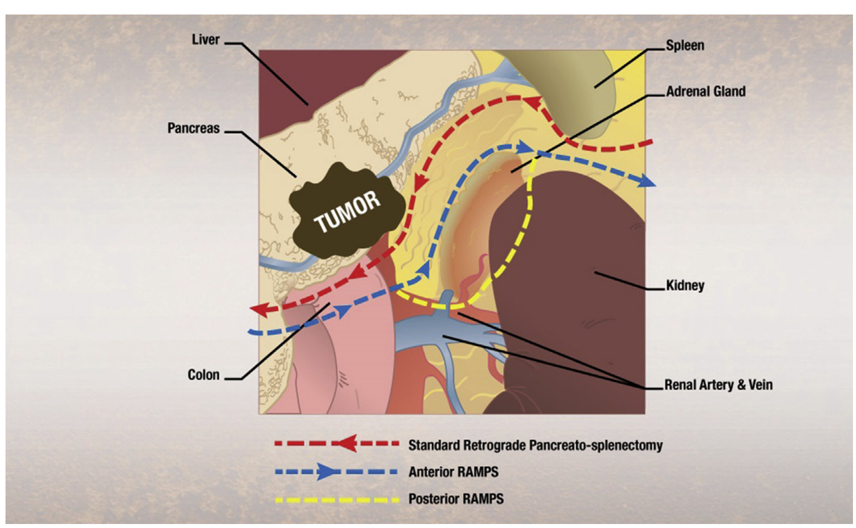

Figure 3 Radical Antegrade Modular Pancreatosplenectomy (RAMPS): In contrast to a standard left pancreatectomy which proceeds retrograde and fails to encompass peripancreatic lymphatics (red line), RAMPS facilitates dissection antegrade along the pancreas in a plane to include (posterior RAMPS, yellow line) or exclude (anterior RAMPS, blue line) the adrenal gland

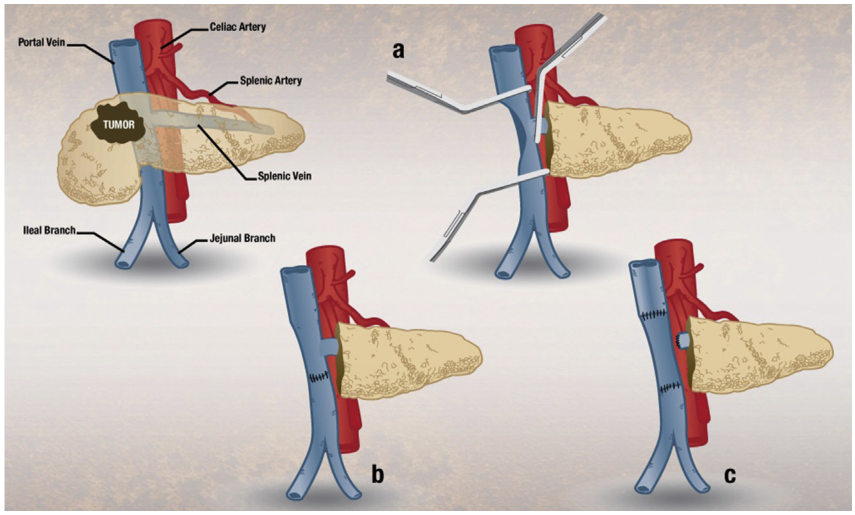

Figure 4 Tumors involving the right portion of the splenic vein/portal vein confluence (Zone 3a) can be treated with partial venous excision and reconstruction (A, B) or with complete en bloc excision with specimen and repair with interposition graft (C)

Venous involvement of the left side of the confluence (Zone 3b), will require a RAMPS approach (Fig. 3).[26] This procedure saves the patient the morbidity of a pancreatic head resection, and venous reconstruction is achieved using a patch. Venous inflow isolation for Zone 3b can present unique challenges with back bleeding from perforators from the pancreatic head, and may require the use of a large side-biting clamp to achieve proper control.

Zone 4

Vascular involvement in Zone 4 extends inferiorly from the SV/SMV confluence to the first jejunal and ileal branches. Given the many variations of anatomy and tumor location, a few basic principles must be kept in mind. First, ligation and resection of either the jejunal or ileal branches can generally be performed without clinical consequence as long as the remaining vessel is of sufficient size to maintain collateral return. A good estimate for sufficiency of caliber involves comparisons to SMA, wherein a venous diameter more than 1.5 times that of the SMA is mandated. Second, in circumstances where the surgeon is afforded a choice with respect to which branch to reconstruct, the ileal branch is preferred given its cranio-caudal directionality and the fact that usually the jejunal branch courses posterior the SMA. Additionally, the jejunal branch tends to be more thin-walled and prone to anastomotic complications. Surgical reconstruction options when tumors involve this region include either primary repair or interposition graft if a circumferential resection is required; a patch repair can be performed for lateral wall resections. If there is short-segment vessel involvement, primary repair can be facilitated by ligation of the splenic vein. In these circumstances, the SMV segment can reach the relatively fixed jejunal and ileal branches without tension once the splenic vein fixation point is removed. However, it is important to confirm patency of IMV drainage in this circumstance as it decreases the risk of SV thrombosis in the long-term.

Zone 5

Vascular involvement along the splenic vein is almost always a result of pancreatic body and tail tumors. However, the vascular encasement may extend to not just the splenic vein, but also the IMV and short gastrics and sometimes into the transverse mesocolon. Therefore, diligence must be undertaken to evaluate the extent of tumor spread. A RAMPS procedure is typically adequate to provide an en bloc R0 resection (Fig. 3), though sometimes adjacent organs (i.e., colon and stomach) or vessels (celiac) must be partially resected.[25]

Conclusions

As HPB surgery is increasingly being performed with improved outcomes, the role of extended resections for advanced malignancies has been reconsidered especially in the era of neoadjuvant therapy. Vascular resections and reconstructions must abide by fundamental principles of surgical oncology. A variety of different surgical approaches and procedures have been refined to allow the surgeon to maximize both the chances of successful and safe extirpation. However careful preoperative preparation along with meticulous dissection and selection of proper reconstruction strategies is equally important for a proper and successful en bloc vascular resection.

Acknowledgments

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Conflicts of interest

None declare.

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