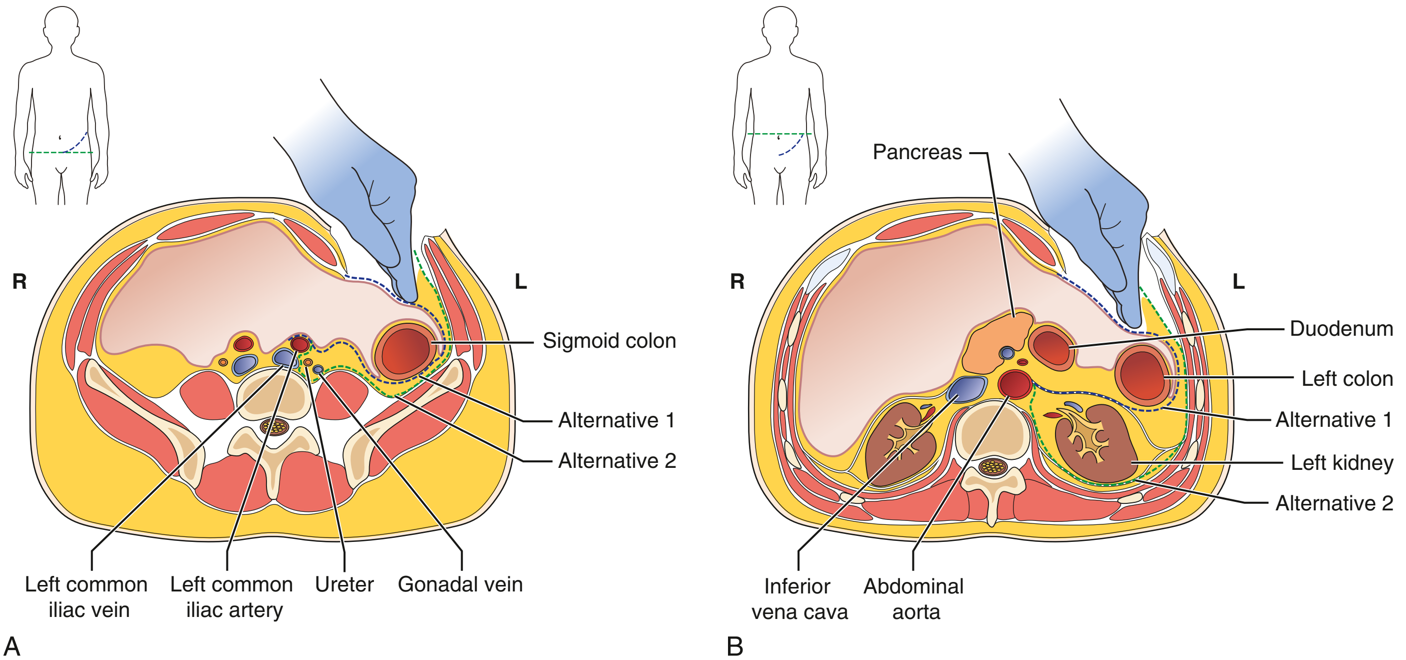

Figure 55.13 Cross-sectional image of the abdominal cavity at the level of the abdominal aorta (**A**) and the iliac arteries (**B**). The schematic shows the surgeon's hand dissecting along the retroperitoneal plane. The dotted lines demonstrate alternate approaches to access the aorta within the retroperitoneal space.

best plane for dissection is in the anterolateral portion of the infrarenal aorta. As the dissection progresses, the origin of the inferior mesenteric artery should be identified, the artery ligated and divided, allowing further retraction of the peritoneum towards the patient's right.

Transperitoneal Approach

A transperitoneal approach should be used to access the visceral and infrarenal aorta, both renal arteries, the hepatic artery, as well as the distal portion of the celiac and superior mesenteric artery. The origins of the superior mesenteric artery and celiac artery can also be exposed, although extensive mobilization of the spleen and pancreas is needed. The approach requires significant manipulation of the abdominal viscera and thus should be used selectively (see Ch. 56, Abdominal Vascular Exposures).

Position

The patient is placed supine with the arms extended laterally.

Incision

A midline laparotomy incision is made extending from the xiphoid process to the symphysis pubis. Alternatively, a transverse reversed "smile" incision can be used. The latter, however, divides the abdominal musculature and causes significant denervation of the abdominal wall muscles. Some surgeons, however, believe it is better tolerated by patients with pulmonary insufficiency.

Dissection

Once the midline fascia is incised and the peritoneal cavity entered, the abdominal contents can be inspected. When necessary, the visceral aorta can be exposed by incising the lateral peritoneal reflection of the left colon and completing a left medial visceral rotation. A self-retaining retractor is placed, the viscera are wrapped in a moist towel and swept to the right. The splenic attachments to the abdominal wall are then released and the spleen is mobilized superiorly and medially. This dissection is carried posteriorly along the space between the spleen and the left kidney by dividing the spleno-phrenic, spleno-colic and spleno-renal ligaments. A plane is then developed following the lateral curvature of the spleen into the space posterior to the pancreas. The spleen and pancreas are then separated from the retroperitoneum and rotated medially until the suprarenal aorta is exposed. The left kidney can be kept in the renal fossa or mobilized medially. Dissection of the retroperitoneal and periaortic fat along with division of the left crus of the diaphragm provides additional proximal exposure of the suprarenal aorta. As with the retroperitoneal exposure, division of the medial arcuate ligament allows for identification of the celiac artery origin.

When limiting the exposure to the infrarenal aorta, visceral rotation is not necessary. The infrarenal aorta can be exposed by elevating the small intestine to the patient's right, incising the base of the small bowel mesentery along its avascular plane. The ligament of Treitz is divided and the duodenum fully mobilized towards the right. It is best to limit the mobilization of the duodenum at the level where duodenal arterial and venous branches are identified. On occasion, ligation of the inferior mesenteric vein allows greater exposure of the perirenal aorta. The left renal vein is identified. Ligation and division of the gonadal vein and the lumbar vein at this level may be necessary, to allow greater and safe cephalad retraction of the left renal vein. Ligation and division of the adrenal vein facilitates safe caudal retraction of the left renal vein. The aorta can then be encircled just below the takeoff of the renal arteries. In the presence of a posterior retro-aortic left renal vein, circumferential mobilization of the aorta should be either avoided or performed with great care, separating the vein from the aorta under direct vision. As the exposure progresses caudally, the inferior mesenteric artery is identified and may be either preserved or ligated and divided.

Distal control can be achieved either around the distal aorta above the bifurcation or controlling the common iliac arteries individually. In either case, care should be taken while encircling the distal aorta to identify the middle sacral artery to avoid bleeding from the posterior aorta. In addition, often the left common iliac vein traverses towards the vena cava just below the aortic bifurcation. When obtaining control of the common iliac arteries, care should be taken to visualize and separate the common iliac vein from the artery to avoid injury with significant bleeding and which is difficult to control. On the right side, the common iliac bifurcation is easily identified and either controlled distally or with individual external and internal iliac artery exposure. On the left side, often the left common iliac bifurcation is difficult to reach from the aortic exposure and often requires further elevation and mobilization of the sigmoid mesentery. Alternatively, the sigmoid colon can be mobilized medially, exposing the distal common iliac artery bifurcation. Excessive dissection of the common iliac arteries is to be avoided to reduce the potential for sympathetic nerve injury. In the presence of a common iliac aneurysm, the graft can be passed through the aneurysm to the bifurcation without dividing the common iliac aneurysm longitudinally but rather transversely just above the bifurcation.

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CHAPTER 56

Abdominal Vascular Exposures

LOAY S. KABBANI and ALEXANDER D. SHEPARD

EXPOSURE OF MAJOR ABDOMINAL ARTERIES

Anatomic Considerations

The aorta enters the abdomen through the aortic hiatus in the diaphragm at the level of T12 vertebra.[1] It is surrounded at this level by the right and left crura of the diaphragm and runs anterior to the spine. The first two branches off the aorta are the two phrenic arteries, which arise anterolaterally. The celiac axis refers to a short arterial trunk originating from the anterior surface of the proximal abdominal aorta as it passes between the diaphragmatic crura. The celiac trunk and its proximal branches are surrounded by tough, splanchnic ganglionic tissue, making dissection challenging. Most often (in 75% of patients) the celiac trunk splits 1 cm beyond its origin, into three branches: the splenic, the common hepatic, and the left gastric artery.[2,3] The common hepatic arises from the celiac and runs on the posterior wall of the lesser sac, forming the lower boundary of the foramen of Winslow. It follows the upper border of the pancreas before it divides into the gastroduodenal and proper hepatic arteries. The proper hepatic lies anterior to the portal vein and gives rise to the right gastric before it divides into the left and right hepatic arteries. In approximately 18% of cases the right hepatic artery is "replaced" and originates from the superior mesenteric artery (SMA). A "replaced" left hepatic artery originates from the left gastric artery in approximately 12% of cases. The SMA arises from the anterior aorta at the level of mid-L1, then courses inferiorly behind the pancreas and anterior to the third and fourth portions of the duodenum, to enter the root of the mesentery. Its origin is associated with large lymphatics which can make exposure tedious. The main branches of the SMA are: the inferior pancreaticoduodenal artery (which forms an arcade with the superior pancreaticoduodenal artery

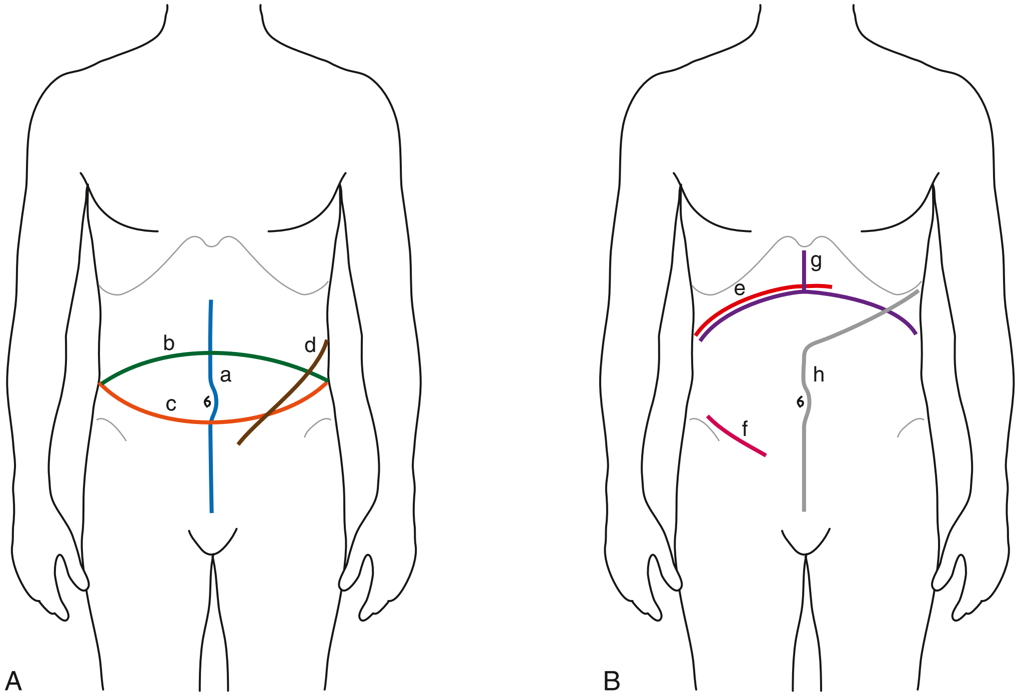

Figure 56.1 Abdominal Incisions on a Supine Patient. (**A**) *a*, Midline incision; *b*, supraumbilical transverse ("frown") incision; *c*, infraumbilical transverse ("smile") incision; *d*, left flank (retroperitoneal) incision. (**B**) *e*, Right subcostal incision; *f*, right lower quadrant "transplant" incision; *g*, chevron incision; *h*, thoracoabdominal incision.

originating from the proper hepatic), several jejunal branches (the first of which is usually spared in embolic occlusions of the SMA[4]), the middle colic, the right colic, and the ileocolic arteries. There are extensive collateral networks between the celiac trunk, SMA, inferior mesenteric artery (IMA), and internal iliac arteries. The celiac axis and SMA collateralize through the superior and inferior pancreaticoduodenal arteries. The SMA and IMA collateralize through the meandering mesenteric artery (arc of Riolan) and the marginal artery of Drummond.[1,5] The meandering mesenteric artery is a collateral vessel that enlarges in the presence of SMA occlusive disease. It lies at the base of the mesentery and is at risk of being ligated along with the inferior mesenteric vein during exposure of the infrarenal aorta.[1] The collateral circulation should be verified when there is SMA and/or celiac occlusive disease, and following colectomy as unnecessary ligation of the IMA may cause intestinal necrosis.

The juxtarenal aorta is the segment of aorta between 1 cm above and 1 cm below the renal arteries and frequently overlaps the visceral segment. The renal arteries usually arise at the level of first lumbar vertebra, but there is considerable variability.[6] Multiple renal arteries occur in up to 30% of patients.[7] The left renal artery runs posterior to the left renal vein (LRV), whereas the right renal artery courses posterior to the vena cava.

The aortic bifurcation is usually at the level of L4–L5, with the IMA arising 2 to 3 cm above this split. The IMA gives rise to the left colic artery, 2–3 sigmoid arteries, and the superior rectal artery. The right common iliac artery runs anterior to the inferior vena cava (IVC) and the origin of the left common iliac vein, hence caution should be exercised when dissecting the whole circumference of the right common iliac artery at its origin. Splanchnic nerve branches providing sympathetic innervation to the pelvis run over the origin of the left common iliac and should be carefully preserved to avoid retrograde ejaculation after open aortic surgery. At the level of the iliac bifurcation each artery is crossed by the ureter. Placing a ureteral stent preoperatively in redo operations helps identify the ureters. During surgery, it is vital that the ureter is not skeletonized and that a prosthetic graft is not placed in direct contact with a ureter.[5] The cisterna chyli lies posterior and to the right of the aorta and passes beneath the right crus of the diaphragm to enter the chest as the thoracic duct.

Abdominal Incisions

Vascular surgeons need to be familiar with a variety of approaches for exposing the abdominal vasculature (Figs. 56.1 and 56.2). Transperitoneal exposure through a midline celiotomy incision is the most versatile and therefore remains the standard approach. Virtually every major artery and vein can be exposed through this incision. Disadvantages compared with transverse or oblique incisions are a greater degree of postoperative pain and a higher incidence of incisional hernia. The risk of incisional hernias after aortic surgery is not insignificant and may be as high as 10% per year for midline incisions.[8] There is increasing evidence that prophylactic mesh placement can decrease the incidence of postoperative hernias after open aortic replacement for aneurysmal pathology.[9] Transverse and oblique retroperitoneal incisions are less painful (helpful in patients with pulmonary compromise) and less prone to hernias (3%–5% per year) but lack the versatility of a midline incision.[8,10,11] The following is a more detailed description of the various abdominal incisions used by vascular surgeons.

Midline Incision

As mentioned previously, this is considered the most versatile approach, allowing unrestricted exposure of the infrarenal

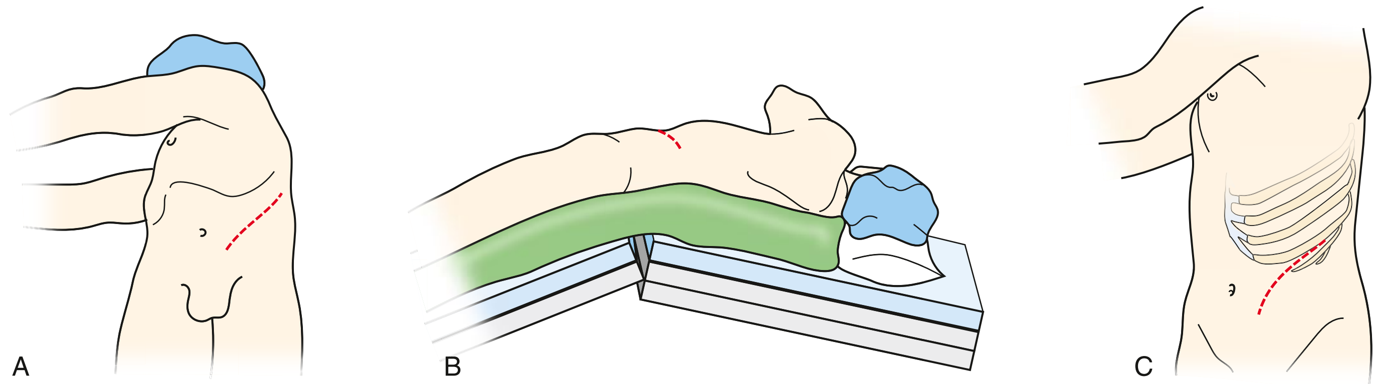

Figure 56.2 **Patient Positioning for Left Flank Approach to Abdominal Aorta.** (**A**) The shoulders are positioned at 50 to 70 degrees to the operating table and the pelvis rotated posteriorly as far as possible (corkscrew position). (**B**) The table can be jack-knifed to widen the space between the left iliac crest and costal margin. (**C**) The incision can be carried into the 10th interspace (as drawn) for more proximal aortic exposure.

aorta and its branches (see Fig. 56.1). It can also provide exposure to the suprarenal aorta when combined with medial visceral rotation. The patient is positioned supine, with one arm abducted to 90 degrees and accessible to the anesthesia team. Skin preparation should extend from the nipples to include both groins down to mid thighs for access to the femoral arteries, and saphenous veins if needed. The incision starts at the level of the xiphoid in the upper abdomen and is carried down around the umbilicus. It can be extended to just above the pubic bone if the iliac vessels need to be exposed. The peritoneal cavity is entered through the linea alba, and the viscera are packed into the lower abdomen if one is working on the upper abdominal vessels, or in the right side of the abdomen if one is working on the infrarenal aorta. If the small bowel is eviscerated, it is placed in a bowel bag to keep the heat in and collect the transudate; a moist towel may also be used. A large mechanical retraction system (i.e., Omni Tract or Thompson) is useful to retract the bowel and help with exposure.

Transverse and Subcostal Incisions

The transverse and subcostal incisions are transperitoneal incisions (see Fig. 56.1). The transverse incision is carried across both rectus muscles from the contralateral anterior/mid-axillary line to the ipsilateral anterior/mid-axillary line (depending on the amount of exposure needed), midway between the costal margins and the iliac crests. When unilateral flank exposure is contemplated, the incision can be limited to one side and end at the contralateral midclavicular line. Transverse incisions can be supraumbilical ("frown") or infraumbilical ("smile"). The apex of the supraumbilical incision is centered halfway between the umbilicus and the xiphoid, and the center of the infraumbilical incision is 3 to 4 cm below the umbilicus. A supraumbilical transverse incision is good for infrarenal aortic exposure, particularly when concomitant distal renal artery exposure is necessary.[12] An infraumbilical incision provides excellent pelvic exposure (e.g., for large iliac/hypogastric aneurysms) but offers poor access to the pararenal aorta. When compared with a midline incision, some studies show a significant decrease in postoperative pain, pneumonia, and hernias,[13] whereas others show no difference in outcomes or complications.[6,14–17]

Subcostal incisions are transverse incisions, infrequently used by vascular surgeons, which run parallel to the costal margins and two fingerbreadths below them. The most common variety is an extended right or left incision which begins at the lateral edge of the contralateral rectus sheath and is carried across the midline as far laterally on the ipsilateral side as necessary (usually the anterior axillary line). The subcostal incision is helpful in exposing the hepatic, splenic, and renal arteries, as well as upper abdominal venous structures.

Oblique Flank Incision

These incisions are usually combined with extraperitoneal dissection and are helpful for exposing the aorta and its branches through the left flank, and the IVC through the right flank. A left retroperitoneal flank incision (see Figs. 56.2–56.4) is excellent for patients with complex aortic anatomy.[18] Different segments of the aorta from hiatus to bifurcation can be exposed based on which intercostal space is used. The restrictions of this incision are limited exposure of the right iliac system and poor visualization of the right renal artery beyond its origin. This approach is extremely helpful in redo-aortic operations, suprarenal aortic pathology, horseshoe kidney with multiple renal arteries, morbid obesity, inflammatory aneurysms, diastasis of the abdominal wall, and in patients with respiratory compromise (because the incision generates less pain). The patient is placed in a modified right lateral decubitus position, with the left shoulder at 50 to 70 degrees to the operating table, and the pelvis rotated posteriorly as far as possible (corkscrew position). A vacuum "bean bag" helps to maintain this position. The left arm is supported on an over-arm board. The table may be broken at the level of the umbilicus to open-up the space between the left costal margin and iliac crest. An oblique incision is made from the lateral edge of the left rectus sheath, a centimeter or so above the midpoint between the umbilicus and pubis and extended a few centimeters into the 11th intercostal space. This incision is particularly good for infrarenal aortic exposure.

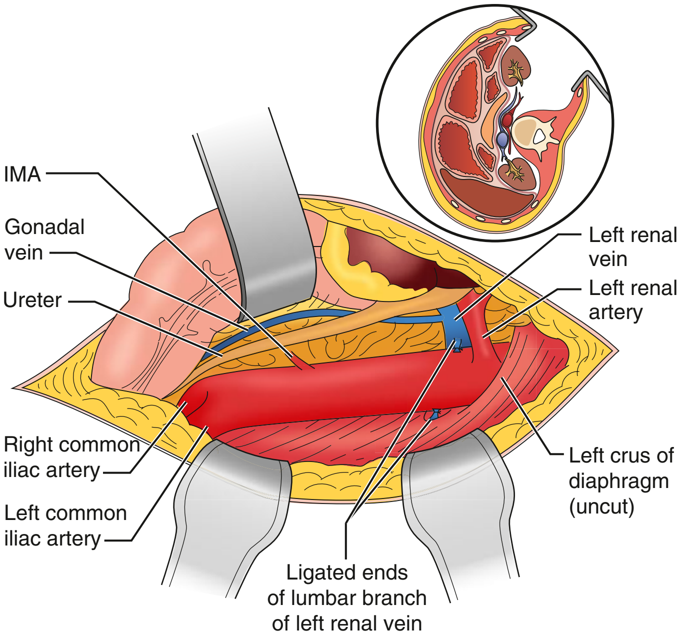

Figure 56.3 Left Flank Incision Retroperitoneal Dissection. The abdominal contents are retracted anteriorly and to the right. The left kidney is mobilized anteriorly, and the lumbar branch of the left renal vein is divided; inset is a cross-sectional view demonstrating a retrorenal dissection plane. *IMA*, inferior mesenteric artery.

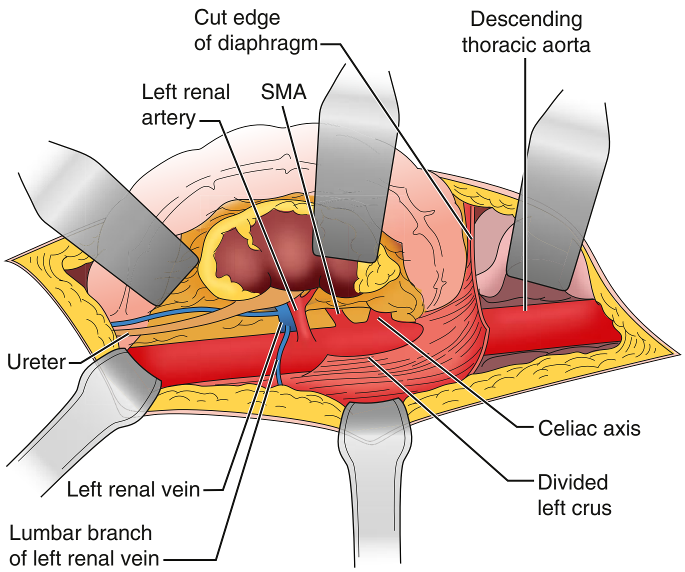

Figure 56.4 Left flank thoracoretroperitoneal approach with exposure of aorta from distal descending thoracic segment to aortic bifurcation. *SMA*, superior mesenteric artery.

Extension across the rectus to the midline aids in more distal right iliac exposure. For more proximal aortic exposure, the incision can be extended posteriorly or taken into a more proximal intercostal space (10th or 9th), which requires entry into the chest (a thoracoretroperitoneal approach; see Figs. 56.2 and 56.4). The external and internal oblique and transversus muscles are divided to the margin of the left rectus sheath medially, which is partially split. Posteriorly the intercostal muscles are divided on the superior aspect of the 12th (or 11th or 10th) rib, making no attempt to stay out of the chest. The extraperitoneal space is entered at the tip of the chosen rib, and the peritoneum stripped away from the musculature anteriorly (with or without the transversalis fascia). Dorsally, the peritoneum is stripped off the lumbodorsal fascia to the level of the psoas, and using blunt dissection, a retroperitoneal plane is developed by retracting the spleen, tail of pancreas, and left colon to the patient's right. This plane is developed either anterior or posterior to the left kidney depending on the nature of the procedure, posterior to the kidney being much easier. A right flank incision can be performed in a similar fashion to expose the IVC. Shorter oblique incisions (extending from the lateral edge of the rectus just to the tip of the 12th rib) can also be used, but these provide very limited exposure.

Thoracoabdominal Incision

This incision is used to expose the upper abdominal and lower thoracic aorta (see Figs. 56.1 and 56.4). It can be considered as an extended version of the retroperitoneal approach for exposure of the thoracic aorta. A double-lumen endobronchial tube is helpful when collapse of the left lung is needed during extensive work on the thoracic aorta; when only limited exposure is required a single lumen endotracheal tube is used and the lung retracted out of the way. After intubation, the patient is rolled into a right lateral decubitus position and the scapula set between 60 and 90 degrees to the table, depending on the exposure needed. The hips are rotated as far posteriorly as 30 degrees to the table if access to the femoral arteries is necessary. A vacuum "bean bag" aids in maintaining the patient's torso in the ideal position. Other safety measures to minimize nerve injury include an axillary roll, and positioning of the lower extremities, with the bottom leg (the right) bent at the knee, the top leg (left) straight, and pillows placed between the legs.

The incision starts above the desired rib, depending on the aortic segment that needs to be exposed and is extended towards the midline ending at the lateral border of the left rectus sheath. The incision is then deepened, preserving the latissimus dorsi if possible, and incising the serratus anterior muscle. Depending on the extent of the aneurysm, the thorax may be entered through any appropriate intercostal space (from the fifth interspace for an extent II thoracoabdominal aneurysm (TAAA), to the ninth interspace for an extent IV aneurysm) (see Ch. 79, Thoracic and Thoracoabdominal Aortic Aneurysms: Open Surgical Treatment). After entering the chest, the inferior pulmonary ligament is divided, and the lung is mobilized and retracted. Distally, the incision may extend to the upper abdomen if the aneurysm involves only the upper visceral aorta (extent I and V TAAA), or it may extend to the midline and then be carried distally if exposure of the infrarenal aorta or iliac arteries is required. The abdomen can be entered through a retroperitoneal plane or transperitoneally, with left medial visceral rotation. The diaphragm is partially divided peripherally (50% of the circumference), 2 to 3 cm away from its attachments to the chest wall.[19,20] This avoids injury to the phrenic nerve. Leaving the diaphragm intact may result in earlier ventilator weaning.[20] A portion of the costochondral cartilage is excised to help with postoperative healing. Excising a 1.5- to 2-cm posterior segment of rib under the paraspinous muscles can assist with the exposure and reduces pain postoperatively.

Lower Quadrant Incisions

Lower quadrant incisions are useful for exposure of the iliac arteries (see Fig. 56.1). The patient is placed supine, with a roll under his flank on the side of the incision. The classic transplant incision is a curvilinear ("hockey stick") incision, beginning one or two fingerbreadths above the symphysis pubis and lateral to the midline. This incision curves up laterally to the edge of the rectus sheath and is then extended superiorly along the lateral edge of the rectus for a distance determined by how much of the iliac system needs to be exposed. The fascia at the edge of the rectus is divided along with the transversalis fascia to expose the peritoneum. The crossing inferior epigastric vessels caudally are ligated and divided. The spermatic cord should be preserved in male patients (freed up laterally and retracted medially), but the round ligament in females can be sacrificed if deemed necessary. A retroperitoneal plane is gently created laterally, and the peritoneal sac and contents retracted medially to expose the iliac vessels from the aortic bifurcation to the inguinal ligament. Shorter suprainguinal incisions, running parallel to, and one or two fingerbreadths above, the inguinal ligament, provide excellent exposure for control of the distal external iliac artery, when femoral artery exposure is deemed hazardous (e.g., in the presence of a large femoral artery pseudoaneurysm).

Exposure of Infrarenal Abdominal Aorta and Iliac Arteries

Transperitoneal Approach

Inframesocolic exposure of the infrarenal aorta (Figs. 56.5 and 56.6) is the most common approach practiced by vascular surgeons.[6,21] It can be performed through a midline or transverse incision and is the preferred approach when access to the right renal artery, distal right iliac system, or intraabdominal organs is necessary. After entering the peritoneal cavity, the transverse colon is reflected superiorly out of the abdomen and the small bowel retracted to the right and protected with a moist towel, or placed in a plastic bag (see Fig. 56.5). Maintaining the small bowel within the abdominal cavity, as opposed to retracting it on to the abdominal wall, helps to reduce bowel wall edema. The peritoneal attachments of the third and fourth portions of the duodenum are divided and the mobilized duodenum reflected to the right. The retroperitoneum overlying the aorta, along with periaortic tissue, is incised. The inferior mesenteric vein is the most superficial venous structure encountered in the retroperitoneum superiorly and can be ligated and divided if necessary. The aorta is palpated and dissected out. The superior extent of the dissection is the LRV (see Figs. 56.6 and 56.7), where draining lymphatic channels are particularly abundant and should be ligated or divided with an ultrasonic scalpel, rather than cauterized, to avoid troublesome chyle leaks postoperatively. The anterior surface of the aorta can be cleared off distally to the level of the bifurcation, with the only structure

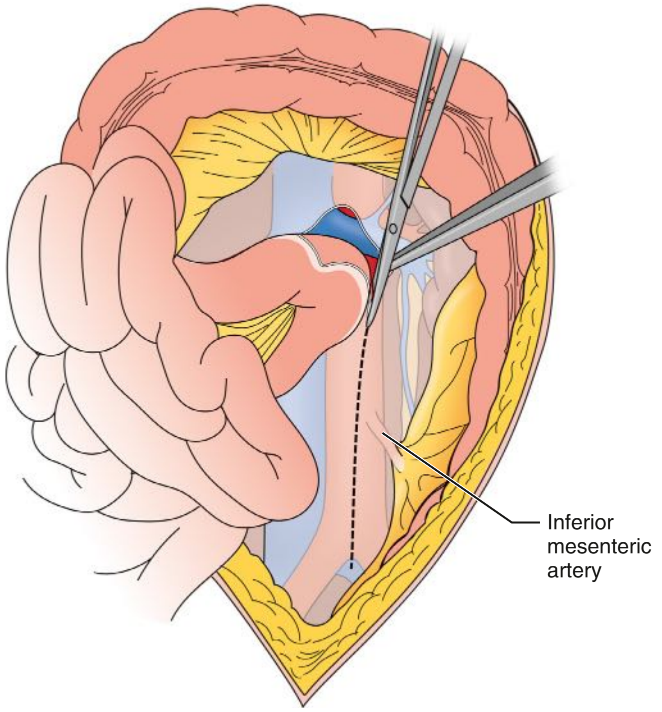

Figure 56.5 Inframesocolic approach to infrarenal aorta (I): reflection of transverse colon superiorly, retraction of small bowel and duodenum to right after division of the ligament of Treitz.

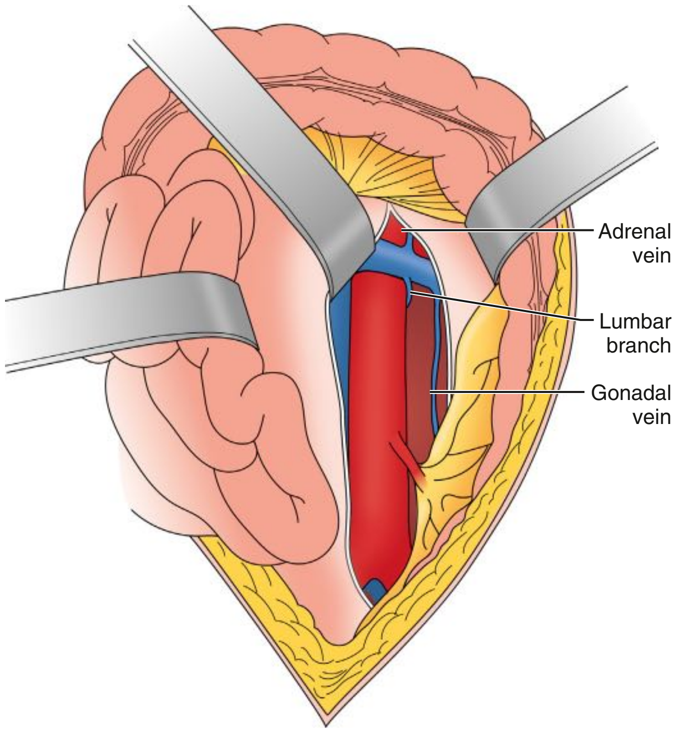

Figure 56.6 Inframesocolic approach to infrarenal aorta (II): infrarenal aorta exposed from left renal vein to just below aortic bifurcation showing origin of the inferior mesenteric artery.

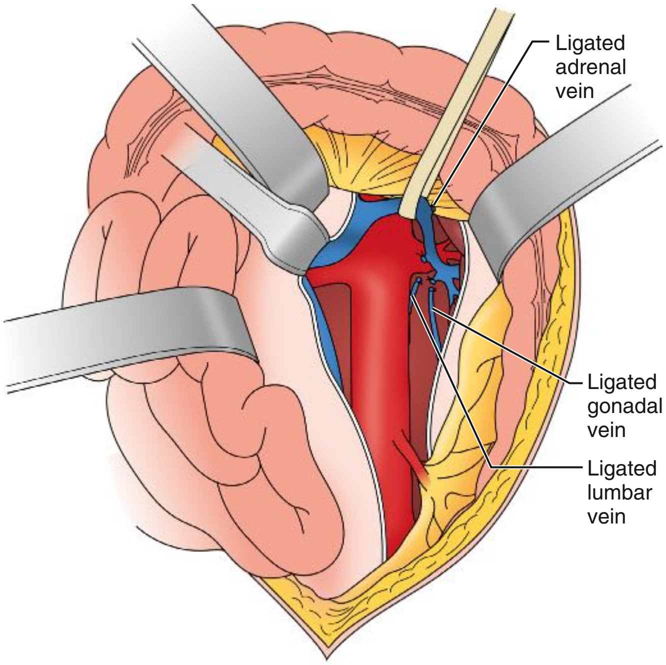

Figure 56.7 Inframesocolic exposure of the pararenal aorta with mobilization of left renal vein (following division of venous branches and retraction) to show renal artery origins.

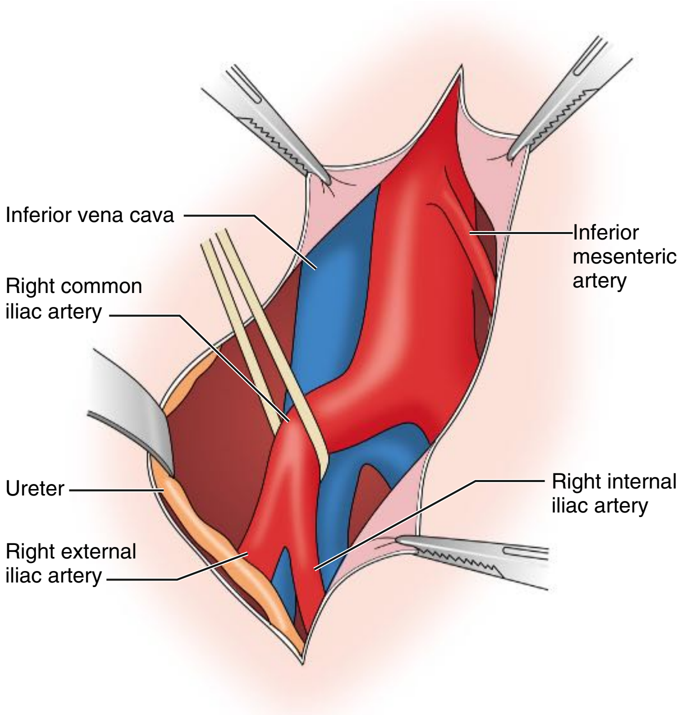

Figure 56.8 Exposure of right iliac artery bifurcation with ureter retracted distally.

at risk being the IMA. This vessel is surrounded by a plexus of nerves which should be avoided if possible. During mobilization of the duodenum and exposure of the retroperitoneal aorta, care must be taken to identify and protect any large visceral collaterals (e.g., the meandering mesenteric artery) that can course at this level.

Exposure of the pararenal aorta (see Fig. 56.7) more superiorly requires full mobilization of the LRV, again taking care to ligate adjacent lymphatics. The vein is freed up from its junction to the IVC to a point past its major branches, which include the left adrenal vein superiorly, the left gonadal vein inferiorly, and a lumbar branch posteroinferiorly. Ligating and dividing these branches allow the LRV to be retracted superiorly or inferiorly with an encircling Penrose drain, as needed. The LRV can be divided to improve exposure, but in this case, its branches (gonadal, adrenal, and lumbar branches) must be preserved to provide venous outflow for the left kidney. Division of the LRV should be performed close to the IVC to help preserve these collaterals. Whether LRV ligation is associated with an increased risk of renal dysfunction is controversial; most studies document only a transient decline in renal function following ligation, with a return to normal function within 2–6 weeks.[22,23] Exposure of the proximal left renal artery is accomplished by dissecting posterior to the mobilized LRV. The right renal artery courses posterior to the IVC, and its origin is visualized by freeing up the LRV–IVC junction. Crural fibers extending down from the diaphragm posterior to the renal arteries can be released to improve exposure. Aortic dissection can be carried superiorly to the origin of the SMA which is the cranial extent of this exposure. Again, large crossing lymphatics at this level should be ligated to avoid a chyle leak. If more proximal aortic exposure is needed, then access through the lesser sac or retroperitoneum is required (see below).

The origins of the iliac arteries (Figs. 56.6 and 56.8) can be exposed by slight distal extension of the retroperitoneal incision used for the infrarenal aorta. This extension can be continued over the course of the right iliac beyond the iliac bifurcation to expose the entire right iliac system. Exposure of the right bifurcation and hypogastric artery requires retraction of the cecum and small bowel laterally and superiorly. At the level of the iliac artery bifurcation, caution is taken to identify and protect the overlying ureter. Exposure of the external iliac artery is achieved by incising the peritoneum over it distal to the ureter.

Only a few centimeters of the left common iliac artery can be exposed as an extension of aortic exposure, because of the overlying sigmoid colon (Fig. 56.9). The tissue crossing over the origin of the left common iliac artery contains sympathetic nerve fibers which should be carefully preserved and retracted rather than incised in sexually active male patients to avoid postoperative erectile dysfunction.[24] Circumferential dissection of the aortic bifurcation and most proximal common iliac arteries should be avoided unless absolutely necessary, because of the risk of injuring the underlying caval confluence, which can be quite adherent to diseased or aneurysmal arteries. Controlling the common iliac arteries just a few centimeters distally is usually safer. To access the left external and hypogastric arteries, the sigmoid colon is reflected medially after incising its lateral peritoneal reflection. The external iliac artery traverses laterally and caudally on top of the psoas muscle to form the common femoral artery beneath the inguinal ligament. The dissection is carried cephalad to identify the iliac bifurcation

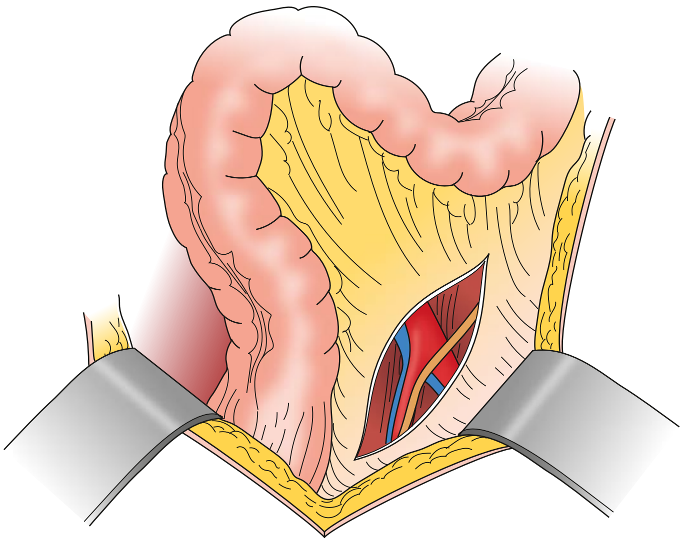

Figure 56.9 Exposure of left iliac artery bifurcation with crossing ureter after incising peritoneal reflection lateral to sigmoid colon.

and crossing ureter. The hypogastric artery is identified as a large branch coming off medially and coursing inferiorly. Careful dissection is performed to separate the internal iliac artery from the underlying vein.

Retroperitoneal Approach

As outlined previously, surgical exposure through a left flank retroperitoneal approach (see Figs. 56.2 and 56.3) offers several advantages.[10,11] An oblique left flank incision is made as described previously. After entering the retroperitoneal space, the surgeon must decide whether to expose the aorta anterior or posterior to the left kidney. A retrorenal plane is most commonly chosen, and the left kidney and ureter are reflected anteriorly along with the peritoneal sac and its contents. When developing this plane, it is important to stay anterior to the lumbodorsal fascia covering the psoas and flank musculature, because of increased bleeding when this fascia is stripped off. As the viscera are retracted to the patient's right, the aorta should become palpable in the base of the wound. Initial efforts are focused on identification of the left renal artery because this is the only major structure that can be injured while clearing off the aorta from this approach. Identification does not necessarily require dissection of all the tissue around the pararenal aorta. A guide to this artery is provided by a large vein (the lumbar branch of the LRV) that crosses the left lateral wall of the aorta at this level; this vein usually requires division for exposure of the juxtarenal aorta. If this vein is quite large, the surgeon needs to be concerned that it may represent a retro-aortic LRV, a possibility which can be checked by a review of preoperative imaging studies. In this instance the retrorenal approach should be abandoned in favor of an exposure plane anterior to the kidney, which will leave this vein undisturbed. Following division of the lumbar branch, dissection of the left lateral wall of the aorta is carried distally to the aortic bifurcation, watching for the origin of the IMA. During exposure of the aortic bifurcation, care should be taken to ensure that the left ureter has been mobilized and retracted out of harm's way. The entire left common iliac artery and its bifurcation can be visualized through this approach, but only the proximal right common iliac artery is accessible. Division of the IMA can improve right iliac exposure, as can extension of the incision across the rectus to the midline, but exposure beyond the iliac bifurcation is rarely possible through this approach.

Exposing the aorta anterior to the left kidney is more tedious because a plane between the kidney and mesocolon must be developed with more sharp than blunt dissection. As the left colon and viscera are retracted anteriorly, the left kidney and ureter are left in their normal anatomic position posteriorly; the ureter must be carefully protected during subsequent left iliac dissection as it courses medially over the iliac bifurcation. Besides a retro-aortic LRV, the only other indication for this approach is the need to expose a long segment of the proximal SMA which is obscured by the crossing left renal artery when approached retrorenally.

As previously outlined, disadvantages of this approach include limited exposure of the distal right iliac system and right renal artery, as well as an inability to perform a complete abdominal exploration. However, a limited abdominal exploration is still possible by making a small rent in the peritoneal sac which can be subsequently closed (see Ch. 73, Abdominal Aortic Aneurysms: Open Surgical Treatment).

Exposure of the Proximal Abdominal Aorta: Hiatus to Renal Arteries

Transperitoneal Approach Through the Lesser Sac

Use of this approach is limited because the exposure provided is confined to 4 to 5 cm of supraceliac aorta, the celiac axis, and the proximal SMA (Fig. 56.10). Indications include visceral bypasses and exposure for supraceliac aortic clamping. The segment of aorta proximal to the celiac artery is usually devoid of plaque and is used for aortic control when the lower aorta is not favorable for clamping (e.g., excessive thrombus, or plaque). Either a midline or supraumbilical transverse incision is used. The triangular ligament of the left lobe of the liver is divided, and the distal end of the left lobe retracted to the right. Care is taken not to injure the left hepatic vein while dividing the triangular ligament. The lesser sac is entered through a longitudinal incision in the gastrohepatic ligament. Identification of the esophagus is greatly aided by the presence of a nasogastric tube, particularly in hypotensive ruptured aneurysm patients, when the aorta is flaccid. During division of the gastrohepatic ligament, care is taken not to divide an aberrant (replaced) left hepatic artery, present in 10% to 15% of patients. When present, it usually runs in the cephalad portion of the ligament, coming off the left gastric artery. After retracting the esophagus and stomach to the left, the right crus of the diaphragm can be exposed, lifted off the aorta with a right-angle clamp and divided with electrocautery. The operator's index finger can then be inserted between the aorta and the median arcuate ligament, which is divided, if necessary, to expose the distal descending thoracic aorta. The pleural cavity is occasionally entered. Circumferential isolation of the aorta

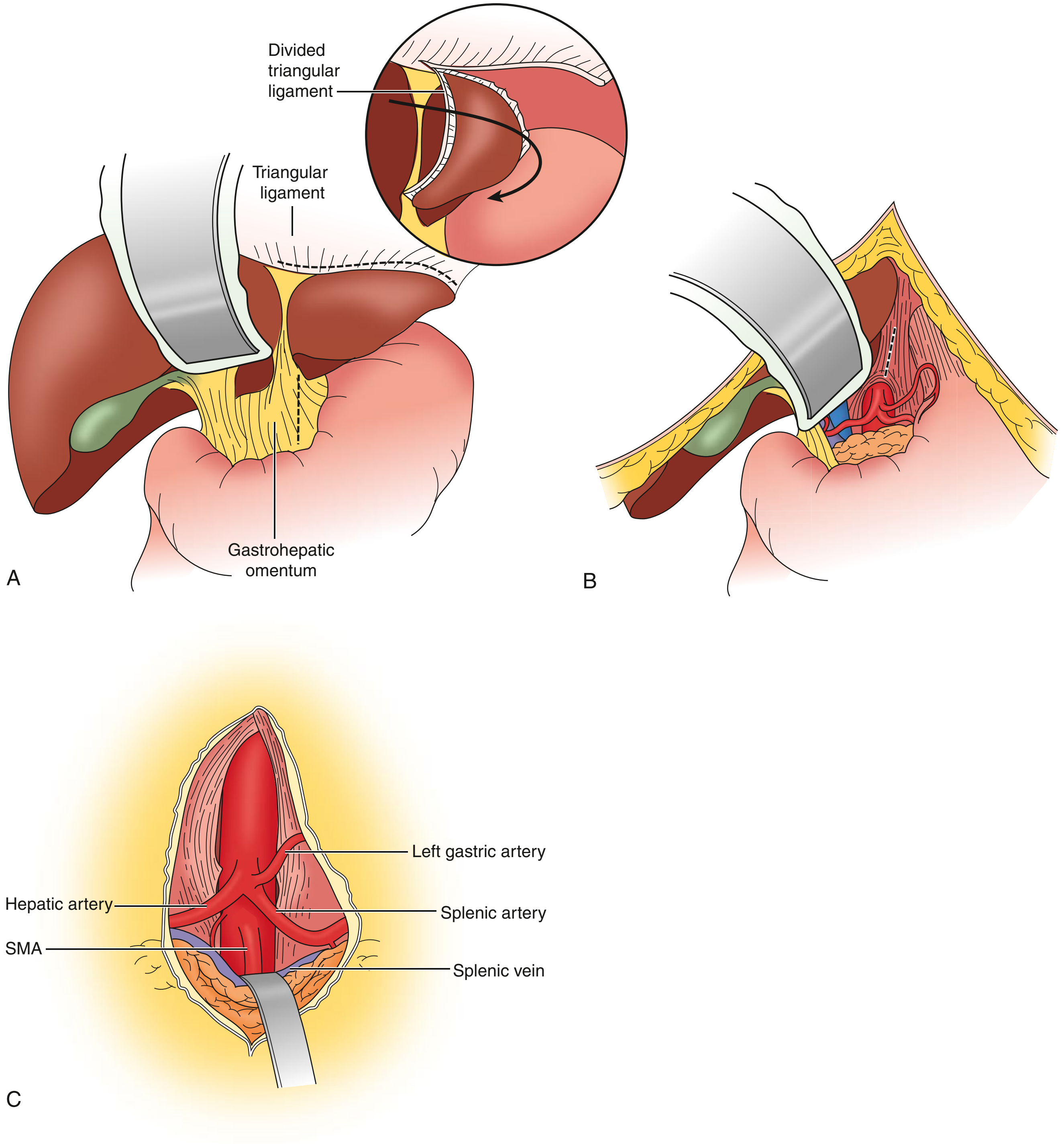

Figure 56.10 Exposure of the Celiac Trunk/Branches and the Superior Mesenteric Artery. (**A**) Division of gastrohepatic omentum and triangular ligament of left lobe of liver; inset shows lateral edge of left hepatic lobe folded back on itself to expose aortic hiatus. (**B**) Lateral segment of left hepatic lobe retracted to the right; dotted line shows division of median arcuate ligament and diaphragmatic crura over anterior surface of aorta; celiac artery and branches are typically covered by a thickened rind of neural/lymphatic tissue (not shown). (**C**) Exposure of celiac artery and proximal branches after division of crura, and resection of neural/lymphatic tissue; superior mesenteric artery is exposed by retracting the superior border of the pancreas distally. *SMA*, superior mesenteric artery.

at this level is usually unnecessary and may injure posterior segmental branches.

In an emergency requiring urgent proximal aortic control, a more rapid supraceliac aortic dissection is performed after entering the lesser sac (Fig. 56.11). The avascular portion of the gastrohepatic ligament is incised, and the esophagus is retracted to the left, guided by the nasogastric tube. The aorta is palpated and compressed against the spine. Blunt index finger dissection is used to separate the aorta from the crura of the diaphragm and surrounding tissues. Once a dissection plane is

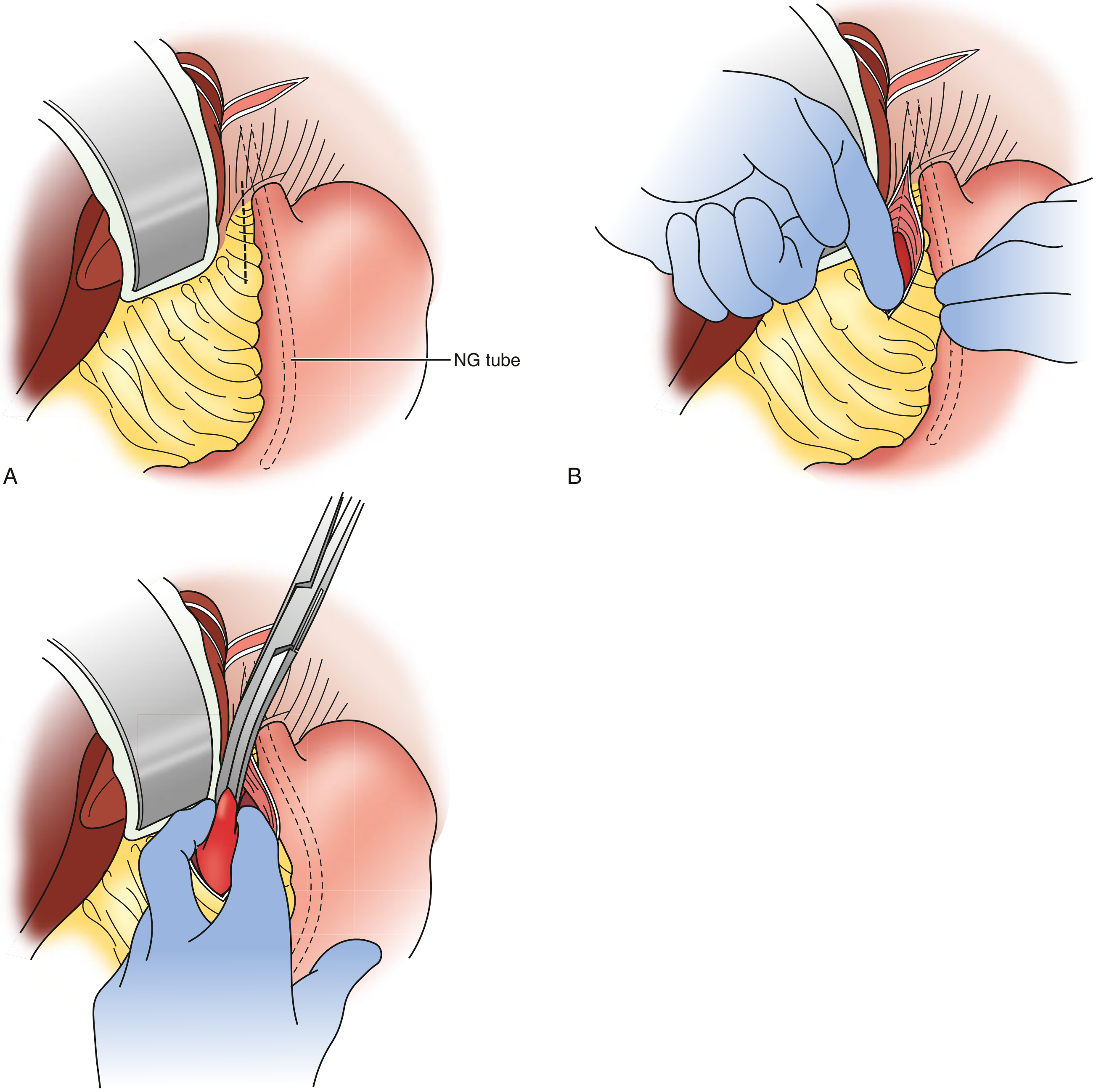

Figure 56.11 Rapid Control of Supraceliac Aorta. (**A**) Retraction of lateral segment of left hepatic lobe and division of gastrohepatic omentum (along *dotted line*). (**B**) Division of overlying diaphragmatic crural fibers and blunt index finger mobilization of supraceliac aorta; palpation of nasogastric tube and retraction of stomach to left reduces risk of inadvertent injury to stomach/esophagus during this maneuver. (**C**) Placement of large, vertically oriented clamp across supraceliac aorta.

completed, the aorta is pinched between the index and middle fingers, while a long vascular clamp is applied.

The celiac axis is exposed by dissecting away the enveloping celiac plexus; this nerve tissue is thick and can be quite adherent to the aorta and celiac artery. As the dissection proceeds distally, the three branches of the celiac artery are encountered and should be treated with care because they are more thin-walled than the main trunk and can be easily damaged. The SMA can be identified just below the celiac; caudal retraction on the mid-body of the pancreas provides exposure to up to 3 to 5 cm of this vessel. Surrounding lymphatics require careful attention to prevent postoperative chyle leaks.

Transperitoneal Approach with Left Medial Visceral Rotation

The entire proximal abdominal aorta can be exposed through a transabdominal approach by performing a medial visceral rotation, the so-called Mattox maneuver (Fig. 56.12).[25,26] This

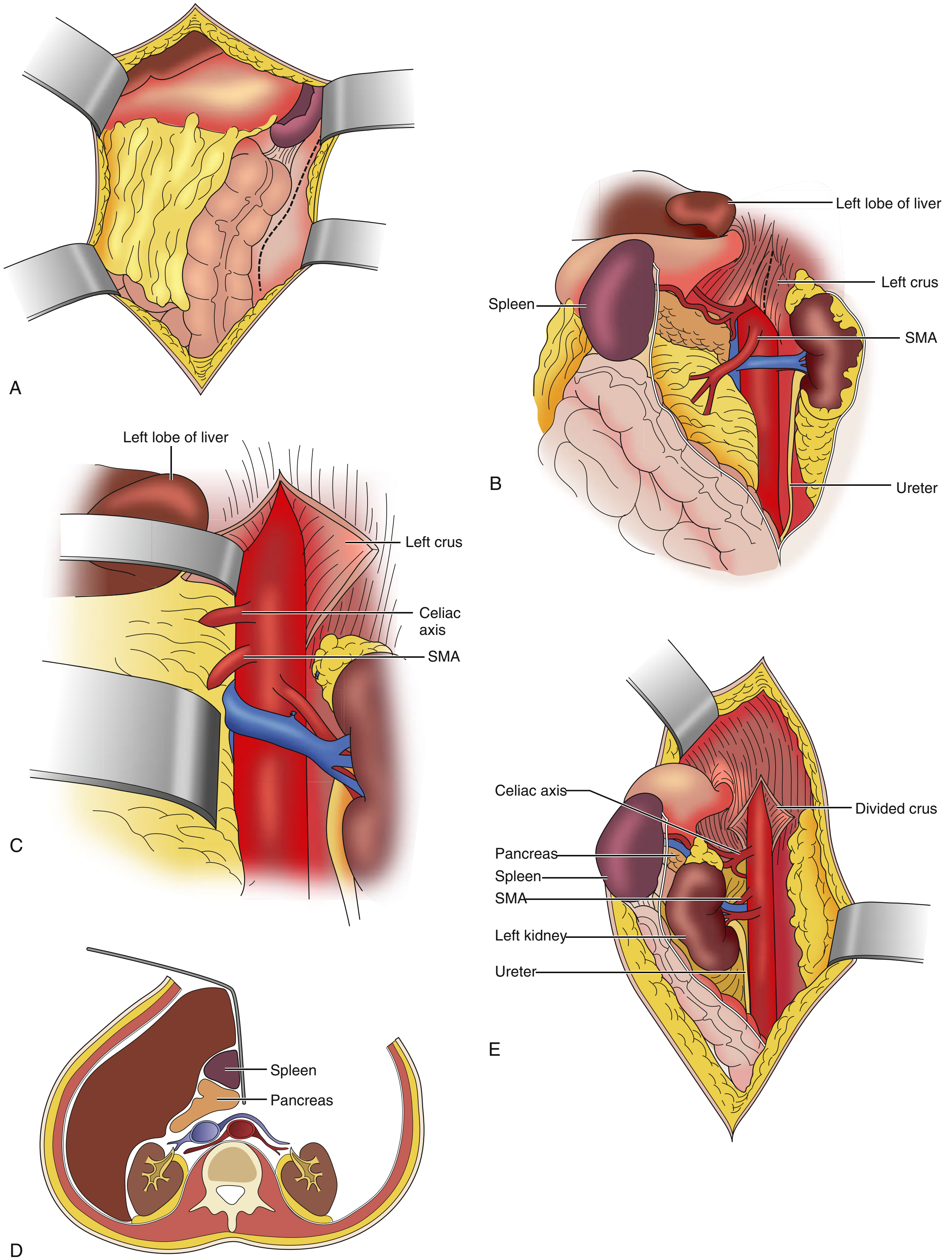

Figure 56.12 Left Medial Visceral Rotation. (**A**) Peritoneal incision lateral to descending colon and spleen. (**B**) Reflection/rotation of abdominal viscera from left to right (medially) in a plane anterior to left kidney leaving kidney in normal anatomic location with exposure of proximal abdominal aorta in base of wound. *Dotted line* is intended division line of left diaphragmatic crus. (**C**) Same exposure following division of left diaphragmatic crus and mobilization of left renal vein. (**D**) Cross-sectional view showing potential retraction injury of spleen and pancreas with this approach. (**E**) Same exposure but dissection plane is carried posterior to left kidney elevating it out of its bed and retracting it medially. *SMA*, superior mesenteric artery.

approach is challenging in obese patients and those with a narrow costal angle, but it does avoid a thoracic incision. The lateral peritoneal reflection adjacent to the descending/sigmoid colon and spleen is incised cephalad, curving toward the aortic hiatus. Using largely blunt dissection, a retroperitoneal plane is developed, and the spleen, tail of pancreas, and left colon are retracted anteriorly and to the patient's right. The left kidney is usually elevated with these structures, and the avascular plane posterior to the left kidney is entered anterior to the psoas and flank musculature, taking care not to strip off the lumbodorsal fascia. When the left kidney is reflected upward, the origins of the celiac trunk, SMA, and the entire left renal artery can be visualized. However, exposure of the SMA beyond its first 2–3 cm is limited by the crossing left renal artery. In the case of a retro-aortic LRV, or when exposure of a longer segment of proximal SMA is necessary, a plane anterior to the kidney may be developed. When the kidney is left down, a much longer segment of SMA (up to 8–10 cm) is accessible, but exposure of the left renal artery then requires mobilization of the LRV. Developing an anterior plane is more tedious than a posterior one, and care must be taken to avoid injury to the left adrenal gland and draining veins.

Exposure of the supraceliac aorta is limited to just a few centimeters with this approach and requires division of the left diaphragmatic crus along the left lateral wall of the aorta. Besides the lack of access to the distal descending thoracic aorta, other disadvantages of this approach include a high incidence of splenic injury (up to 20%), and complications of excessive visceral retraction (e.g., bowel ischemia and pancreatitis; see Figs. 56.12D and E).[26] Nevertheless, when combined with standard transperitoneal exposure techniques, this approach provides the greatest versatility for exposing the entire abdominal aorta and all its branches.

Left Flank Retroperitoneal/Thoracoretroperitoneal Approach

The proximal abdominal aorta can also be exposed through a left flank incision in the 10th or 9th interspace, depending on how much proximal exposure is necessary (see Figs. 56.2–56.4). The 10th interspace is adequate for supraceliac clamping and pararenal exposure; however, paravisceral procedures are best accomplished through a 9th interspace incision. When going through a 10th or 9th interspace incision the left chest is entered, and it is necessary to divide the diaphragm to prevent tearing it when the ribs are retracted apart. A circumferential division 2 to 3 cm away from the chest wall avoids the risk of phrenic nerve injury, which can cause postoperative pulmonary dysfunction. As noted earlier with respect to exposure anterior or posterior to the left kidney, a retrorenal plane is preferred. Longitudinal division of the left diaphragmatic crus improves visualization of the left renal artery origin and is *essential* for exposing the celiac trunk and SMA origins. As previously described, circumferential isolation of the suprarenal/-celiac aorta is not necessary for clamping at this level as long as the anterior and posterior surfaces are cleaned off enough to allow placement of the blades of a cross-clamp.

Exposure of the Visceral Arteries

Celiac Axis

Exposure of the proximal celiac through the lesser sac has been described above (see Fig. 56.10).

Superior Mesenteric Artery

Exposure of the proximal SMA can be accomplished transperitoneally through the lesser sac (allowing for 3–5 cm of exposure; see Fig. 56.10), via medial visceral rotation, or through a left flank retroperitoneal approach (providing 8–10 cm of exposure; see Figs. 56.3, 56.4 and 56.12). Distal SMA exposure requires an inframesocolic approach (Fig. 56.13). Through a transperitoneal incision, the transverse colon is reflected superiorly, and the small bowel retracted to the right and inferiorly. The SMA is dissected out to the right of the ligament of Treitz in the root of the mesentery, as it emerges from underneath the pancreas. In SMA embolism a proximal pulse is frequently present and serves as a guide to the artery; if not, an occluded SMA can usually be palpated as a firm tubular structure 5 to 6 mm in diameter. The superior mesenteric vein (SMV) lies immediately to the right of it. With this approach one can usually dissect out the SMA from just proximal to the middle colic artery to its distal ileocolic branches.

Hepatic Artery

A transperitoneal upper midline or an extended right subcostal incision is usually used (see Fig. 56.10). Elevation of the right flank on a rolled sheet may be helpful. The liver is retracted superiorly and the right transverse colon and small bowel inferiorly. The gastrohepatic ligament is incised transversely, and the lesser sac is entered. The common hepatic artery and proximal portion of the proper hepatic artery are easily palpated within the hepatoduodenal ligament. The common hepatic artery is dissected out as it passes over the pancreatic head and followed distally until the gastroduodenal artery is found. Gentle traction on the common hepatic artery will facilitate exposure of its branches, the gastroduodenal and proper hepatic. The proper hepatic artery is located more distally within the porta hepatis, anterior to the portal vein and medial to the common bile duct.[2,3]

Splenic Artery

A transperitoneal upper midline or extended left subcostal incision is appropriate, with a rolled sheet placed under the left flank. The proximal third of the splenic artery is best approached through the lesser sac, which is entered either by dividing the gastrohepatic omentum above the lesser curvature of the stomach (see Fig. 56.10) or dividing the gastrocolic ligament, after reflecting the greater omentum superiorly and the transverse colon inferiorly. The posterior gastric wall is then separated from the underlying pancreas, and the superior edge of the pancreas is exposed. The splenic artery is located along the superior surface of the body and tail of the pancreas. For distal splenic artery exposure, a partial medial visceral rotation is performed by incising the lateral peritoneal reflection of the descending colon and retracting the left colon medially. The

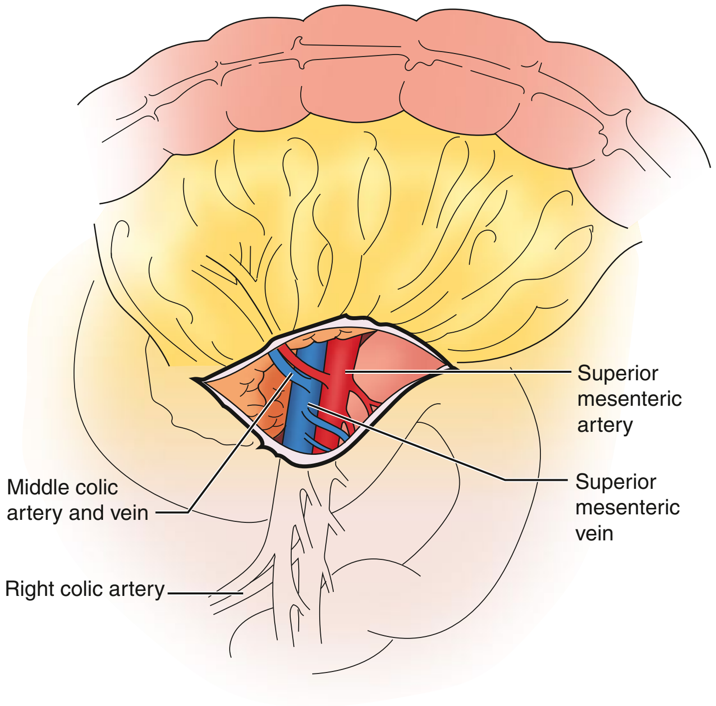

Figure 56.13 Superior Mesenteric Artery (and Vein) Exposure at Base of Mesentery.

pancreas and spleen are mobilized anteriorly and medially away from the left kidney, which is left in its normal anatomic location. The splenic artery is palpable and dissected out along the superior border of the pancreas.

Exposure of Renal Arteries

The origins (and first 2–3 cm) of the renal arteries can be exposed through an inframesocolic approach, as detailed in the section on infra/pararenal aortic exposure (see Fig. 56.7). The peritoneum over the aorta is incised, and the duodenum is reflected to the right. The avascular plane under the pancreas is entered. The LRV is mobilized, and the lumbar, gonadal, and adrenal branches are ligated and divided. This allows for cephalad or caudal retraction of the vein, depending on the exposure required. The left renal artery is typically posterior to the LRV. The left crus of the diaphragm may be partially incised to help with exposure. The proximal right renal artery is exposed by mobilizing the IVC–LRV junction. Usually a lumbar vein or two need to be ligated to retract the vena cava to the right. The LRV is retracted superiorly, exposing the origin of the right renal artery. Overlying lymphatics may need to be ligated and divided to enhance the exposure of the right renal artery origin. Again, dividing a portion of the right crus of the diaphragm helps with this exposure. More of the left renal artery (5–6 cm) than the right renal artery can be exposed from the inframesocolic approach with the IVC obscuring more distal exposure on the right.[21,24]

As described above, the entire length of the left renal artery can be exposed with a full medial visceral rotation (see Fig. 56.12)[25] or through a left flank retroperitoneal approach (see Figs. 56.3 and 56.4). It should be noted that the left renal artery is put on considerable "stretch" when approached posteriorly; this should be kept in mind when retracting the left kidney anteromedially. Therefore, bypasses to the left renal artery in this position should always be performed under some tension; otherwise, there is a risk of graft redundancy/kinking when the kidney is returned to its normal anatomic position.

The right renal artery (in particular its mid to distal portion) requires a right medial visceral rotation (partial Cattell–Braasch maneuver), either through a midline or transverse transperitoneal incision (Fig. 56.14).[27,28] The lateral peritoneal reflection of the ascending colon from cecum to hepatic flexure is incised and the colon reflected medially. The underlying second portion of the duodenum and head of the pancreas are mobilized medially with a Kocher maneuver to expose the right kidney. The right renal vein is mobilized circumferentially from its caval junction as far distally as necessary, with the attendant ligation of the small proximal tributaries. This vein may then be easily retracted during dissection of the underlying renal artery. The right renal artery travels under the IVC to its origin off the aorta, and more proximal exposure requires mobilizing the IVC from the midline (see Fig. 56.7). Any lumbar veins encountered in this process should be divided with stitch ligatures on the caval side to avoid tie dislodgement during retraction.

EXPOSURE OF THE ABDOMINAL VEINS

Inferior Vena Cava

The internal and external iliac veins converge at the sacroiliac joint to form the common iliac veins. The ureter, spermatic cord (male) and round ligament (female) and gonadal vessels

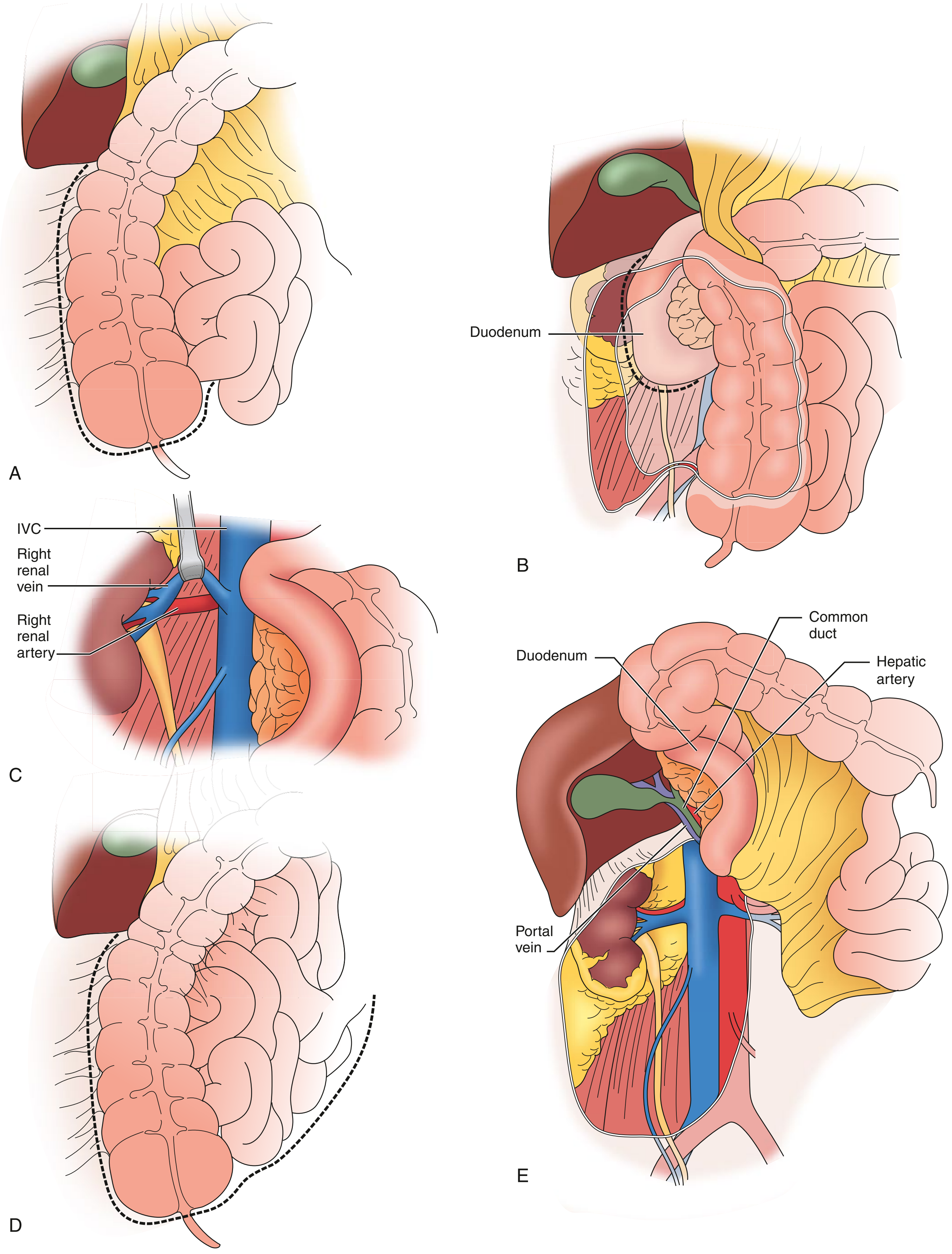

Figure 56.14 **Exposure of Infrahepatic Inferior Vena Cava and Right Renal Artery through the Right Medial Visceral Rotation (Cattell–Braasch Maneuver).** (**A**) The lateral peritoneal reflection of the ascending colon is incised (from cecum to hepatic flexure). (**B**) The right colon is reflected medially and anteriorly, and the lateral peritoneal attachments of the duodenum are incised (*dotted line*). (**C**) The underlying second portion of the duodenum and the head of the pancreas are mobilized with a Kocher maneuver and reflected medially to expose the right kidney and inferior vena cava. (**D**) The retroperitoneum is incised from the cecum medially along the root of the mesentery to the midline and carried proximally (*dotted line*) to extend exposure. (**E**) The cecum is reflected superiorly and to the patient's left to expose the infrarenal vena cava to its bifurcation and the infrarenal aorta.

cross the external iliac veins at this level. At the bifurcation of the aorta and vena cava, the iliac veins are closely related to the dorsal surface of the iliac arteries. This makes them prone to injury during hasty exposure of these arteries, especially in trauma cases. The IVC starts at the level of L5 to the right of the midline, with the confluence of the common iliac veins. The aortic bifurcation is slightly more cephalad and anterior than the caval confluence, which results in the IVC bifurcation and left iliac vein being crossed anteriorly by the right common iliac artery. There can be significant "adhesions" between the back wall of the aortic bifurcation and the front wall of the caval bifurcation and proximal iliac veins in this overlap zone, which can make dissection in this area quite hazardous. The infrarenal IVC has three pairs of lumbar veins that arise, posteriorly tethering it to the psoas muscles. The renal veins enter the vena cava at the level of L1–L2 and are usually single. The retrohepatic IVC receives three large hepatic veins at the level of the dome of the liver and more caudally several small caudate lobe branches. The IVC then enters the chest at the level of T8 and drains into the right atrium. Damage to the IVC can result in massive bleeding demanding a thorough understanding of its anatomy. Surgically important variations in venous anatomy include: left-sided cava (0.2%–0.5%), duplicated IVC (0.2%–0.3%), retro-aortic LRV (1.7%–8.7%), and rarely, a circum-aortic LRV.[29]

Infrarenal/Suprarenal Inferior Vena Cava

A variety of incisions are available to expose the infrahepatic IVC, with the choice depending on the amount of exposure desired (Fig. 56.14). A midline, transperitoneal incision is standard in trauma cases and is the most frequent approach used. A right transverse transperitoneal or right flank retroperitoneal approach is also useful but is slightly more limited in visualizing branches beyond the caval bifurcation. A subcostal incision may also be used for limited exposure. With transperitoneal approaches, the small bowel is retracted to the left and a right medial visceral rotation is performed by incising the lateral peritoneal reflection of the ascending colon, as described previously. Following a Kocher maneuver, the pancreatic head and second and third portions of the duodenum are retracted to the left, exposing the IVC and renal veins. This also allows the porta hepatis and distal SMV to be dissected out behind the pancreas.[28] This dissection can be carried cephalad, exposing the retrohepatic vena cava. Some surgeons report that extending the incision into the ninth intercostal space of the right chest improves exposure of the retrohepatic IVC. Dividing the diaphragm can expose the juxta-atrial IVC, along with the major hepatic branches. For more distal exposure (caval confluence and both iliac veins), the peritoneal reflection of the cecum is incised to the level of the ileocecal junction, and the entire right colon is retracted leftward (Cattell–Braasch maneuver) (see Fig. 56.14).[27,28] The IVC from the common iliac veins to the level of the caudate lobe can be visualized with this approach. Additional exposure, including the infrarenal aorta, can be gained by incising the retroperitoneal attachments of the small bowel from the right lower quadrant to the ligament of Treitz and reflecting the entire small bowel and right colon out of the abdominal cavity. Ligation/division of tethering lumbar veins permits mobilization of the IVC, but it is advisable to place suture ligatures on the caval side of these branches to prevent accidental dislodgement. One method to provide rapid exposure to the IVC bifurcation and proximal iliac veins in a trauma situation is to divide the overlying right iliac artery to expose the underlying injury. After venous repair, the artery is reanastomosed and distal blood flow re-established (see Fig. 56.15).[30,31]

Retrohepatic and Suprahepatic Inferior Vena Cava

A midline approach with superior extension into a sternotomy is the most widely used incision to expose these IVC segments, particularly in trauma situations (see Figs. 56.16 and 56.17). A chevron incision, with or without sternotomy, or an eighth or ninth interspace right thoracoabdominal incision can provide excellent exposure in elective cases. A transperitoneal approach is greatly facilitated by upward and lateral retraction of the costal margins. After entering the peritoneum, the right triangular ligament is divided, along with the peritoneal attachments to the right lobe of the liver, and the right lobe is mobilized and retracted medially and anteriorly. This exposes the retrohepatic IVC. A number of small venous tributaries draining the caudate lobe and sometimes the posterior right lobe are encountered during this mobilization and should be carefully ligated and divided to prevent avulsion. Of the three hepatic veins, only the right can be reliably visualized from this approach. Exposure of the other hepatic veins and the suprahepatic IVC requires wider mobilization. The round and falciform ligaments have to be divided and all the superior peritoneal reflections of the liver (coronary ligaments) incised, to expose the "bare area" of the liver. The liver is then retracted caudally to visualize the suprahepatic IVC and hepatic veins. If control of the IVC between the hepatic veins and diaphragm proves difficult, intrapericardial control of the IVC can be accomplished after performing a sternotomy.

Portal Vein and Branches

The SMV lies to the right of the SMA in the root of the mesentery. It tracks over the third portion of the duodenum and uncinate process of the pancreas and dives under the neck of the pancreas to join the splenic vein, which runs in a groove along the back of the pancreas. The inferior mesenteric vein lies to the immediate left of the infrarenal aorta and crosses over it to drain into the splenic vein. The portal vein is formed by the confluence of the splenic and SMV at the level of L2 and courses toward the liver within the gastrohepatic ligament, lateral to the medially located hepatic artery and posterior to the common bile duct.

A subcostal incision extending into the right flank or a midline incision is appropriate. After dividing the falciform ligament, the right lobe of the liver is retracted cephalad and the

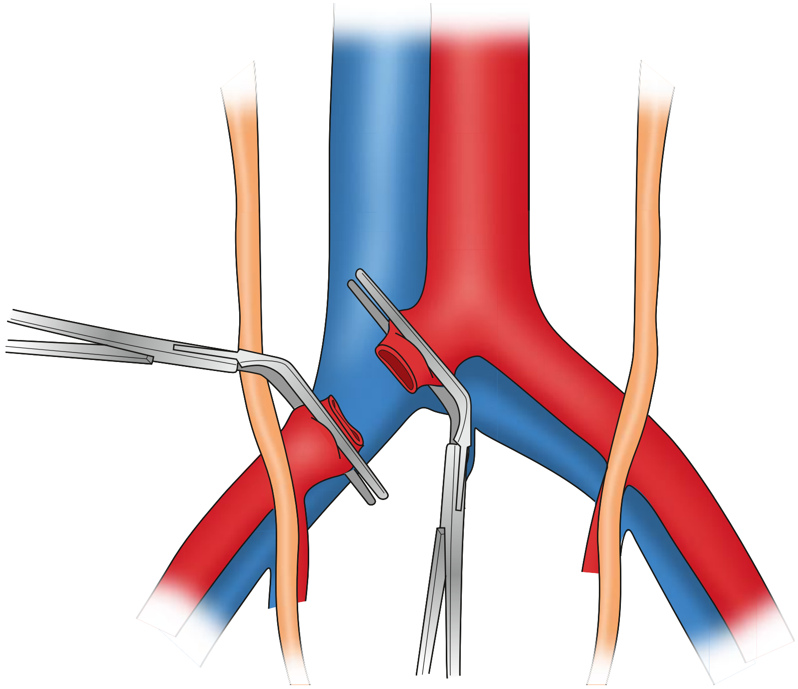

Figure 56.15 Exposure of the inferior vena cava–iliac vein confluence by dividing the right common iliac artery.

hepatic flexure of the colon caudally. After a partial Kocher maneuver, the first and second portions of duodenum are mobilized and retracted downward and slightly to the left, to expose the porta hepatis structures (Fig. 56.18). The portal vein is the most posterior structure of the hepatoduodenal ligament and is best isolated by longitudinally dividing the peritoneum along the right posterior aspect of the ligament to avoid injury to the common bile duct. After the lateral wall of the vein has been dissected free proximally and distally, the common bile duct can be gently retracted superiorly and to the left, enhancing exposure. A replaced right hepatic artery, if present, runs parallel and to the right of the vein and should be carefully preserved. Mobilization of the portal vein from the pancreas to its hepatic bifurcation can be accomplished by carefully isolating and dividing tributaries, which usually enter the vein medially and posteriorly. Mobilizing the right lobe of the liver by dividing the triangular ligament and pushing the liver anteriorly and caudally with laparotomy pads packed behind it greatly improves exposure of the porta hepatis. Uncontrollable bleeding from the porta hepatis or liver can be managed by inserting an index finger through the foramen of Winslow and pinching the entire porta hepatis between the thumb (on the anterior surface of the porta) and the index finger (Pringle maneuver).[32]

Superior Mesenteric Vein

Exposure of the SMV is similar to that of the SMA (see Fig. 56.13). After elevating the transverse mesocolon to expose the root of the mesocolon, the small bowel is retracted inferiorly, and the SMA is palpated. The SMV lies just to the right of the SMA.

Splenic Vein

The most direct approach to the splenic vein is through the lesser sac (Fig. 56.19). A subcostal incision extending to the left or a midline incision is used. After entering the peritoneal cavity, the lesser sac is reached by dividing the gastrocolic ligament. The greater curvature of the stomach is elevated, and the inferior border of the pancreas is exposed. The splenic vein is dissected out under the inferior border of the pancreas. Multiple small branches drain into it, making the dissection tedious. This approach is useful for distal splenorenal shunts.

The splenic vein can also be approached below the transverse mesocolon. As discussed previously in exposure of the left renal artery through an inframesocolic approach, the transverse colon is elevated and the small bowel retracted to the patient's right. The ligament of Treitz is divided, mobilizing the third and fourth portions of the duodenum to the right. The LRV is identified as a landmark. The inferior border of the pancreas is identified and the inferior mesenteric vein running along the left side of the aorta traced cephalad to its junction with the splenic vein. The inferior border of the pancreas is rotated superiorly to expose the splenic vein running along its posterior surface.

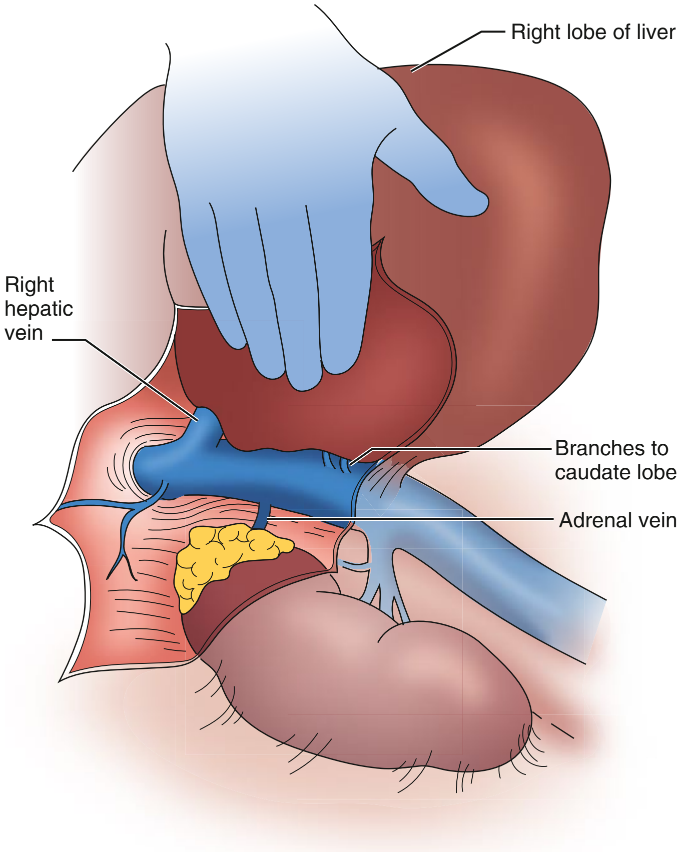

Figure 56.16 Exposure of retrohepatic inferior vena cava and right hepatic vein by mobilizing and retracting the right lobe of the liver to the left.

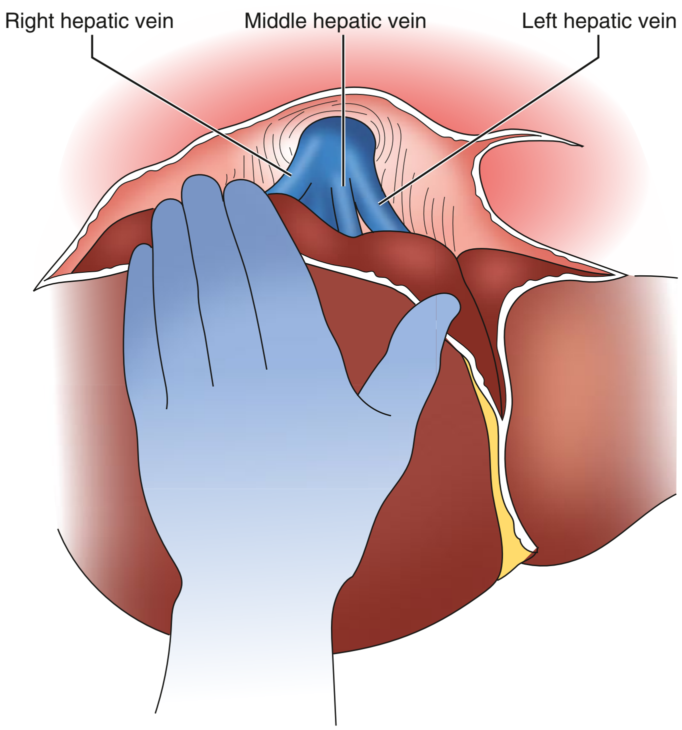

Figure 56.17 Exposure of suprahepatic inferior vena cava and hepatic veins after incising the coronary ligaments and retracting the liver caudally.

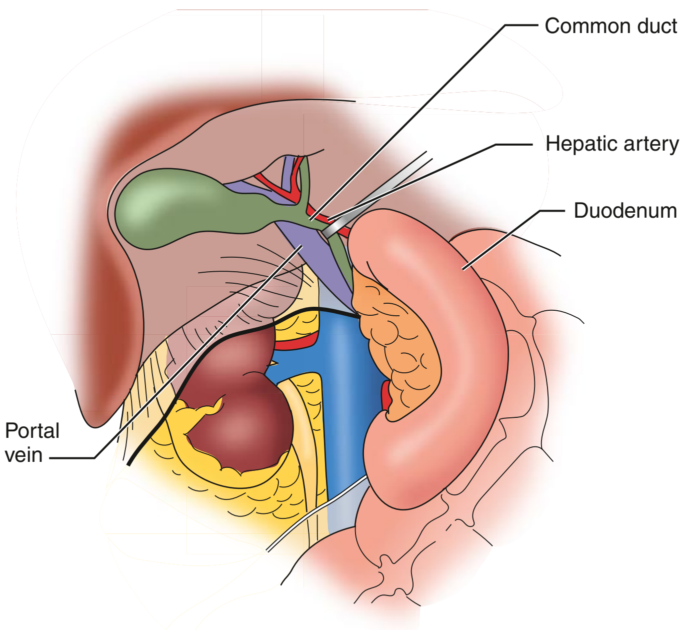

Figure 56.18 Portal vein exposure after mobilizing the hepatic flexure of the right colon and performing a Kocher maneuver on the duodenum. Small retractor is displacing common bile duct to patient's left.

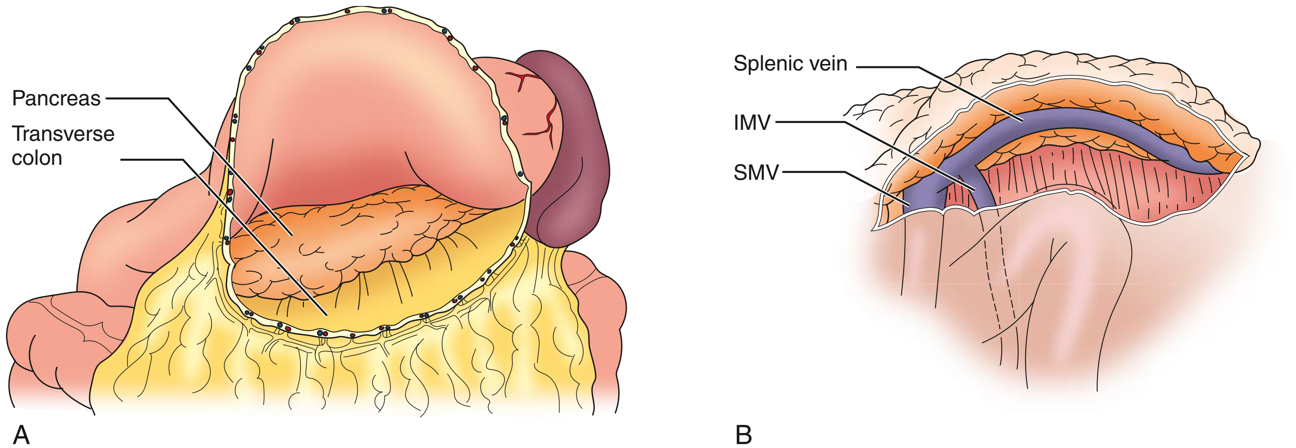

Figure 56.19 **Exposure of Splenic Vein.** (**A**) Lesser sac is entered by dividing the gastrocolic ligament. (**B**) Pancreas elevated superiorly with splenic vein under it; the splenic veins joins the superior mesenteric vein *(SMV)* to form the portal vein. The inferior mesenteric vein *(IMV)* drains into the splenic vein.

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57 CHAPTER

Cerebrovascular Exposure

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Based on a previous edition chapter by Linda M. Harris and Maciej Dryjski

ANATOMIC CONSIDERATIONS

The aortic arch gives off, from right to left, the innominate, the left common carotid, and left subclavian arteries. The innominate artery passes beneath the left innominate vein before it divides into the right subclavian and the right common carotid arteries (CCA). The vertebral arteries come off the subclavian arteries 2 or 3 cm from the arch, but many variations may occur. The left CCA may arise from the innominate and crosses to a relatively normal position on the left side. The right vertebral artery may arise as part of a trifurcation of the brachiocephalic trunk into common carotid, subclavian, and vertebral arteries, and the left vertebral artery may arise directly from the aortic arch. Occasionally, an aberrant right subclavian artery may arise distal to the left subclavian artery from the aortic arch and crosses to the right side.

The CCAs on each side travel in the carotid sheath up to the neck before dividing into external carotid (ECA) and internal carotid arteries (ICA) just below the level of the mandible. Important branches of the ECA include the superior thyroid, which may arise from the CCA; the ascending pharyngeal, which is important in that it accompanies the superior laryngeal nerve; the lingual and occipital arteries that have a close association with the hypoglossal nerve. No branches of the ICA occur in the neck.

The carotid sinus is a baroreceptor located in the crotch of the carotid bifurcation. It is innervated by the sinus nerve of Hering (branch from the glossopharyngeal nerve). The carotid body is a very small structure lying in the crotch of the bifurcation and functions as a chemoreceptor, responding to low oxygen or high carbon dioxide levels in the blood. It is also innervated by the sinus nerve of Hering.[1]

PREOPERATIVE PREPARATION

Most patients undergoing CEA receive general anesthesia with intra-arterial pressure monitoring. Although some surgeons prefer local or cervical block anesthesia, general anesthesia has the advantage of increasing cerebral blood flow and reducing several metabolic demands. Endotracheal intubation provides good airway control and reduces physician and patient anxiety. Nasotracheal intubation can be utilized to facilitate exposure for high carotid stenosis or in patients undergoing reoperation (see Ch. 93, Carotid Endarterectomy).

The patient should be positioned supine, with the head averted from the operative side and slightly extended by placing a small roll behind the shoulder blades transversely. The bed should also be placed slightly in a reverse Trendelenburg position to decompress the surrounding venous structures.

Both arms can be tucked to allow for the surgeon and assistant to stand across from each other or with one at the head of the bed and one at the side of the involved vessel, depending on surgeon preference. The area to be prepped should include the jawline and the inferior aspect of the ear to below the clavicle. If regional anesthesia is being performed, this is done prior to prepping and draping. It is also advantageous to place a small squeeze toy in the contralateral hand to allow for neurologic assessment throughout the procedure. This allows the patient to demonstrate function of that limb when regional blocks are being utilized.[1]

EXPOSURE OF THE EXTRACRANIAL CAROTID ARTERY FOR CAROTID ENDARTERECTOMY

Incision Types

Standard Approach

1. The cervical vertical incision is made parallel and somewhat anterior to the sternocleidomastoid muscle and centered over the carotid bifurcation (Fig. 57.1).[1] This can be extended proximally to the sternal notch for more proximal CCA lesions, and distally to the mastoid process for higher exposure. The upper end of the incision should be angled posterior to the earlobe, if needed, to avoid the parotid gland.

   An alternative incision placed obliquely in the skin crease over the carotid bifurcation can be used (Fig. 57.2).[1] This incision has the advantage of a more cosmetically acceptable scar than the vertical incision, but has the following limitations: more difficult to gain additional proximal/distal arterial exposure and the necessity of raising skin flaps.
2. Dissection is continued through platysma, typically with electrocautery. The external jugular vein frequently has to be divided. Several small nerves of the superficial cervical plexus may have to be divided, which may lead to areas of hypoesthesia around the incision. The great auricular nerve may be visualized when the incision is high. The nerve should be protected if possible; if divided, it results in numbness to the ear lobe, which usually regresses within a few months. Care should be taken at the angle of the mandible to remain lateral to avoid dissection into the parotid gland. The dissection is continued through the tissues along the medial border of the sternocleidomastoid until the carotid sheath is encountered. The CCA is generally mobilized for a sufficient length proximal to the carotid lesion. More proximal control of the CCA can be obtained by division of the omohyoid muscle, and ligation of the associated vessels. Dissection is continued upward to isolate the ECA. The ICA is mobilized to a point where the vessel is completely normal. It may be necessary to inject a local anesthetic in the area of the carotid bifurcation to block the nerve to the carotid body to prevent reflex bradycardia. During the dissection, a small sternomastoid branch of the superior thyroid artery usually has to be ligated; other small perforating vessels supplying the SCM can be divided with cautery. At this point one must avoid injury to the accessory nerve, which can be found at the superior aspect of the incision. Once the sternocleidomastoid has been retracted laterally, a Weitlaner or Henle retractor should be utilized to hold the tissues in place. If regional block is utilized, it is occasionally necessary to supplement with additional lidocaine at the carotid sheath.

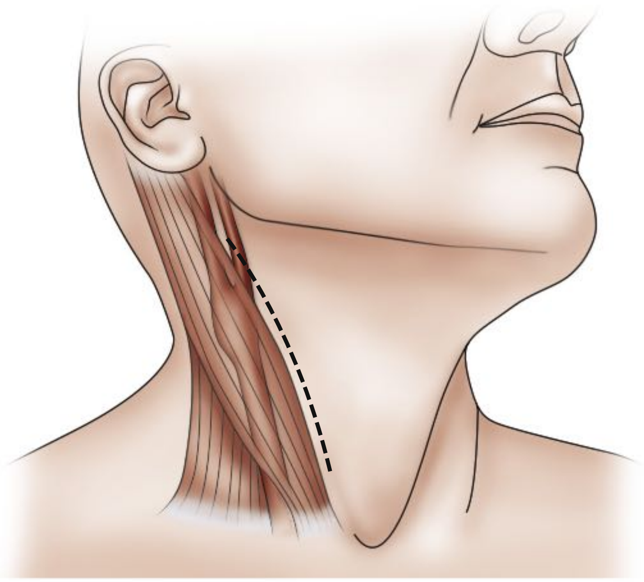


Figure 57.1 Incision for carotid endarterectomy.

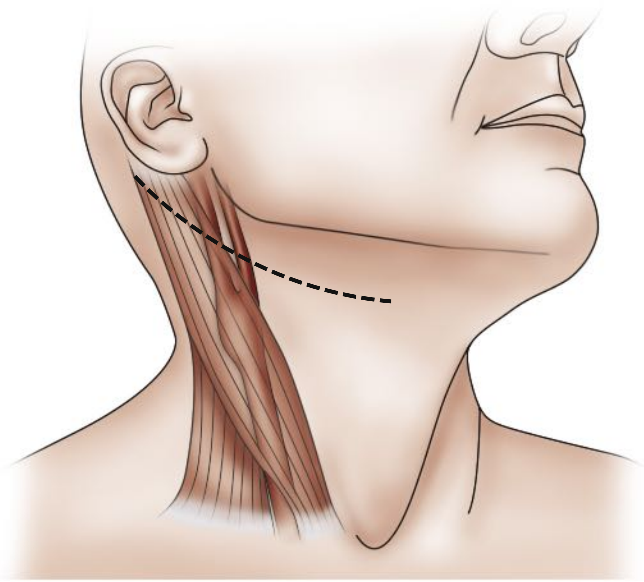


Figure 57.2 Oblique incision for carotid endarterectomy.

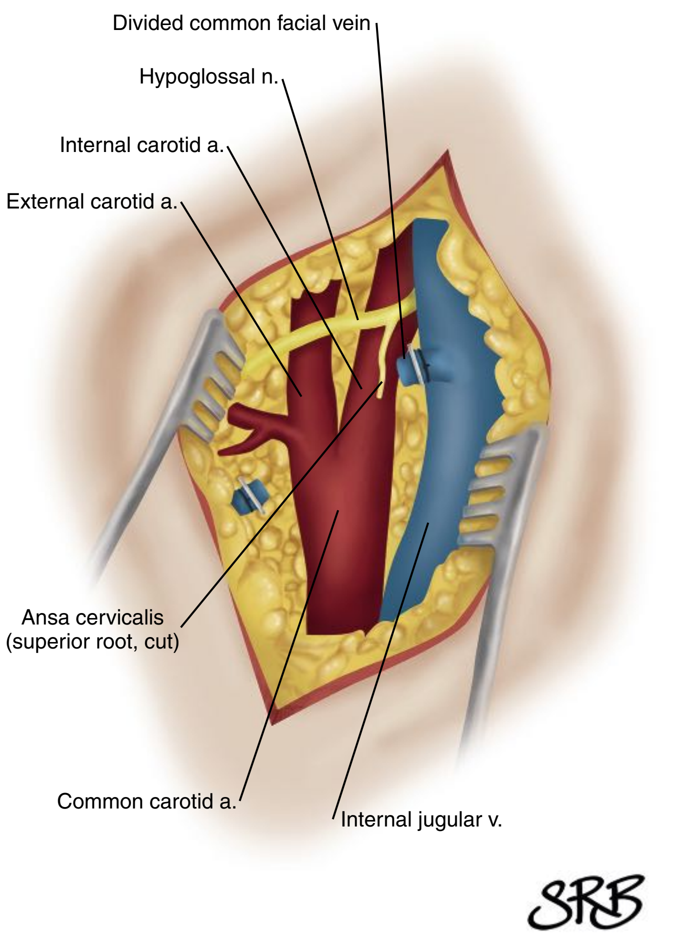


Figure 57.3 Traditional carotid exposure with division of facial vein and ansa cervicalis. Left CEA approach.

3. The internal jugular vein is dissected along the medial border and retracted posteriorly. This maneuver requires division of the common facial vein (Fig. 57.3). Since the anatomy of the venous structures is quite variable, there may be a single vein or, alternately, two or three veins separately joining the internal jugular vein, in which case they must be separately ligated and divided. The connective tissue between the facial vein and the digastric muscle is rich in lymph nodes, which can be dissected from the vein and, if necessary, divided with cautery.
4. Dissection should stay anterior to the CCA to avoid injury to the vagus nerve, which usually lies in the posterior lateral position within the carotid sheath but occasionally may spiral anteriorly, particularly in the lower end of the incision. Attention should be paid to various cranial nerves, including IX, X, XI, and XII, the marginal mandibular branch of VII, and the rare nonrecurrent laryngeal nerve that comes directly off the vagus on the way to innervate the vocal cord. This nerve can cross anterior to the carotid artery and be mistaken for a part of the ansa hypoglossi, resulting in cord paralysis. This anomaly is most often noted on the right side of the neck (Fig. 57.4).[1] The vagus nerve may be closely adherent to the carotid bulb, and it becomes nearly confluent with the hypoglossal nerve near the styloid process. The hypoglossal nerve is often surrounded by small veins that should be ligated carefully. The hypoglossal nerve may be injured by retraction; therefore, the structures that tether it in place, such as the artery and vein to the sternocleidomastoid muscle, the descending hypoglossal branch of the ansa cervicalis, and the occipital artery may require division to mobilize the nerve for distal ICA exposure. Careful attention should also be given to the superior laryngeal nerve, which is usually located medial to the ICA. The superior laryngeal nerve divides into external and internal branches that pass posterior to the superior thyroid artery, and it may be harmed while controlling either of these two vessels. The glossopharyngeal nerve crosses the ICA near the base of the skull and is best protected by maintaining dissection very close to the anterior surface of the ICA. Excessive or prolonged retraction of the upper aspect of the incision may cause temporary compression injuries laterally to the greater auricular nerve or medially to the marginal mandibular branch of the facial nerve. Once exposure has been completed, the CCA, ECA, and the ICA are controlled using silastic loops (Figs. 57.5 and 57.6).[1]

Retrojugular Carotid Approach

With the standard approach, when bleeding occurs postoperatively, it is frequently venous, specifically related to the facial vein. The ICA is located more posteriorly with this approach, and it may be difficult to access more distal disease. The vagus nerve is also not well visualized during the standard approach, which can lead to clamp injuries. With the retrojugular approach, the ICA is anterior. Visualization of the external carotid artery (ECA) is slightly more limited, but the origin and superior thyroidal arteries are easily identified and controlled, with markedly better visualization of the ICA. There is no need for ligation or division of major venous structures, thus decreasing the potential for postoperative bleeding, and the ansa hypoglossi is also not divided.

1. Skin incision and initial approach are identical to the standard exposure. Once the sternocleidomastoid has been retracted and the carotid sheath exposed, the dissection diverges from the standard approach.
2. The sheath overlying the vessels is divided at the *lateral* border of the internal jugular vein. Once fully dissected, the vein is then retracted medially, using a blunt Weitlaner. Occasionally there may be small venous branches posteriorly that require ligation and division. The vagus nerve is visualized and left lateral to the carotid artery. This approach avoids division of the facial vein, ansa cervicalis, and the vascular bundle associated with the hypoglossal nerve, as all of these structures are retracted medially with the jugular vein. This approach allows greater visualization of the internal carotid artery (Fig. 57.7).
3. At this point, the dissection is the same as for the standard carotid approach, with mobilization of the ICA, ECA, and common carotid artery (CCA) for isolation (using silastic loops) as well as the superior thyroid artery. However, the vagus nerve has already been identified laterally and does not fall into the area of concern when encircling the CCA.

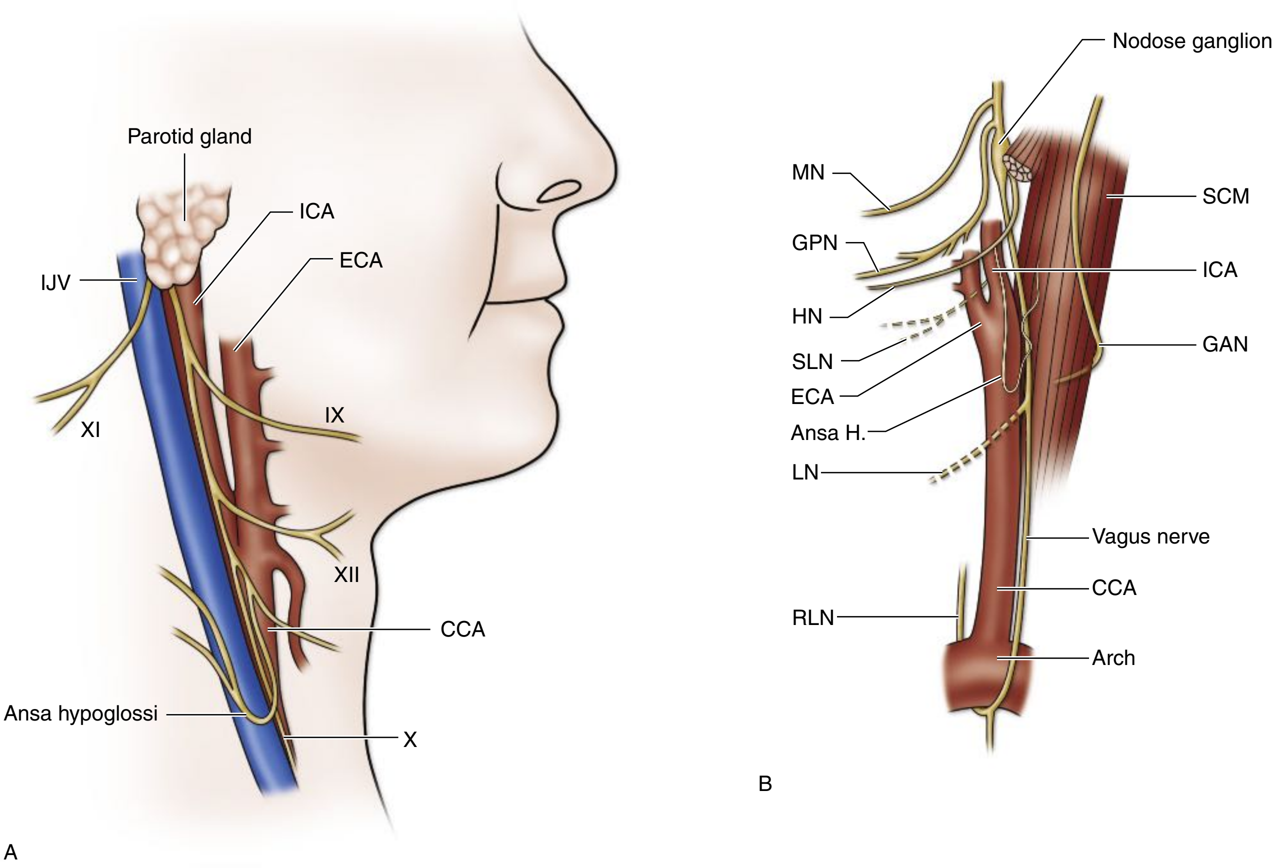


Figure 57.4 (**A**) Illustration showing relation of cranial nerve to carotid bifurcation. *IJV*, internal jugular vein; *ICA*, internal carotid artery; *ECA*, external carotid artery; *XI*, accessory spinal nerve; *IX*, glossopharyngeal nerve; *XII*, hypoglossal nerve; *CCA*, common carotid artery; *X*, vagus nerve. (**B**) Illustration of various cranial/cervical nerves and their anomalies. *MN*, marginal mandibular nerve; *GPN*, glossopharyngeal nerve; *HN*, hypoglossal nerve; *SLN*, superior laryngeal nerve; *ECA*, external carotid artery; *Ansa H*, ansa hypoglossal nerve; *LN*, nonrecurrent laryngeal nerve (anomaly); *RLN*, recurrent laryngeal nerve; *SCM*, sternocleidomastoid muscle; *ICA*, internal carotid artery; *GAN*, greater auricular nerve; *CCA*, common carotid artery.

4. Carotid endarterectomy (CEA) is then performed in either standard fashion or with the eversion technique.
5. At completion of the procedure, after hemostasis has been verified, the jugular vein is allowed to return to its normal location, lateral to the artery, and the wound is closed in the standard fashion with reapproximation of the platysma and subcuticular skin closure.

Posterior Carotid Approach

Most vascular surgeons are not familiar with this approach. This technique has been described by Berguer. It allows exposure of the ICA, medial to the sternocleidomastoid, between the hypoglossal and vagus nerves.

1. The patient is placed prone/lateral with the contralateral arm placed under the head.
2. The incision is initially transverse, beginning at the occipital protuberance and extending to the mastoid process, where it is curved downward along the posterior border of the SCM for 2 to 3 cm.
3. The fibers of the trapezius, splenius capitis, semispinalis capitis, and longissimus capitis muscles are divided.
4. The greater occipital nerve, which is a dorsal ramus of C2 and courses over the semispinalis capitis muscle, may have to be divided.
5. At this point the internal jugular vein, carotid artery, and the accessory nerve are exposed.

Exposure for High Carotid Lesions

1. With the standard approach, more distal exposure may be obtained by mobilizing the hypoglossal nerve. This requires division of the sternomastoid artery and vein, which form a sling around the structure and may also be facilitated by dividing the ansa cervicalis. Ligation of occipital artery may also be helpful. This allows mobilization of the vessel up to the level

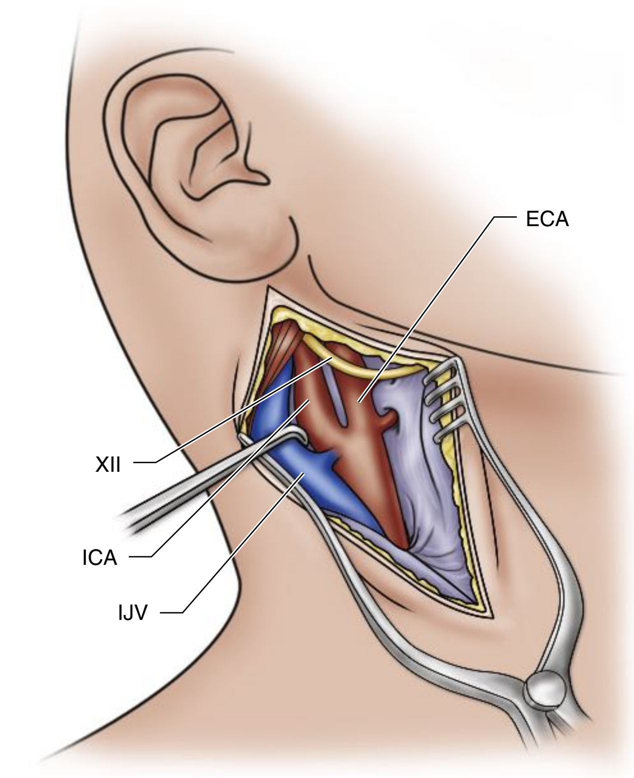


Figure 57.5 Exposure of distal CCA, ICA, and ECA. *XII*, hypoglossal nerve; *ECA*, external carotid artery; *ICA*, internal carotid artery; *IJV*, internal jugular vein.

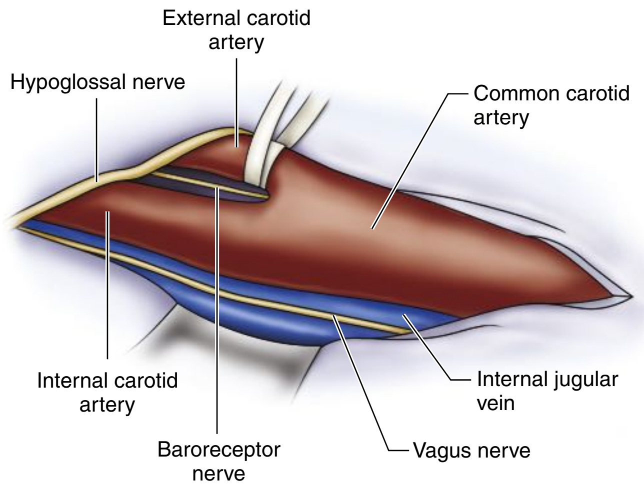


Figure 57.6 Isolation of carotid artery bifurcation during carotid endarterectomy.

where the vagus nerve joins the hypoglossal. Further dissection can also be performed above the level of the nerve, which can be gently retracted with a vein retractor or vessel loop.

2. For more distal exposure, the accessory spinal nerve should be identified as it enters the sternocleidomastoid; it can be followed proximally to the digastric, with care taken not to

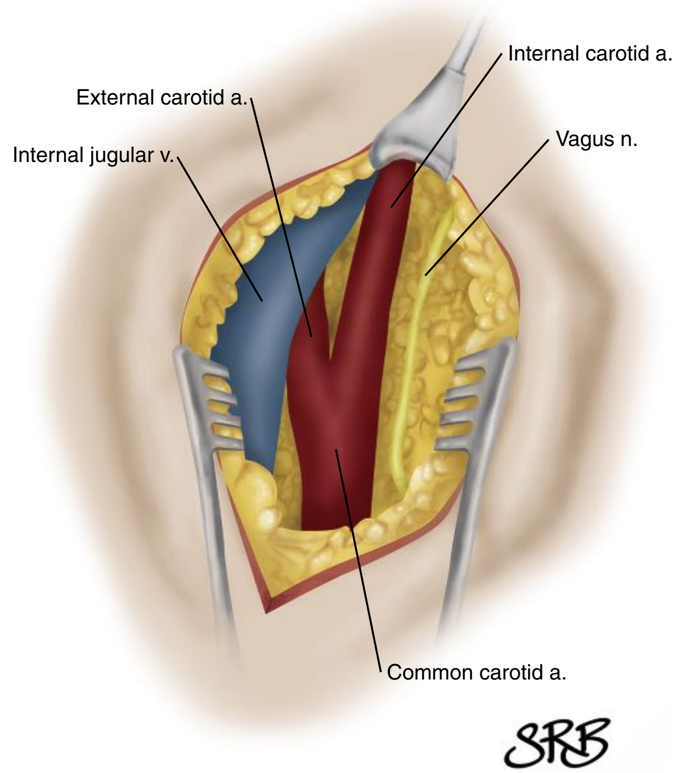


Figure 57.7 Retrojugular approach to carotid artery with medial rotation of internal jugular vein to expose internal carotid artery. Left CEA approach.

injure the nerve. To facilitate exposure, both the internal jugular (IJ) and the vagus nerve should be retracted medially, over the top of the carotid artery. The superior laryngeal nerve arises in this area and passes posterior to the ICA. Just -bove this level, the superior cervical sympathetic ganglion ·ill be seen. Depending on the extent of exposure needed, ıe posterior belly of the digastric can be retracted or divided Fig. 57.8). Such division should be done sharply to avoid ıermal injury to the glossopharyngeal nerve, which would ·sult in difficulty swallowing. Retraction can also result ı nerve injury and should be performed cautiously. The erve runs on top of the ICA and under the ECA and may resent with either a single or double trunk. The muscle ıould be divided close to the attachment with the mastoid. further mobilization is needed, the styloid process can e transected. If high access to the ICA is anticipated, this ıould prompt consideration for general anesthesia with asotracheal intubation and preoperative consultation with ENT to allow for subluxation of the mandible if all above maneuvers are insufficient (Fig. 57.9) (see Ch. 93, Carotid Endarterectomy).

Mini-Incisions for Carotid Endarterectomy

Short transverse and longitudinal incisions for eversion and standard patch endarterectomy have been popularized in the recent years. The outcome and operative time is generally the same as for standard, long incision.

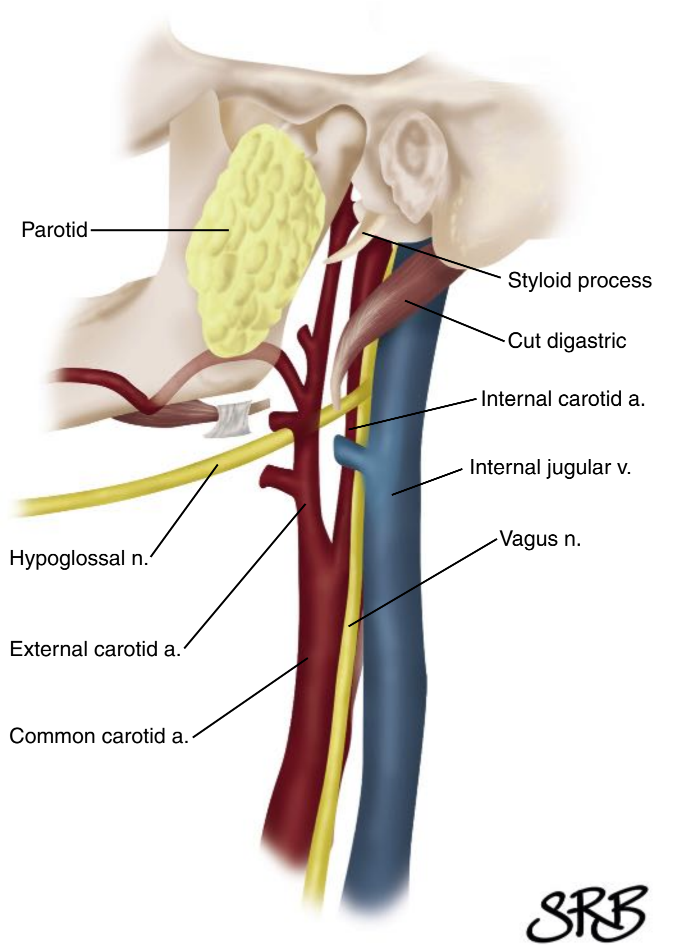


Figure 57.8 High exposure of internal carotid artery with division of digastric muscle.

Short Transverse Incision

1. Duplex is recommended to identify and mark the skin at the carotid bifurcation before draping. If duplex is not used, the incision is made in the skin crease at the level of the upper margin of the cricoid medial to the sternomastoid muscle. The length of the incision is approximately 4 cm which can be extended if exposure is inadequate.
2. After division of the platysma transversely, two self-retaining retractors are placed at 90-degree angles to each other and dissection is carried out in the same fashion as for the standard carotid exposure. Use of the self-retaining retractors allows exposure of up to 1.5 to 2 cm on each side of the carotid bifurcation.
3. Small bulldog clamps, which can be placed deep in the wound, allow the length of the exposed carotid arteries to be longer than the length of the skin incision both in the transverse and longitudinal mini-incision.

Longitudinal Mini-Incision

1. After appropriate positioning of the patient on the operating table and prior to prepping and draping, duplex is used to identify and mark on the skin the carotid bifurcation and the anticipated skin incision. Length of the incision depends on the depth and extent of the lesion and varies from 2.5 to 5 cm.

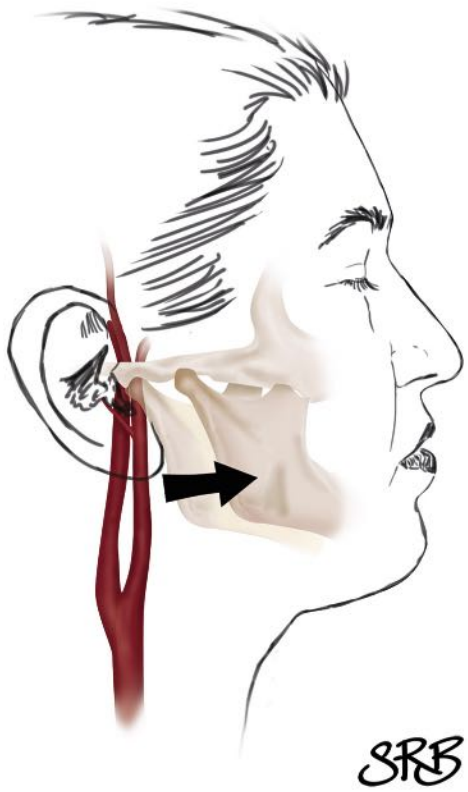


Figure 57.9 Subluxation of mandible for high carotid exposure.

2. The dissection and approach to the carotid bifurcation is essentially the same as for the standard longitudinal incision. Use of two self-retaining retractors and skin laxity allow for traction and exposure of a longer segment of carotid arteries than the length of skin incision itself (Fig. 57.10).

REOPERATIVE EXPOSURE FOR CAROTID STENOSIS

Morbidity of reoperative procedures is increased due to risk of cranial nerve (CN) injury from scarring, making the identification of critical structures more difficult. The surgeon must also be prepared to resect the involved segment and replace it with an interposition graft. Either autologous vein grafts, using the proximal great saphenous vein (GSV), or prosthetic grafts may be used.

The retrojugular approach may be preferred for reoperative procedures to decrease nerve mobilization and dissection and the ability to work in a field that has not previously been dissected. The surgeon should anticipate the need for more distal and more proximal exposures to an area of healthy artery.

EXPOSURE FOR SUBCLAVIAN–CAROTID INTERVENTIONS

These interventions initially declined markedly in the era of endovascular intervention, with stenting of the subclavian or

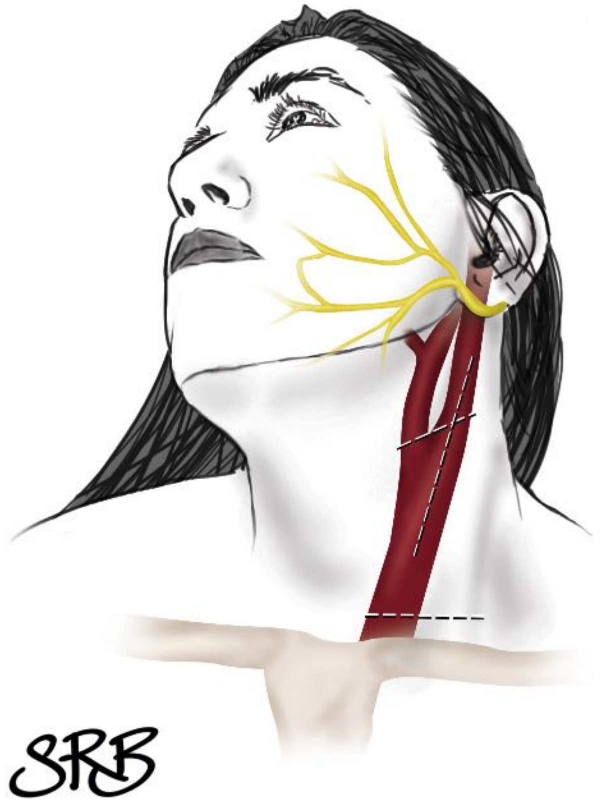


Figure 57.10 Incisions for standard carotid exposure, mini-incision carotid exposure, and subclavian artery exposure.

innominate arteries, but then there was a resurgence with the advent of TEVAR and the need for coverage of the left subclavian artery or additional great vessels with debranching procedures.

Subclavian to Carotid Transposition

These transpositions are ideal except in patients with lesions involving the distal portion of the subclavian artery or extensive lesion of the common carotid artery (CCA) where transposition will not be a suitable technique. In general, the principle of transposition is to divide the artery distal to the obstructed lesion and anastomose it to neighboring artery, which is free of disease, as new inflow. It has the appeal of a single artery-to-artery anastomosis at the cost of simultaneously clamping both donor and recipient arteries.

Transposition of the subclavian artery (SA) into the CCA is generally contraindicated in patients who had previous LIMA (myocardial revascularization using the ipsilateral internal mammary artery). Transposition of the SA into the CCA has also the drawbacks of any technique that uses the CCA as a source of inflow and, in addition, requires simultaneous clamping of both arteries (e.g., it is not recommended when the contralateral carotid artery is occluded). For a patient who is in need of a CEA on the same side, the transposition can be performed using a shunt inserted through the carotid bifurcation arteriotomy with the proximal end of the shunt low in the CCA (Fig. 57.11). After completion of the transposition,

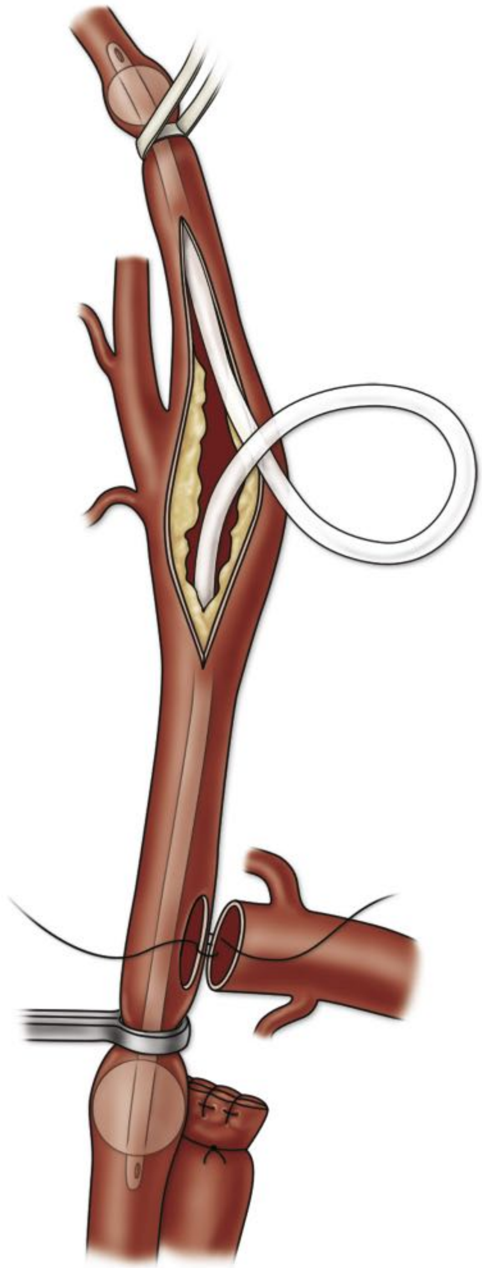


Figure 57.11 Use of a shunt for transposing the subclavian artery to the common carotid artery when the opposite carotid is occluded and there is a need to repair the ipsilateral internal carotid artery.

the shunt can be moved distally to proceed with the standard endarterectomy.[2]

1. The patient is placed supine, with a roll under the scapula transversely and the head averted toward the contralateral side, with care taken not to hyperextend the neck. A slight reverse Trendelenburg position is preferred. Both arms should be tucked.
2. A transverse incision is made one fingerbreadth above the clavicle, extending from medial to the lateral head of the SCM for about 6 cm (see Fig. 57.10). Superficial dissection

includes division of the platysma and superficial cervical aponeurosis. The external jugular vein can be ligated and divided. Dissection can be confined between the bellies of the sternomastoid muscle and the entire dissection can be confined to the space medial to the internal jugular vein, vagus nerve, and prescalene fat pad. The CCA is dissected proximally and isolated (Fig. 57.12). Care must be taken not to enter the pleural cavity or stretch the vagus or phrenic nerves.[2] The vein should be mobilized laterally to allow for visualization for transposition and access of the artery prior to the takeoff of the vertebral branch. On the left side, it is important to identify the thoracic duct, which can be ligated and divided if necessary. This structure passes over the subclavian artery and joins the internal jugular vein on the left. There may be one main duct or several smaller ducts. Right-sided thoracic ducts have been reported in patients with aberrant right subclavian arteries; care should be taken in patients with this anatomic variant to avoid injury. Inadvertent injury to the duct can lead to lymphatic leak, requiring reoperation. The sternal head of the SCM and subhyoid are retracted medially, as is the common carotid artery. The vertebral vein should be identified, ligated, and divided. The sympathetic ganglion or chain typically has fibers around the subclavian artery at this level just medial to the vertebral vein. Injury should be avoided if possible to prevent Horner syndrome. The vertebral artery superiorly and the internal mammary artery inferiorly should be controlled with vessel loops. At the more proximal aspect of the subclavian artery, the vagus, which crosses anteriorly, and the recurrent laryngeal nerve, which passes posteriorly to the subclavian, should be identified and preserved. The left subclavian artery is deeper than the right and can be slightly more difficult to access proximal to the vertebral artery. After adequate mobilization of the subclavian artery, the common carotid artery, which is in the medial portion of the field, is dissected to allow for a tension-free anastomosis and for adequate vascular control at the level of the subclavian artery. Care should be taken to avoid kinking the vertebral artery during transposition. It is also important to ensure complete hemostatic control of the subclavian stump prior to losing control of this segment as it retracts into the chest.

3. More proximal exposure of the subclavian artery can be gained by division and resection of the medial head of the clavicle. This facilitates exposure up to the junction with the carotid on the right. This is infrequently necessary today and is typically reserved for situations with hemorrhage, when endovascular maneuvers are insufficient or not available to control proximal bleeding. For right-sided proximal exposure of the subclavian artery, the incision can be extended to include a median sternotomy. This may require division of the innominate vein to facilitate full exposure of the more proximal subclavian and carotid arteries and the brachiocephalic trunk. On the left side, anterolateral thoracotomy can be performed to gain access to the origin of the left subclavian. After systemic heparinization, the proximal SA is clamped using a small Satinsky clamp and ligated with cardiovascular suture proximal to the clamp. After which the vertebral artery, the distal subclavian artery and occasionally the internal mammary artery are isolated or clamped and the proximal subclavian artery is divided immediately above the proximal clamp. The subclavian artery is obliquely transected about 1 cm proximal to the origin of the vertebral artery. Then attention is made to the proximal CCA, which can be again isolated or clamped using partial Satinsky clamp and a small arteriotomy is made in the CCA for the subclavian to CCA anastomosis (Figs. 57.11 and 57.12).[2] The arteriotomy in the CCA should be somewhat posterolateral to accommodate a larger-caliber SA. It is important to avoid kinking in the vertebral artery that may result from the anastomosis being too high in the CCA. Similar principles are done for transposition of the CCA to the SA for treating proximal occlusion of the CCA (Fig. 57.13).[2] In this situation, the CCA is ligated as low as possible, and then transected and transposed to be anastomosed end-to-side to the SA. This anastomosis can be done to the retroscalene SA depending on local anatomy and physician preference. If retroscalene SA anastomosis is chosen, the CCA should be mobilized extensively before being tunneled behind the internal jugular vein so it can reach the distal SA.

Carotid–Subclavian Bypass

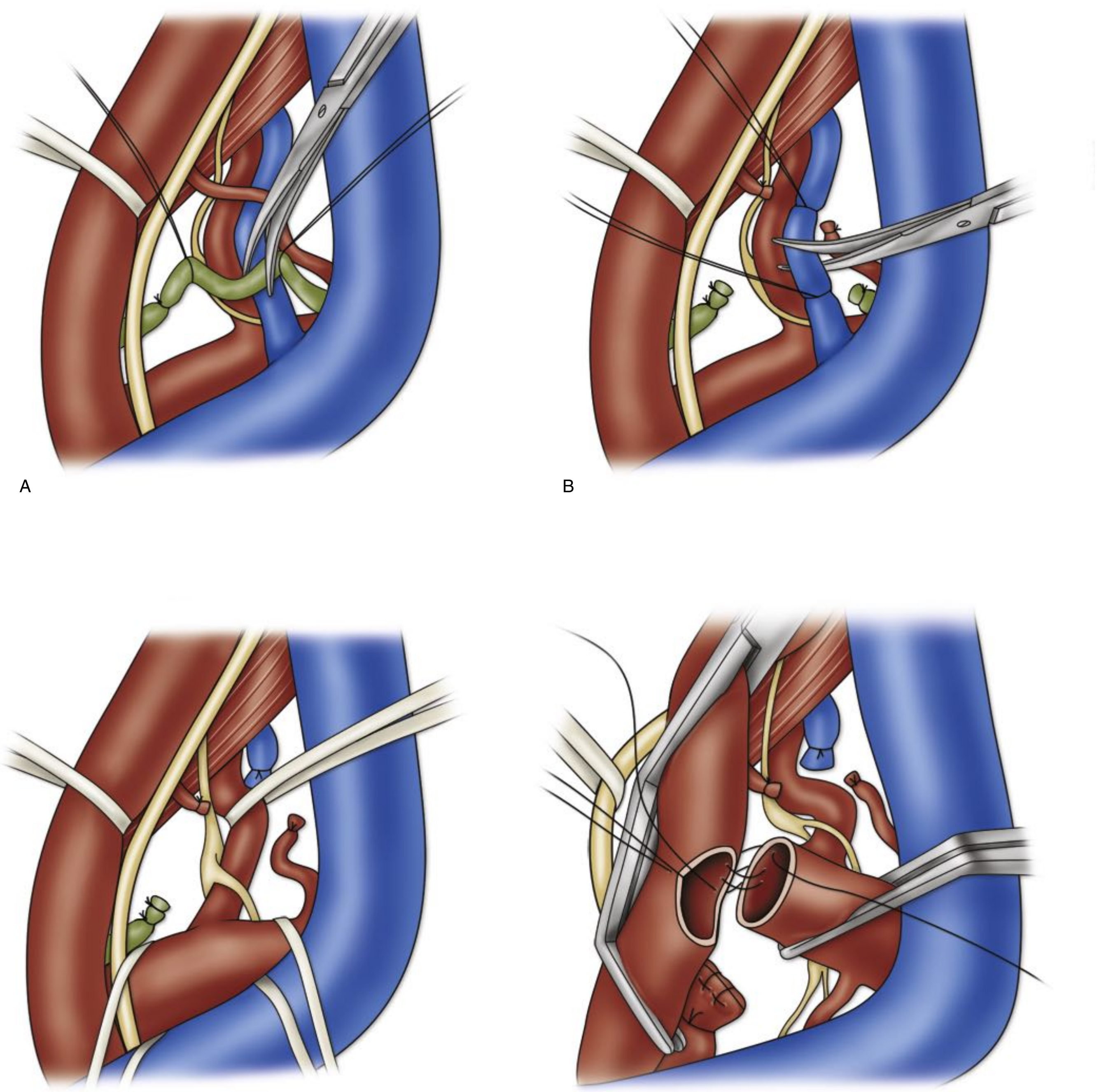
1. This dissection is similar to the supraclavicular approach for thoracic outlet syndrome (TOS) (see Ch. 125, Thoracic Outlet Syndrome: Arterial). The incision is extended about 6 cm from the medial border of the clavicular head of the SCM one fingerbreadth above the clavicle. Superficial dissection is similar to transposition. The clavicular head of the SCM is divided. The scalene fat pad is mobilized inferiorly and medially and retracted superolaterally with a self-retaining retractor. The anterior scalene is next divided sharply after the phrenic nerve is first dissected; it is protected with a vessel loop. Electrocautery should be avoided to prevent thermal injury to the brachial plexus and surrounding nerves. The muscle should be divided as close to the insertion on the first rib as possible. The subclavian artery lies immediately beneath the anterior scalene. The thyrocervical trunk is typically visible and can be divided if necessary or controlled with vessel loops (Fig. 57.14). This exposure provides an adequate length of vessel for bypass with proximal control distal to the vertebral and mammary arteries.

VERTEBRAL ARTERY EXPOSURE

Traditionally, the vertebral artery has been exposed in four segments, a classification proposed by Berguer (Fig. 57.15).[2] The proximal V1 segment involves vertebral artery from its origin at the subclavian artery to the point where it enters C6 transverse process. The V2 segment lies in the transverse process of C6 to C2 and is seldom exposed primarily for control of hemorrhage. V3 segment is between C2 and the base of the skull before the artery enters foramen magnum. The V4 segment is intracranial and begins at the atlanto-occipital membrane and terminates at the level where the vertebral arteries merge to form the basilar artery.

Exposure of the V1 Segment of the Vertebral Artery

Two approaches to exposure of V1 segment have been described. The more common supraclavicular approach is frequently used for transposition of the vertebral artery into the CCA. This approach allows the exposure of the origin of the vertebral artery and may require transection of the SCM and limits exposure of the distal V1 segment. In contrast, the anterior cervical approach does not require muscle transection and allows access to the more distal V1 segment.



A

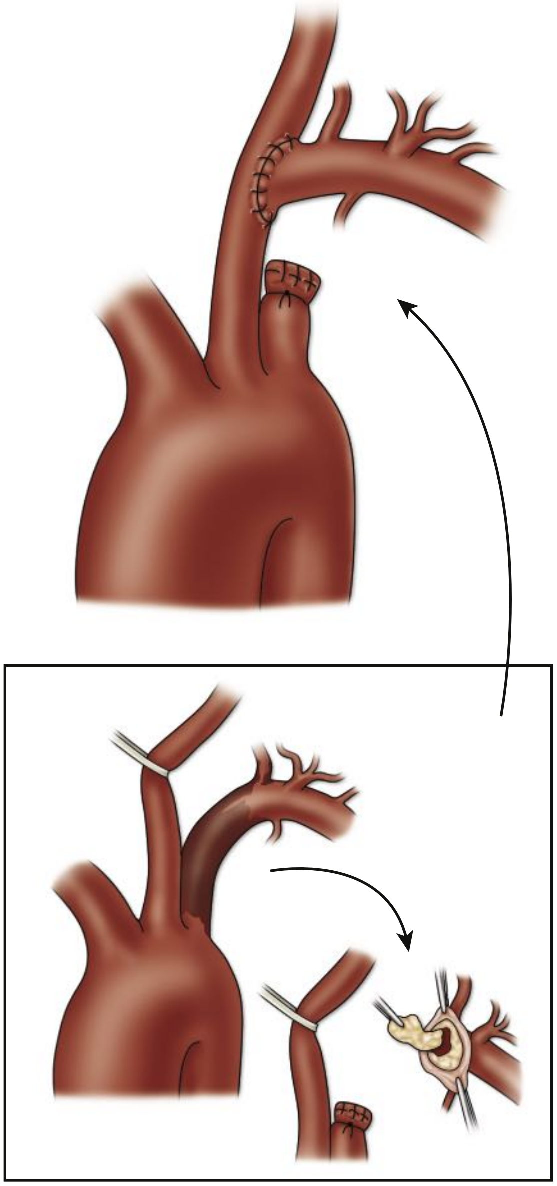
B

C

D

Figure 57.12 Left subclavian-to-carotid transposition. (**A**) Approach to both proximal subclavian and common carotid arteries and division of the thoracic duct. (**B**) Division of the vertebral vein. (**C**) Isolation of the vertebral and common carotid arteries and pre- and post-vertebral segment of the subclavian artery. (**D**) End-to-side anastomosis of subclavian to common carotid artery.

Continued



E

Figure 57.12 Cont'd (**E**) Completed operation.

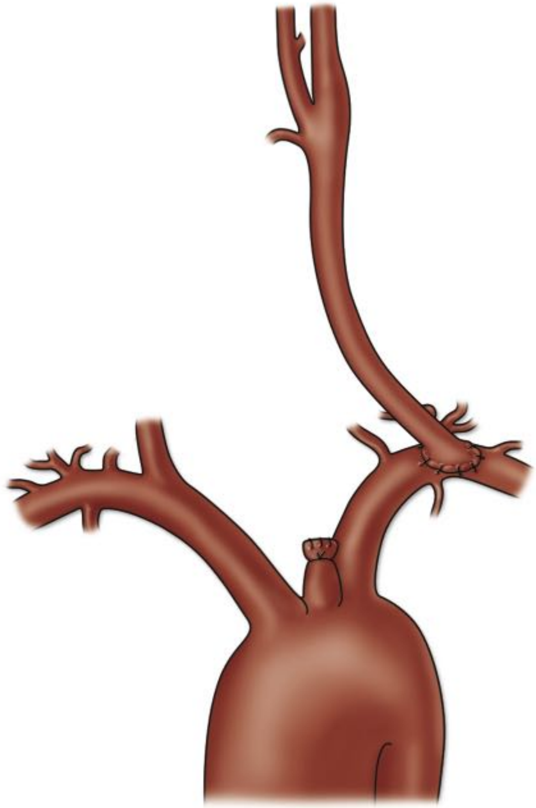


Figure 57.13 Transposition of the common carotid to the subclavian artery.

Supraclavicular Approach

1. The patient is placed supine, with the head turned away from the surgery site.
2. A transverse incision is made a fingerbreath above the clavicle, beginning at its head and extending laterally for 6 to 8 cm.
3. The platysma muscle, superficial fascia, and external jugular vein are divided.
4. Dissection is carried out between the two bellies of the SCM.
5. Alternatively, the clavicular head of the SCM may be divided, followed by division of the omohyoid muscle.
6. The internal jugular vein is then identified, dissected free on the medial aspect, and retracted laterally.
7. Subsequently the vagus nerve is identified and retracted either medially with the common carotid artery or laterally with the IJV. The dissection is carried upward and downward between the IJV, the subclavian vein, and the carotid artery.
8. On the left side, the thoracic duct is identified and divided between two ligatures. The dissection is medial to the prescalene fat pad that covers the phrenic nerve. On the right side large lymphatic channels may be identified; this is not uncommon. In such cases these channels should be ligated to avoid lymph leakage.
9. The inferior thyroid artery, which runs transversely, is ligated and divided. Subsequently the vertebral vein is identified. It often has some small branches that have to be controlled. The vertebral vein should be ligated and divided in its proximal aspect (Fig. 57.16).
10. At this point, the vertebral artery and sympathetic ganglion are easily identified in the center of the angle formed by the anterior scalene and longus colli muscles. The ganglion should be dealt with carefully to avoid Horner syndrome. The vertebral artery should be dissected free from sympathetic fibers and encircled with a vessel loop. This then allows for intervention on the V1 segment. This may include transposition of the proximal vertebral artery to the CCA for which this supraclavicular intersternocleidomastoid approach is the best approach. The proximal vertebral artery can also rarely be transposed to

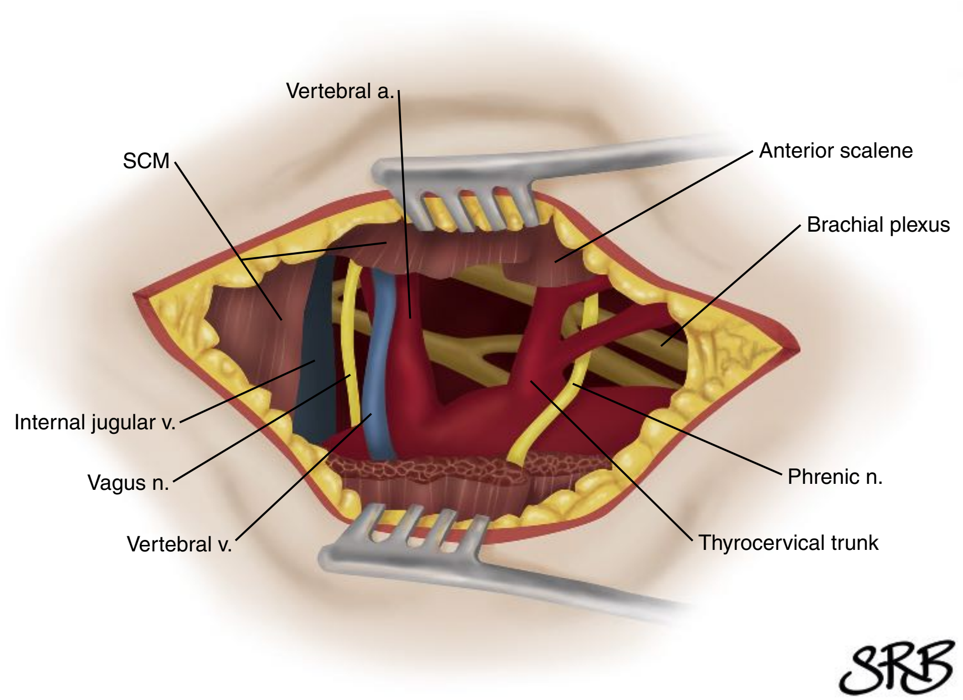


Figure 57.14 Traditional exposure of subclavian artery after division of anterior scalene muscle for carotid subclavian bypass. *SCM*, sternocleidomastoid muscle.

another SA or subclavian vertebral bypass. This will require exposure of the second portion of the SA after dividing the scalene anticus muscle.

Anterior Cervical Approach

1. The positioning is the same as for the supraclavicular approach.
2. A vertical incision is made from the clavicular head up to the retromandibular area, on the anterior border of the SCM; the dissection is similar to that of standard carotid artery exposure.
3. The superior belly of the omohyoid muscle is often divided. The vagus nerve as well as sympathetic chain should be identified and protected.
4. In the lower aspect of the incision, the scalene fat pad is identified and retracted laterally, exposing the anterior scalene muscle and phrenic nerve.
5. The inferior thyroid artery should be ligated and divided, exposing the vertebral artery. The entire extraosseous vertebral artery (V1 segment) can be easily exposed to the level where it enters the transverse process of C6.

Exposure of the V2 Segment of the Vertebral Artery

Exposure of the V2 segment is usually performed for bleeding control and has become less common in the endovascular area. Since the V2 segment runs through the foramen tranversaria, direct access is possible only by unroofing the transverse process. The exposed vertebral artery in the V2 segment is surrounded by a network of veins referred to as the vertebral transverse sinus. Injury to this vein system adherent to the adventitia and periosteum may lead to significant blood loss.

1. The incision is the same as that used for the anterior cervical approach to the V1 segment and extends from the clavicular head to the mastoid process.
2. The platysma muscle is divided and the SCM is retracted laterally to expose the carotid sheath.
3. Larynx, pharynx, and carotid sheath are dissected free from the prevertebral fascia and retracted medially, exposing the sympathetic ganglia and the anterior longitudinal ligament.
4. The ganglia are preserved and the ligament is incised vertically for the entire length of the incision.
5. The ligament is retracted laterally exposing the prevertebral fascia, longus colli, and longus capitis muscles, which are removed with a periosteal elevator from the transverse processes. In order to prevent cervical nerve injury, it is important to not extend the dissection beyond the lateral border of the transverse processes.
6. Access to the vertebral artery in the bony canal is obtained by carefully removing the anterior arch of the transverse process with a rongeur.

Exposure of the Atlantoaxial (V3) Segment of the Vertebral Artery

Access to the V3 segment has been used for bleeding control resulting from traumatic injuries to the distal vertebral artery

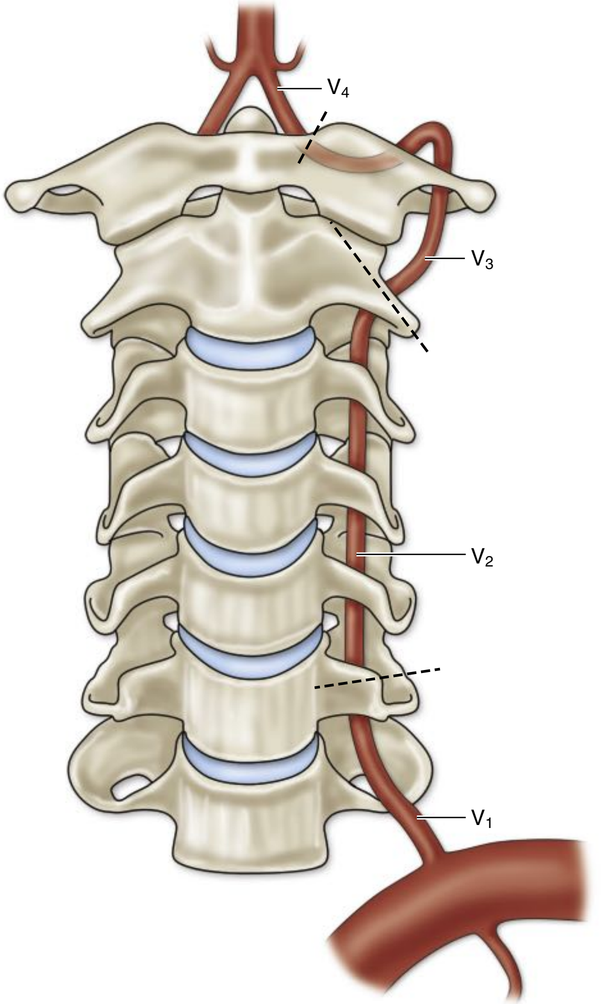


Figure 57.15 Relation of the vertebral artery and cervical spine. The dotted line indicates the level at which the vertebral artery becomes intradural. The trajectory of the VA from its origin to the basilar artery is approximately 25 cm in length. Its outside diameter is fairly constant throughout its course: about 5 mm.

as well as to create the distal anastomosis in vertebral bypasses. Today exposure of V3 is rarely used since many of vertebral artery pathologies are treated with transcatheter techniques. At this level, the vertebral artery is fragile and susceptible to traumatic injury. In addition, the artery is encircled by the periarterial venous plexus. Thus it is recommended to dissect the artery at the subadventitial level.

1. The positioning of the patient is similar to that for carotid exposure, although some authors recommend a semiseated position to reduce venous pressure in the neck.
2. The vertical incision is carried on along the anterior aspect of the SCM from the level of the cricoid and curved posteriorly beneath the earlobe to cross over the mastoid. The platysma muscle is divided and the dissected carotid sheath is retracted medially and SCM laterally.
3. Partial or complete transection of the SCM at its origin significantly improves the exposure.
4. It is imperative to identify and preserve the spinal accessory nerve, which enters the sternocleidomastoid approximately 2 to 3 cm below the mastoid tip. The nerve should be retracted anteriorly and the transverse process of the first cervical vertebra identified by palpation. The C1 transverse process serves as the point of attachment for the levator scapulae, splenius cervicalis, and inferior oblique muscle, covering the interspace between C1 and C2, where an approximately 2-cm segment of the vertebral artery is readily accessible.
5. These three muscles are carefully divided, paying attention to avoid injury to the anterior ramus of the C2 nerve root, which lies on the anterior border of the levator scapulae muscle. In order to avoid nerve injury, the muscle division is performed over a right-angled clamp or small retractor, which is inserted between the C2 nerve and the muscles.
6. To increase exposure of the intertransverse space and vertebral artery, the cephalad muscle fibers are resected and the lower end of the divided muscle is either resected or retracted inferiorly.

POSTERIOR EXPOSURE OF THE SUBOCCIPITAL VERTEBRAL ARTERY (V4) SEGMENT

This technique, as described earlier for posterior carotid exposure, can also be used to treat dissections or aneurysms involving the most distal segment of the extracranial vertebral artery.

1. The patient is placed in the prone/lateral position with the contralateral arm placed under the head, with the incision as previously described for the posterior approach to the carotid.
2. Once the internal jugular vein and the accessory nerve are exposed, further dissection requires ligation and division of the condyloid emissary vein.
3. This is followed by partial division of the rectus capitis posterior muscle, allowing exposure of the vertebral artery, which is covered by a large venous plexus.

The overlying veins must be dissected away from the artery, which requires meticulous technique. Eventually the vertebral artery can be dissected to the level of the atlanto-occipital membrane.

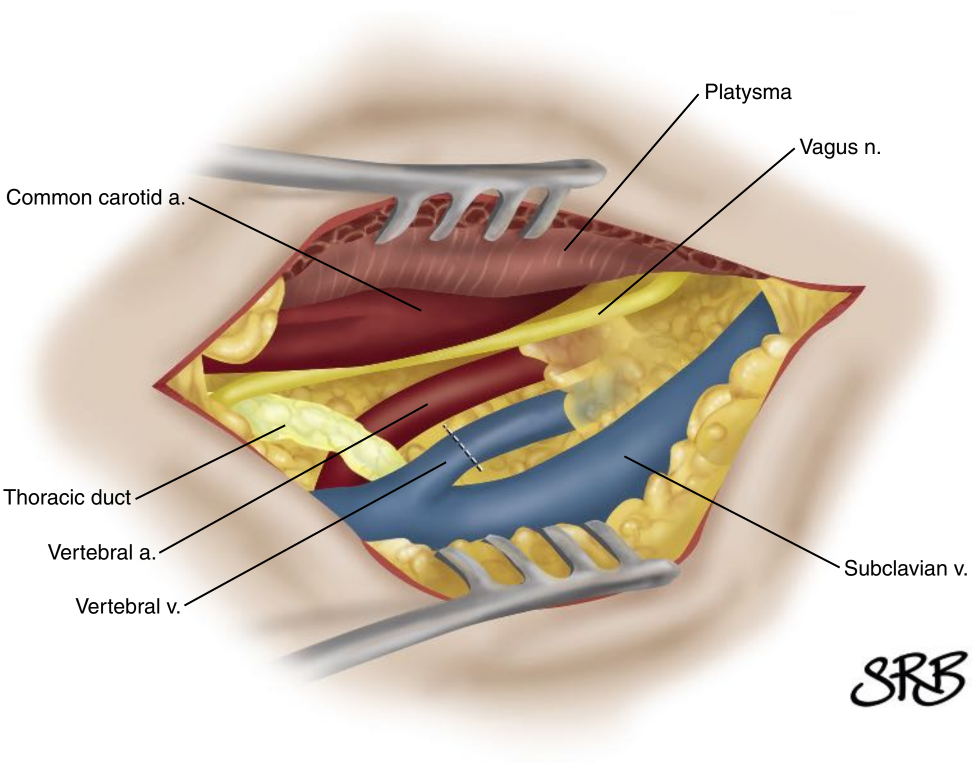


Figure 57.16 Supraclavicular approach to V1 segment of vertebral artery demonstrating overlying and vertebral vein and thoracic duct.

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CHAPTER 58

Lower Extremity Arterial Exposure

J. ELI ROBINS and MICHAEL C. STONER

Based on a previous edition chapter by Frank B. Pomposelli Jr., Scott Prushik, and Kate Shean

INTRODUCTION

Operations involving the arteries and veins of the lower extremity are among the most frequently performed open vascular surgical procedures in clinical practice (see Ch. 112, Infrainguinal Disease: Surgical Treatment). Having good familiarity with both the usual and alternative surgical exposures used in the lower extremity should be part of every vascular surgeon's repertoire. Typically, exposure is made through linear, vertical incisions placed directly over the arterial or venous segments in question (Fig. 58.1). In bypass procedures done for treatment of intermittent claudication, femoral endarterectomy, profundaplasty, and when embolectomy or thrombectomy is done for acute limb ischemia, exposure is usually confined to the femoral artery in the groin and the medial approach to the popliteal artery above or below the knee. However, in procedures performed for critical limb ischemia and in reoperative surgery, exposure of the more distal crural and pedal vessels is frequently required. Moreover, in procedures performed for or in the presence of infection, in obese patients, in many reoperative procedures, and those performed for traumatic injury, it may be necessary to use incisions or exposure techniques not frequently employed in everyday practice.

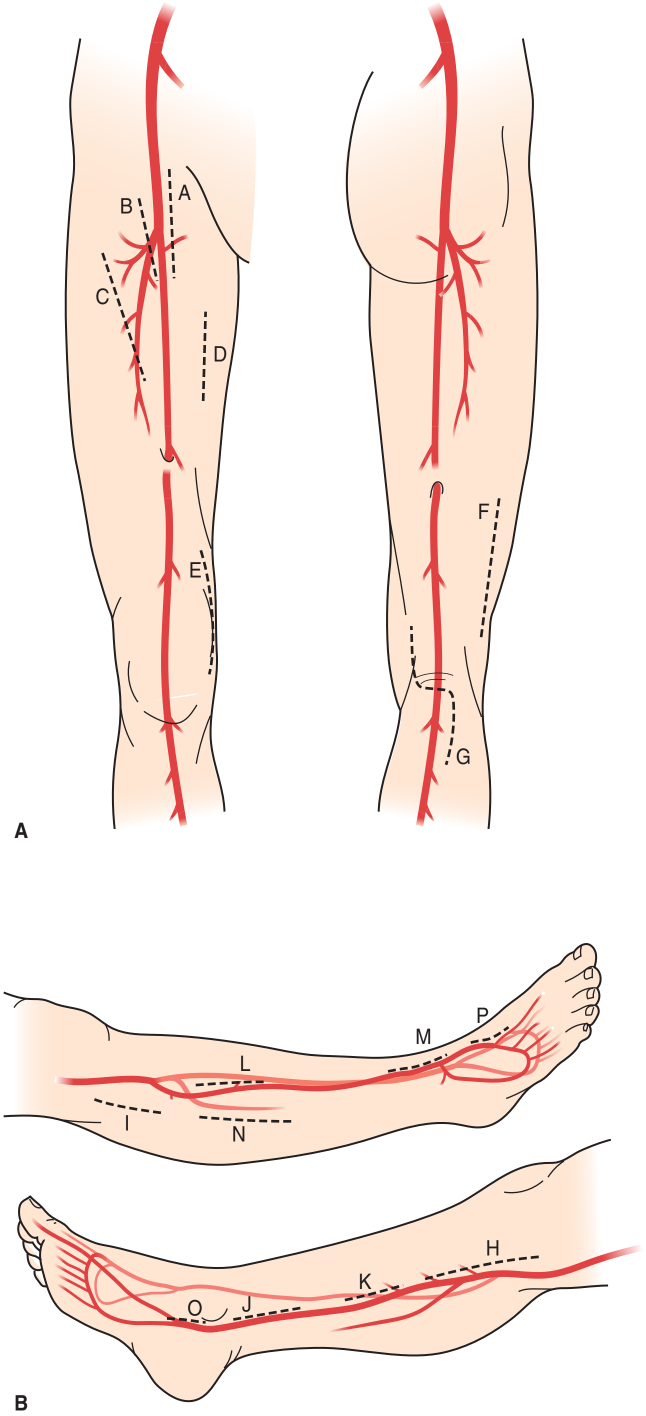


Figure 58.1 (**A**) Location of the vertical incisions to expose the arteries in the thigh: common femoral, deep femoral, superficial femoral, and popliteal arteries, (**B**) and in the calf: popliteal, tibioperoneal trunk, anterior tibial, posterior tibial, and dorsalis pedis arteries. (Figures 67 and 68 from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993:114 and 115.)

Regardless of the exposure employed, we have found the following general principles to be critical:

- Make an incision of adequate length – do not compromise exposure
- Use self-retaining retractors whenever possible
- Have a sterile continuous-wave Doppler probe available
- Make liberal use of the cautery for dissection except in close proximity to adjacent nerves
- Ligate all transected lymphatics
- Ensure meticulous hemostasis
- Adhere to the basic principles of traction/countertraction, bloodless field, meticulous blunt and sharp dissection as close to the artery as possible, obtain proximal and distal control with enough space to perform an anastomosis comfortably, avoid clamping or crushing of heavily calcified segments whenever possible
- Vein conduits should be handled gently and carefully; poorly prepared veins result in inferior outcomes
- Ensure good lighting and make use of magnification when anastomoses are being constructed.

FEMORAL ARTERY EXPOSURE

Anatomy

The common femoral artery (CFA) is located deep to the inguinal skin fold as a continuation of the external iliac artery as it passes beneath the inguinal ligament. It lies medial to the femoral nerve and lateral to the common femoral vein. The femoral neurovascular bundle is contained within the femoral sheath, which is formed by elements of the iliac, pectineus, and transversalis fascia in the femoral triangle.[1] The femoral triangle is covered by the tensor fascia lata and bound by the adductor longus muscle medially and the sartorius muscle laterally. The CFA bifurcates into the superficial femoral artery (SFA) and profunda femoris or deep femoral artery (DFA).

Common Femoral Artery

Longitudinal Approach

The CFA is usually exposed through a longitudinal incision over the femoral pulse just distal to the inguinal ligament. If no pulse is present, the artery is usually still palpable as a firm, cylindrical mass slightly medial to the midpoint of the inguinal ligament. The incision should be extended proximally to expose the inguinal ligament. The length of the incision varies based on the patient's body habitus and the extent of atherosclerotic disease, but typically about one-quarter to one-third of the incision should extend proximal to the ligament and the remainder distally. In very obese patients with a large overhanging pannus, it is important to identify the exact location of the inguinal ligament prior to making an incision. Often it is much more proximal than it may appear, making it possible to keep the distal end incision proximal to the fold in the pannus, which avoids the troublesome wound separation that invariably occurs when a vertical incision needlessly crosses this point. The subcutaneous tissue should be divided directly over the artery to avoid the creation of a medial or lateral flap, which can also lead to troublesome and occasionally disastrous problems with wound healing. Any small venous or arterial branches of the superficial epigastric and superficial circumflex artery encountered should be ligated and divided. The authors

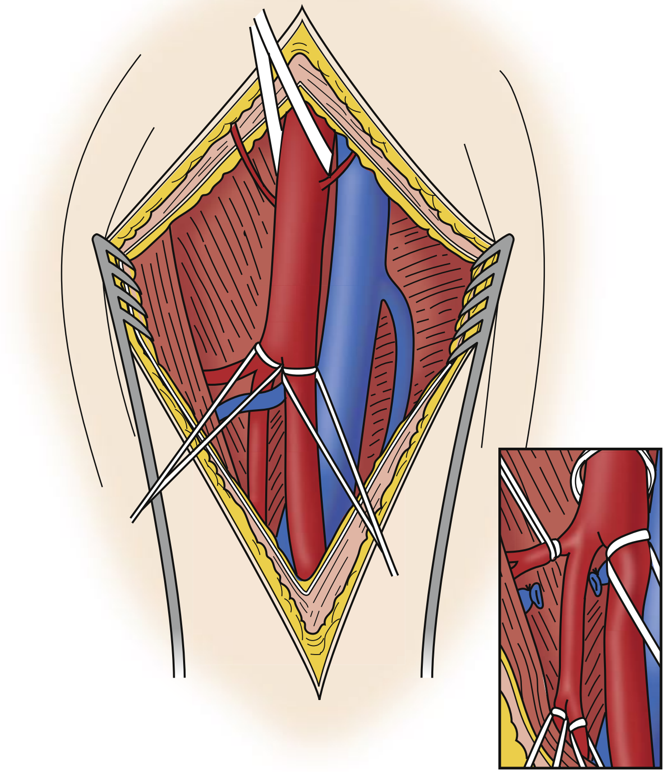


Figure 58.2 The proximal deep femoral artery origin is typically identified as a posterolateral branch of the common femoral bifurcation. Additional exposure is obtained by extending the vertical incision to expose the lateral femoral circumflex vein, which is divided where it crosses over the deep femoral artery. (Figure 71 from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993:123.)

also routinely ligate any divided lymphatics to minimize lymphatic leaks. The saphenous vein typically lies medial to the artery but is often encountered. Care should be taken to extend the dissection lateral to its course to prevent its injury.

The fascia lata lies deep to the subcutaneous tissue and is divided medial to the medial edge of the sartorius muscle over the artery to enter the femoral sheath. Most commonly, exposure will extend to the inguinal ligament. If more proximal exposure is needed, the inguinal ligament can be mobilized and retracted superiorly to increase visibility. Additional exposure can be obtained by dividing the ligament, which must always be repaired at the time of closure. If extended exposure of the proximal SFA is needed, the sartorius muscle can be mobilized and retracted laterally. The DFA typically arises somewhat lateral and posterior to the CFA (see below). Care must be taken to avoid straying too far posterior and lateral to the CFA, which would risk injury to the femoral nerve. Medially, the common femoral vein is in very close proximity and not uncommonly adherent to the CFA. Careful sharp dissection is required to avoid its injury, especially in redo dissections.

Transverse Approach

The transverse approach is useful provided that only limited arterial exposure is needed, as for femoral embolectomy or a cutdown for endovascular aneurysm repair (EVAR). It begins with a horizontal skin incision 2 fingers' breadth above to the groin crease, parallel to the inguinal ligament. Once the incision has been made, it is deepened through subcutaneous tissue and Scarpa's fascia until the inguinal ligament is encountered. The ligament should be freed and mobilized to allow retraction superiorly. The dissection is deepened directly over the femoral pulsation until the femoral sheath is encountered, which is then incised longitudinally to expose the CFA. Self-retaining retractors are essential for adequate exposure. Although most of the CFA can usually be exposed through this approach, it provides only limited access to the superficial and deep femoral arteries.

Deep Femoral Artery

Conventional (Proximal) Approach

The DFA originates approximately 2 to 5 cm distal to the inguinal ligament and has a lateral course relative to the CFA in most patients. Exposure of the DFA begins with longitudinal exposure of the CFA, as previously described. As the CFA is exposed distal to the inguinal ligament, the origin of the DFA is usually encountered on the lateral or posterior lateral side of the CFA at the point where the CFA caliber becomes noticeably smaller as it bifurcates into the DFA and SFA. In most cases a few centimeters of the DFA can be exposed before the lateral femoral circumflex vein is encountered (Fig. 58.2); it crosses over its anterior surface and must be carefully divided and suture-ligated for additional exposure. Further dissection may require division of other crossing veins and lateral retraction of the sartorius muscle. Lymphatics are often encountered in extended exposure of the PFA and should be ligated. The femoral nerve is in close proximity and care should be taken to avoid its injury. The length of the proximal profunda varies from a few to as many as 8 cm. Branch points and bifurcations increase in frequency with more distal exposure. Both the medial and lateral circumflex arteries most commonly originate from the DFA, although either or both can originate from the CFA, usually near the DFA origin; they may be injured during careless posterior dissection of the CFA or DFA.

Lateral (Distal) Approach

The lateral approach to the DFA is useful in reoperative surgery as an alternative source of either inflow or outflow when the more proximal femoral vessels are encased in dense scar and/or infection or when a more distal inflow site is needed in the case of limited venous conduit.[2,3] The incision is made parallel to the course of the sartorius muscle usually 6 or 7 cm distal to the femoral pulsation or just distal to the end of a previous femoral incision. It can be placed on either the medial or lateral side of the sartorius depending on the situation and the likely course of the bypass graft; for example, lateral for a profunda–anterior tibial or axillary–profunda graft or medial for a femoral–profunda or profunda–popliteal graft (Fig. 58.3). Regardless of the chosen incision, approaching the distal PFA requires dissection lateral to the superficial femoral vessels and adjacent nerves,

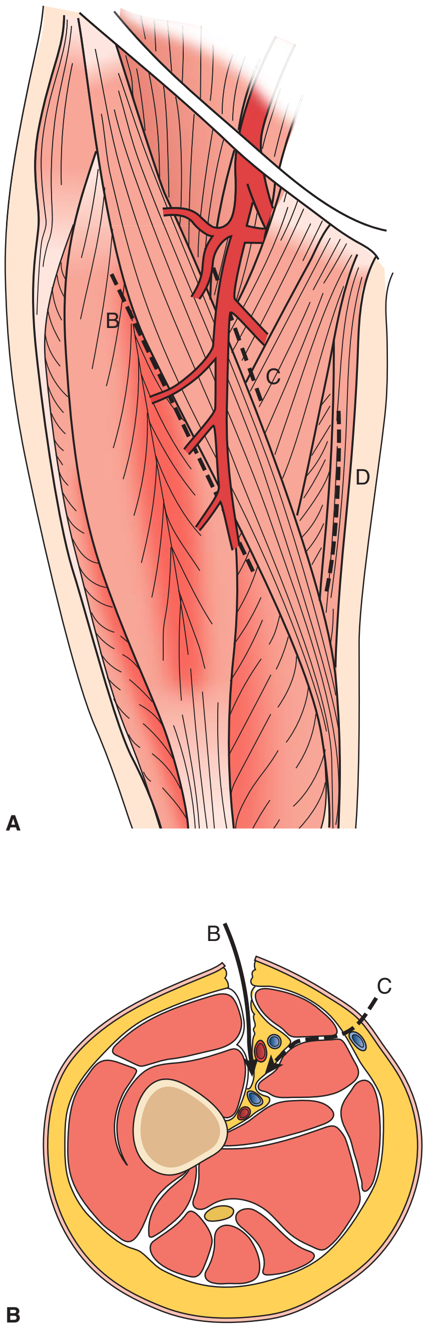


Figure 58.3 (**A**) The distal deep femoral artery can be approached from either medial or lateral to the sartorius muscle, depending on the course of the bypass. (**B**) In both cases, the dissection is performed lateral to the superficial femoral vessels. (Figure 73A and B from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993:128–129.)

which can be easily injured with retraction, especially when Gelpi or sharp-toothed Weitlaner retractors are being used. The dissection continues deep to the superficial femoral vessels in a plane between the vastus medialis and adductor longus muscles (Fig. 58.4). Usually a raphe created by the intersecting fibers of the fascia of these muscles is encountered, which, when opened, exposes the underlying deep femoral vein. The artery is usually found deep to the vein. In difficult cases, a handheld Doppler probe is useful for identifying the location of the artery.

Superficial Femoral Artery

Proximal Approach

The SFA lies in a plane deep to the sartorius muscle, crossing over the adductor longus muscle. The proximal SFA is easily exposed by distal extension of the longitudinal incision made for exposure of the CFA. The SFA is located under the proximal sartorius muscle, which can be mobilized and retracted laterally. It can also be exposed in this fashion without exposing the CFA or DFA with a more distal incision placed along the anterior edge of the sartorius muscle (see below).

Mid/Distal Approach

The SFA follows a course between the anterior and medial compartments of the thigh in an aponeurotic tunnel, the adductor (Hunter) canal, created by components of the investing fascia of the vastus medialis, sartorius, and the adductor longus muscles.[1,4] In addition to the SFA, the Hunter canal contains the femoral vein deep to the artery and two branches of the femoral nerve: the sensory saphenous nerve and the motor nerve to the vastus medialis muscle. To approach the SFA, the patient is placed with the leg externally rotated and the knee flexed to 30 degrees. A longitudinal incision is then made parallel to the anterior border of the sartorius to avoid disrupting the blood supply to the muscle, which enters on its inferomedial edge. The incision is carried down to the fascia lata, which is incised to expose the sartorius muscle. The muscle is then reflected in a posterior direction to reveal the roof of the Hunter canal. The fascia is opened to expose the SFA and vein. The vessels are often densely adhered to one another requiring careful dissection to separate them. Typically several large branches of the vein are encountered crossing over the artery, which should be divided. The SFA, even when widely patent on imaging, usually has some degree of atherosclerosis and is often calcified. In the authors' experience, the surgeon should be prepared to extend the initial exposure either proximally or distally to find the most suitable area for clamping and/or placing an anastomosis.

POPLITEAL ARTERY EXPOSURE

Anatomy

The popliteal artery is the extension of the SFA across the knee. It courses from the adductor hiatus at its superior border to the popliteus muscle at its inferior border.[1,4] It is important to understand the relationships of the muscles, nerves, fascia, and arteries to perform adequate exposure for safe arterial reconstruction. The vessels are encased in a connective tissue sheath and are loosely adherent to the tibial nerve. The entire neurovascular bundle is enclosed within the fat pad of the popliteal space, which can be quite bulky and extensive, especially in obese individuals. The popliteal artery gives rise to several small

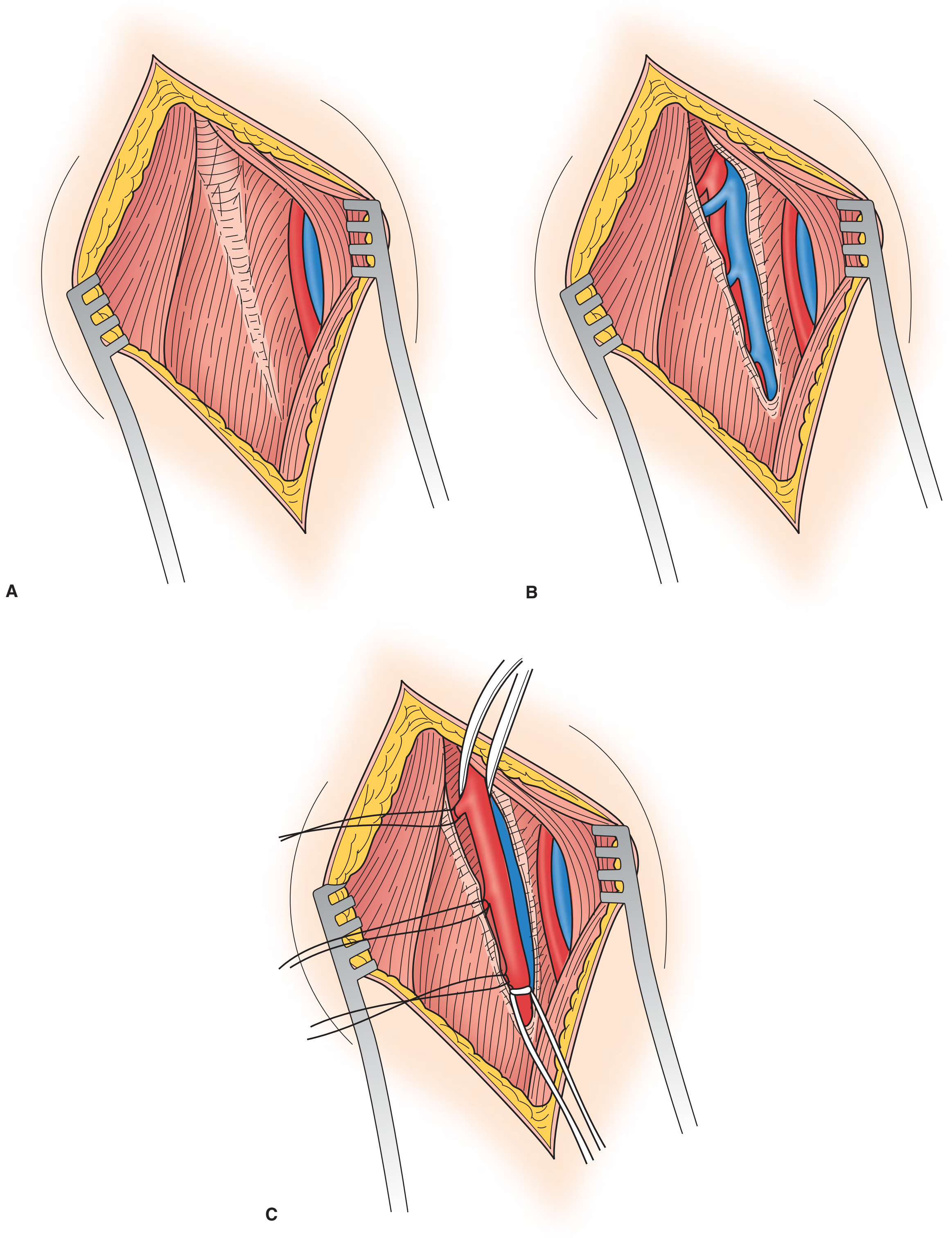


Figure 58.4 (**A**) There is a raphe formed by the intersecting fibers of the vastus medialis and the adductor longus muscles, which is divided to reveal the (**B**) deep femoral vessels with the vein lying superiorly. (**C**) The artery is dissected free from the vein with careful attention paid to the fibers of the femoral nerve. (Figure 73C to E from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and exposure*. Philadelphia: WB Saunders; 1993:128–129.)

arteries around the knee joint that form important collaterals with the DFA.

Suprageniculate Popliteal Artery

Medial Exposure

The patient is placed supine with the leg externally rotated on a bump at the level of the knee. The incision is made in the distal third of the medial thigh along the anterior border of the sartorius muscle at the lower edge of the vastus medialis. Alternatively, the incision is made through the bed of the saphenous vein harvest incision, which results in a slightly more posterior approach. The fascia lata is incised and the sartorius muscle is retracted posteriorly. The deep fascia should be incised slightly inferior to the edge of the vastus medialis muscle. A small artery and vein is often encountered as well as a branch of the saphenous nerve. The artery and vein should be divided but the nerve can often be spared. Upon entering the popliteal space, the popliteal fat pad is encountered. The dissection commences in this envelope of fat in close proximity to the posterior aspect of the femur. The artery is usually firm or calcified and easily palpated even in the absence of a pulse. In obese patients the fat pad is thicker and more extensive and the artery can be difficult to find. In this case, palpation of the firm mass of the adductor magnus tendon is a good reference point, since the artery pierces the tendon to enter the popliteal space and is easily found at its edge. It should be encircled with a vessel loop or tape and placed on some traction by attaching the loop to a self-retaining retractor, which greatly facilitates its exposure, especially during the creation of an anastomosis. The popliteal artery is usually encountered anterior and medial to the vein, which is often paired, with multiple bridging veins across the popliteal artery that must be divided. Like the SFA, this artery is often heavily calcified and rarely free of some degree of atherosclerotic disease. Finding the best place for clamping may require exposure of the entire segment from the adductor hiatus to the point where it crosses under the medial head of the gastrocnemius muscle.

Lateral Exposure

The leg is internally rotated and the knee is flexed. The incision is made in the distal third of the lateral thigh between the iliotibial tract and the biceps femoris muscle. The fascia lata is incised posterior to where the iliotibial tract joins the lateral intramuscular septum. The popliteal space is entered between the short head of the biceps femoris muscle and the lateral femoral condyle. The neurovascular bundle can be palpated in the popliteal fat pad. The popliteal vein, which is located lateral to the artery, is usually encountered first (Fig. 58.5). When dissecting the popliteal artery free from the popliteal vein, careful attention must be paid so as not to injure the common peroneal nerve.[2]

Mid-Popliteal Artery

Posterior Approach

The posterior approach to the popliteal artery is especially useful in the repair of popliteal aneurysms[5–7] or for diseases confined to the midpopliteal artery, such as adventitial cystic disease.[8] The patient is placed prone on the operating table with the foot and ankle resting on a pad to slightly flex the knee. An S-shaped incision is chosen to avoid scar contracture across the posterior knee joint. The incision is made from the posterior medial aspect of the thigh across the skin crease and down the posterior lateral leg. The small saphenous vein is identified in the subcutaneous tissue; it can be ligated or dissected free and retracted to expose the deep fascia. The deep fascia is then incised vertically and the sural nerve retracted laterally. The tibial nerve is the most superficial of the neurovascular structures and should be retracted laterally along with the common peroneal nerve, which runs along the biceps femoris tendon. This will expose the popliteal vessels, which lie medial and deep to the nerves (Fig. 58.6). To facilitate distal exposure, the medial and lateral heads of the gastrocnemius muscle are retracted apart. The popliteal artery lies slightly deep and medial to the vein and can be readily dissected free. One limitation of this approach is proximal exposure of the distal SFA prior to its exit from Hunter's canal. Exposure necessitates division of Adductor Magnus posteromedially. As the dissection is carried cranially, the artery becomes inaccessible as it courses to the anterior portion of the femur.

In cases of long, fusiform aneurysms, which necessitate distal SFA control, the author's preferred method, for both safety and ease, is the medial approach. The midpopliteal artery can also be exposed from the medial approach through an extended incision by dividing the tendinous attachments of the medial head of the gastrocnemius and sartorius muscles. These are best reattached with heavy-gauge sutures during closure.

Infrageniculate Popliteal Artery

Medial Exposure

The patient is placed in the supine position with the knee flexed, using a bump under the thigh. The incision starts at the knee joint, one finger's breadth inferior to the medial border of the tibia, which is usually superior to the course of the great saphenous vein. The vein should be identified to avoid inadvertent injury. When the saphenous vein is planned for conduit, it should be mobilized first and the resulting incision used to expose the artery. The crural fascia is then incised to enter the popliteal space. At the proximal end of the incision the semimembranosus tendon is encountered; it can be divided to facilitate exposure. The medial head of the gastrocnemius is retracted posteriorly to reveal the neurovascular bundle, which lies under the medial edge of the tibia. The first structure encountered is the medial branch of the paired popliteal veins. The artery is then dissected circumferentially and encircled with vessel loops or tapes to elevate it into the incision. The artery can then be separated from the veins with sharp dissection. Overlying crossing veins are uncommon but should be divided, while large collateral arterial branches should be preserved.

Lateral Exposure

The patient is placed in the supine position with the leg internally rotated and the knee flexed. A longitudinal incision is then made over the head of the fibula and extended distally.

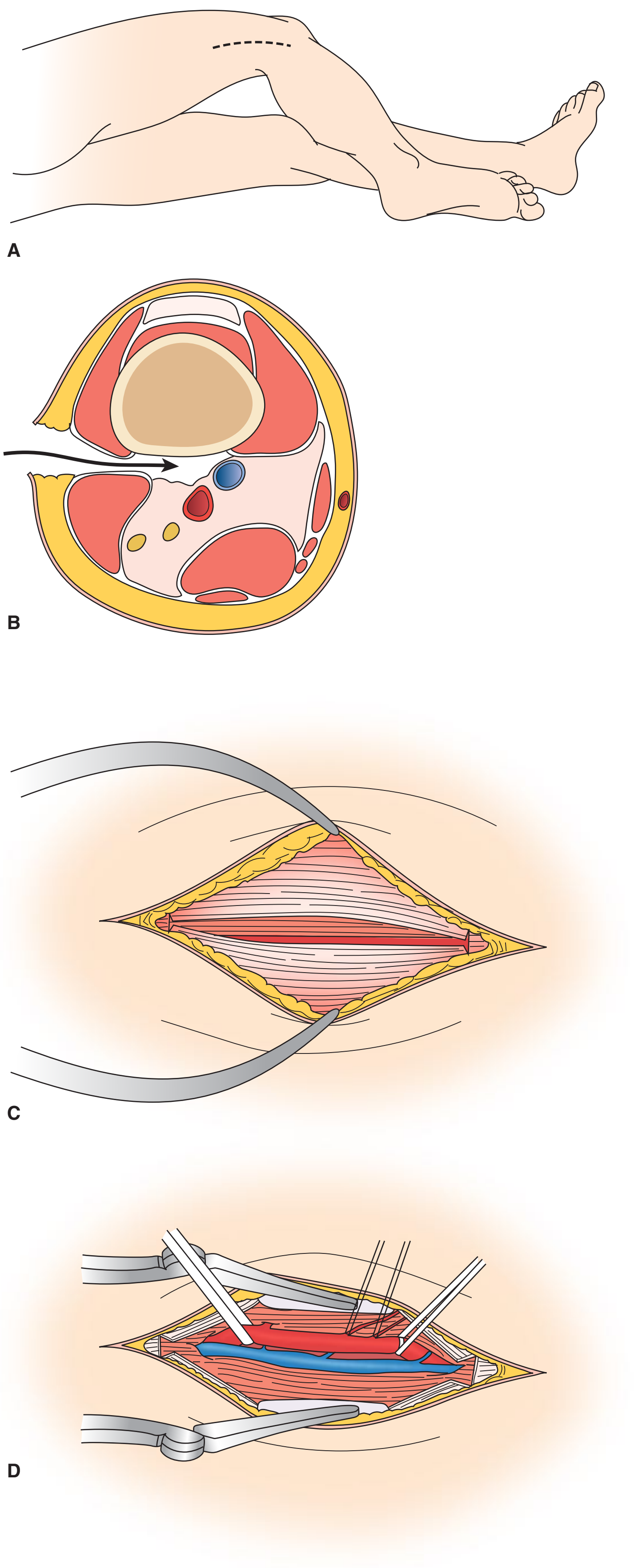


Figure 58.5 (**A**) With the leg internally rotated and the knee flexed, the incision is made in the distal third of the thigh between the iliotibial tract and the biceps femoris muscle. (**B**) The popliteal space is entered between the short head of the biceps femoris and the lateral condyle of the femur. (**C**) A cruciate incision is made through the tough fibers of the iliotibial tract to facilitate retraction. (**D**) The femoral vessels are identified in the popliteal fat pad and the artery is dissected free. (A, Figure 17.7 (top picture) from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:448. B–D, Figure 76 (B to D) from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993:139.)

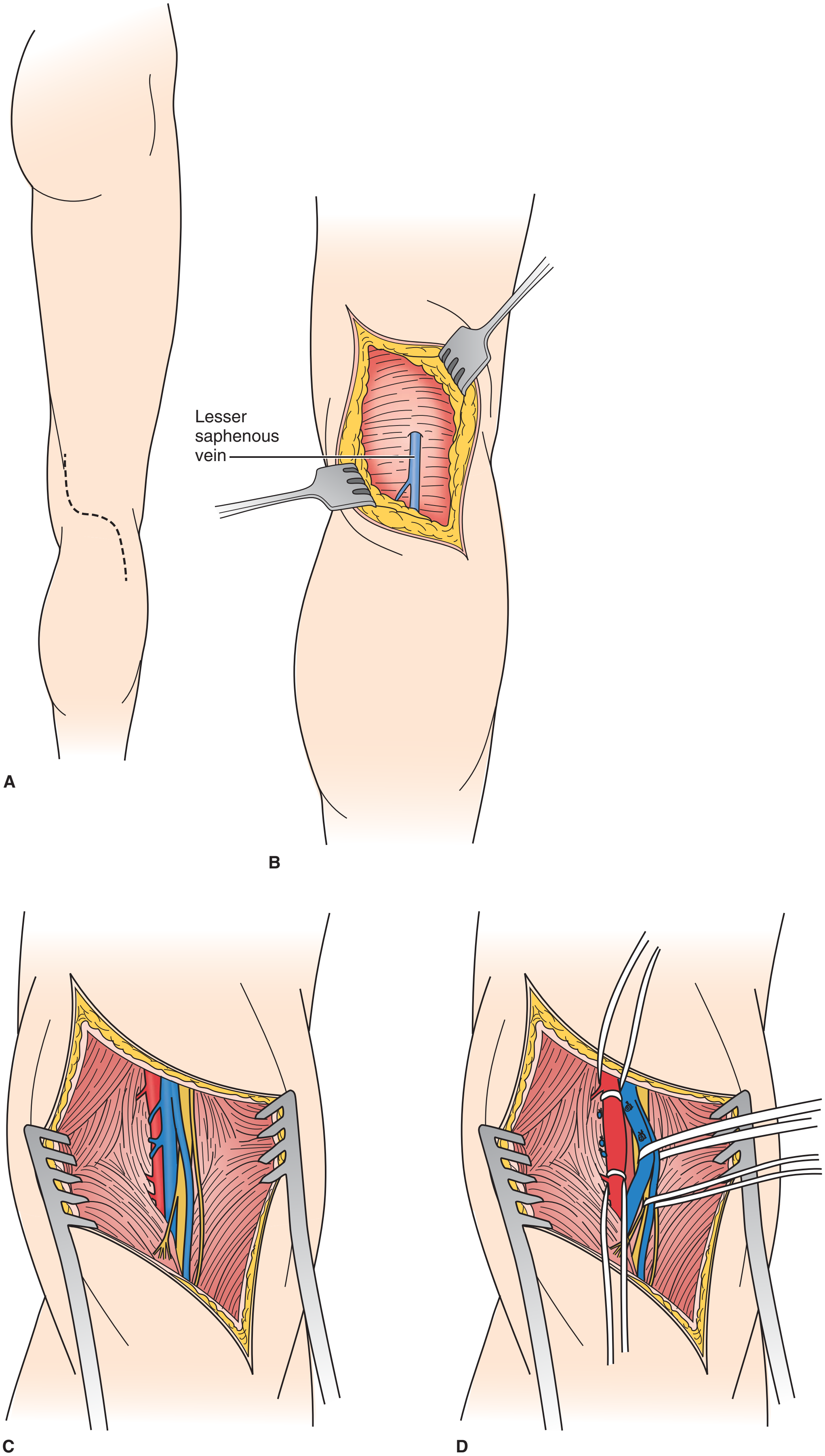


Figure 58.6 (**A**) The incision for the posterior exposure of the popliteal artery is made as a "lazy S" shape to avoid scar contracture across the knee. (**B**) The small (lesser) saphenous vein is identified in the subcutaneous tissue. (**C**) The deep fascia is incised and the sural nerve is gently retracted laterally to facilitate the dissection (**D**) of the popliteal artery from the popliteal vein and the tibial nerve, which lies most superiorly. (A,B, Figures 17.35 and 17.36 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:462 and 463. C,D, Figure 77C and D from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993: 142.)

The common peroneal nerve is then identified posterior to the tendon of the biceps femoris muscle. The nerve should be gently dissected and retracted anteriorly as the tendon is divided to reach the fibula. The attachments to the fibula and fibular head are detached bluntly with a periosteal elevator. The proximal third of the fibula is then divided and removed. The popliteal artery is encountered deep to the fibula and can then be dissected free from the veins and encircled with vessel loops (Fig. 58.7).[2]

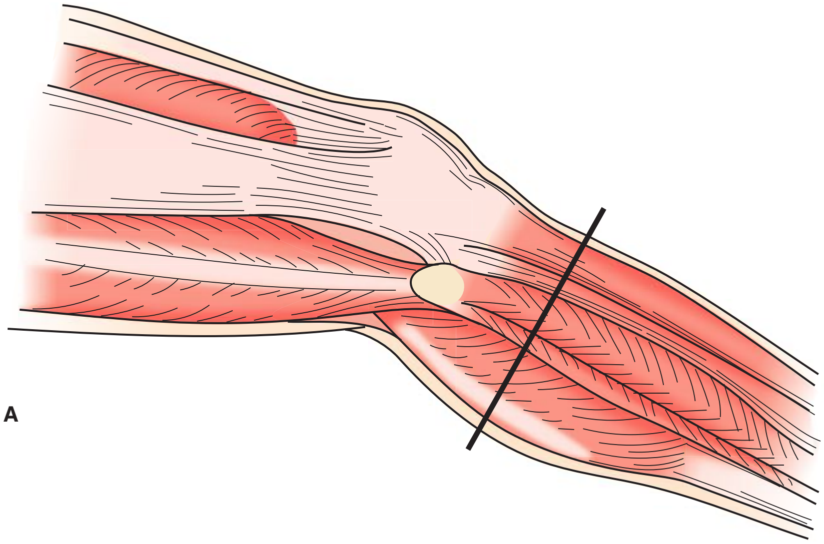
EXPOSURE OF THE TIBIAL AND PERONEAL ARTERIES

Anterior Tibial Artery Exposure

The anterior tibial artery is the most distal branch of the infrageniculate popliteal artery, arising from its lateral aspect and immediately passing through the interosseous membrane before entering the anterior compartment of the lower leg. Consequently the first 2 or 3 cm are most often not accessible for bypass and are frequently associated with significant atheromatous disease. Although a technique for medial exposure of the anterior tibial artery through the popliteal fossa has been described,[9,10] in the authors' experience it is rarely needed.

The proximal and middle third of the anterior tibial artery is exposed by a vertical incision on the anterolateral aspect of the calf and centered over the location of the planned anastomosis. The anterior tibial artery and vein lie on or in close proximity to the interosseous membrane. With the foot and ankle relaxed, it is often possible to palpate the cleft between the tibialis anterior and extensor digitorum longus muscles on the lateral calf approximately at the midpoint between the fibula and the tibia. The incision should be made directly over the cleft starting about 2 or 3 cm distal to the head of the fibula. The overlying fascia should be incised in line with the skin incision with the fascial incision extending for several centimeters distal and proximal to the skin incision to facilitate exposure, especially in heavily muscled individuals. Care must be taken to avoid injury to the peroneal nerve with this maneuver. Blunt finger dissection is used to separate the muscle bellies of the tibialis anterior and extensor digitorum longus muscles. Deep in the cleft at the level of the interosseous membrane, the anterior tibial

A



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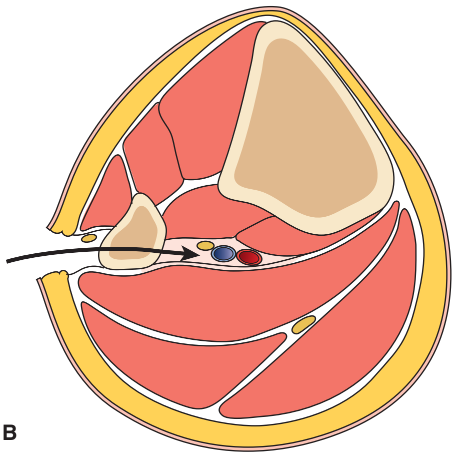


Figure 58.7 **(A)** Axial plane. **(B)** Depiction of axial anatomy and relationship of vascular structures and proximal fibula. The lateral approach to the below-knee popliteal is performed by incising overlying the proximal third of the fibula. The common peroneal nerve is identified and gently retracted anteriorly. The attachments to the fibula are taken down bluntly with a periosteal elevator, and the fibula is then divided proximally and distally to reveal the neurovascular bundle. (Figure 79 from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993:149.)

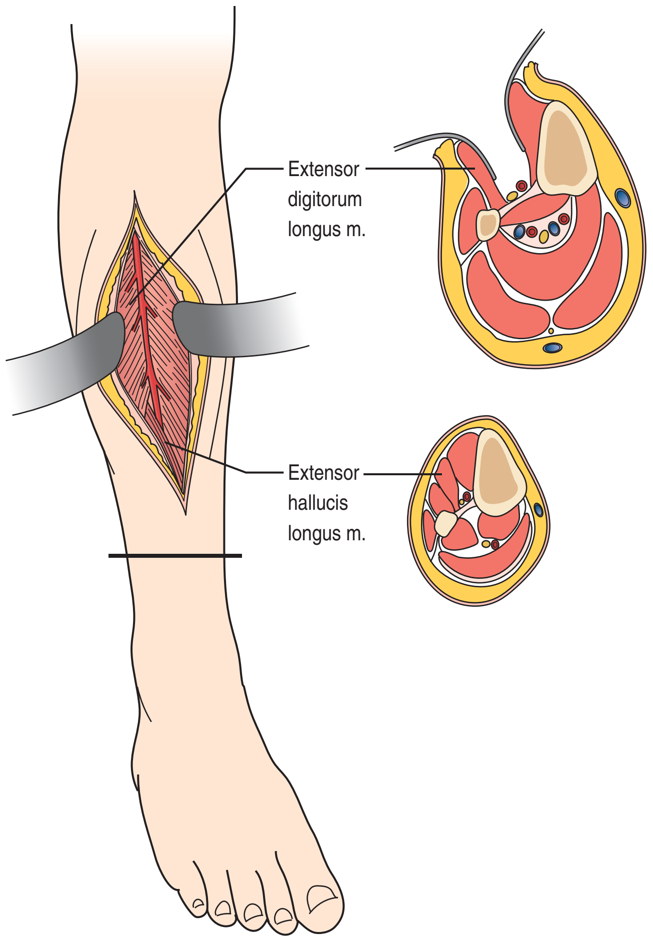


Figure 58.8 The proximal anterior tibial artery is exposed through an incision lateral to the tibia between the tibialis anterior and the extensor digitorum longus muscles. The anterior tibial artery is identified deep in the cleft between these two muscles along the interosseous membrane. (Figure 18.41 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:508.)

artery and vein are usually easily identified (Fig. 58.8). Self-retaining retractors are crucial in this location. Small branches of the anterior tibial artery are often seen on the surface of the muscle bellies and are easily torn with overly aggressive blunt dissection or retraction. Quite often the vein is anterior to the artery and must be carefully dissected free from the underlying artery to facilitate exposure. A number of small crossing veins are often encountered on the anterior surface of the artery and should be ligated and divided to avoid troublesome bleeding. Similarly, great care should be taken in dissecting to free the artery, which has numerous small side branches; this can also lead to troublesome bleeding if they are torn during dissection. The authors prefer the use of a fine-tipped mosquito clamp to dissect along the surface of the artery and favor encircling the artery with small-caliber vessel loops for proximal and distal control. Heavily calcified anterior tibial arteries are better controlled with tourniquet occlusion after exsanguinating the lower leg with an Esmarch bandage.

The distal half of the anterior tibial artery can be exposed in similar fashion to the more proximal artery. However, if adequate conduit is available, the distal anterior tibial artery is best exposed at the ankle just proximal to the malleoli and flexor retinaculum. The tendons of the numerous extensor muscles of the ankle and foot come together in this location, and care must be taken in deciding the best way to expose the artery to avoid compressing or kinking the vein graft when the ankle is dorsiflexed. The best route is to separate the tendons of the extensor hallucis longus and extensor digitorum longus muscles. Once these tendons have been separated, the artery and vein are usually easily found and dissected free as previously described.

Because of its lateral location, vein grafts arising from the femoral triangle to the anterior tibial artery must be tunneled laterally, either subcutaneously or through the interosseous membrane. This anatomic reality can lead to graft thrombosis from kinking or twisting of the vein graft when done incorrectly. Subcutaneous vein grafts arising from the groin to the proximal anterior tibial artery can be easily tunneled across the anterior surface of the thigh (the authors' preferred approach), crossing the knee at the midpoint of the lateral femoral condyle and anterior to the head of the fibula, taking care to avoid injury to the peroneal nerve. The graft should not cross the knee joint in a more anterior location to avoid compressing the vein graft with flexion of the knee joint. When tunneling across the anterior thigh, it is important to place the tunnel in the subcutaneous tissue as close to the anterior fascia of the thigh muscles as possible to provide the maximal amount of soft tissue coverage and minimize kinking at the groin. Tunnels created too superficially, especially in obese patients, will result in a kink of the vein graft by the thick layer of subcutaneous tissue of the femoral arterial exposure incision at the point where the graft exits the femoral triangle. Tunnels created too deeply may cross underneath the sartorius muscle, leading to graft compression. Often it is necessary and prudent to make a counterincision on the anterolateral thigh midway between the knee and groin dissection to facilitate the creation of the tunnel.

Tunneling an anterior tibial graft through the interosseous membrane has the advantage of needing a shorter length of vein conduit and also reduces the likelihood of graft exposure if there is wound breakdown, especially when the graft is also tunneled under the sartorius muscle and through the popliteal space. Special care must be taken to linearly mark the conduit and create an adequate opening in the membrane to avoid inadvertent kinking of the bypass graft. For *in situ* vein grafts and bypasses arising from the above- or below-knee popliteal artery, tunneling through the interosseous membrane is the only feasible pathway for bypasses terminating in the proximal or middle third of the anterior tibial artery. More distal bypasses to the supramalleolar anterior tibial artery can be tunneled across the anterior surface of the tibia. Although this approach is simpler, it may result in graft compression by the underlying tibia in patients where the skin and soft tissue in this location is thin and taut.

When creating the interosseous tunnel, the authors prefer to have the knee flexed at 90 degrees in the "sit up" position. The tunnel is created by simultaneous dissection medially from the below-knee popliteal space and laterally from the anterior compartment with surgeon's finger and blunt-tipped instrument

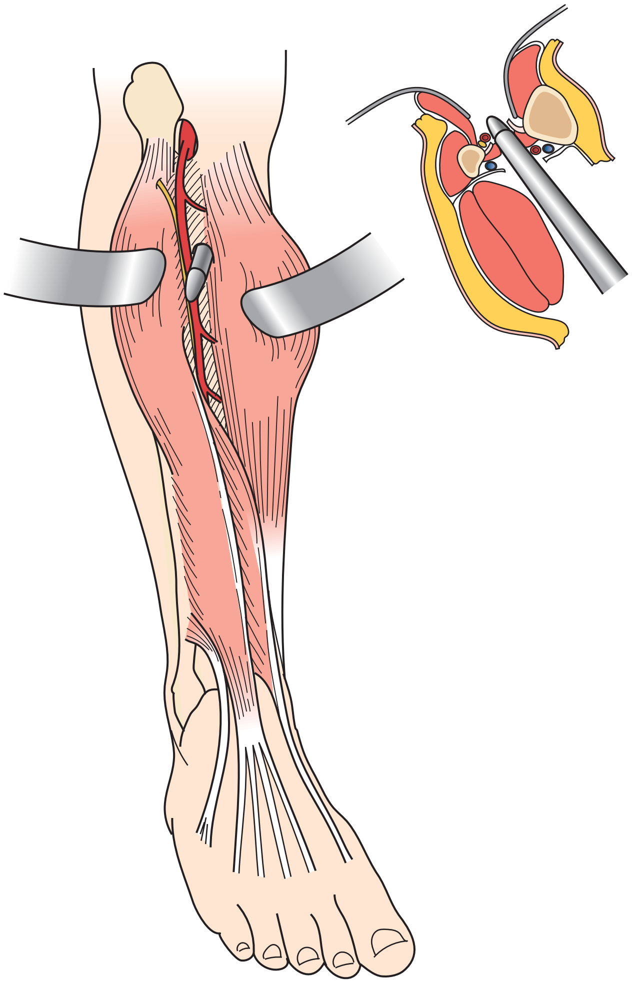


Figure 58.9 Bypass grafts originating from the medial leg can reach the lateral leg by traversing the interosseous membrane. The membrane is exposed with gentle blunt dissection from both the medial and lateral sides. The graft is then tunneled several centimeters proximal to the planned site of the distal anastomosis. (Figure 18.42 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:509.)

(Fig. 58.9). The graft should be tunneled several centimeters proximal to the planned point of anastomosis to the anterior tibial artery. Many surgeons will expose the interosseous membrane from the lateral aspect of the leg and perform a cruciate incision to expand the space and prevent compression of the graft by the firm edge of the fascia. Once the membrane has been incised, the authors prefer to pass a gently curved clamp from the popliteal space in close proximity to the point where the anterior tibial artery crosses the membrane. The jaws of the clamp can be partially opened to widen the tunnel. Careless or overly forceful tunneling can lead to very troublesome venous bleeding from the anterior tibial vein.

Tibioperoneal Trunk and Proximal Posterior Tibial and Peroneal Artery Exposure

Anatomy

The tibioperoneal (TP) trunk and proximal posterior tibial and peroneal arteries are found in the deep posterior compartment underneath the soleus muscle. The dissection commences with exposure of the below-knee popliteal artery from the medial aspect of the leg. Once the distal popliteal artery has been identified, the tip of a finger or the end of a right-angled clamp can be used to enter the potential space where the artery crosses beneath the soleus muscle, using cautery to divide the soleus about a finger's breadth posterior to where it attaches to the tibia. Starting the dissection is the most difficult part, since large veins can be encountered; these must be carefully ligated or suture-ligated. Once the soleus has been divided, the arteries are usually easily identified. The TP trunk is often found posterior to its corresponding vein, which must be mobilized to facilitate its exposure. The distal TP trunk bifurcates into the posterior tibial and peroneal arteries. The posterior tibial artery is more superficial and easily dissected free from its adjacent vein in this location. Dissection of the peroneal artery can be more difficult, since it lies more deeply as it turns laterally to run its typical course along the medial side of the fibula. Veins are often encountered in this area, which must be carefully ligated to avoid troublesome bleeding.

Posterior Tibial Artery Exposure

Exposure begins with an incision on the medial aspect of the calf about one or two fingers' breadth posterior to the edge of the tibia. Alternatively, the incision can be made through the base of the incision of the harvested great saphenous vein. Once the deep fascia has been incised, the soleus muscle will be encountered, which should be detached from the tibia using electrocautery to enter the deep posterior compartment. The posterior tibial vessels are then immediately encountered. The posterior tibial vein is usually slightly superior to the artery, whereas the posterior tibial nerve is usually posterior to both (Fig. 58.10). Crossing veins are often encountered and must be divided. The artery often has small side branches, which must be controlled. Soft arteries are easily controlled with vessel loops, while heavily calcified arteries are best controlled with a tourniquet after exsanguination of the lower leg.

Distal exposure of the posterior tibial artery beyond the lower edge of the soleus muscle is easily accomplished in most cases and is the preferred location for *in situ* femoral posterior tibial bypasses, since the vein harvest incision can be used to expose the artery as well. The artery is exposed through an incision made posterior to the tibia and anterior to the Achilles tendon (Fig. 58.11). Once the fascia has been incised, the artery and vein will be encountered in an investing layer of fatty tissue. A Doppler probe is useful for identifying the precise location of the artery in this location. Numerous crossing veins are almost always present; these should be divided to expose an adequate length of artery.

Peroneal Artery Exposure

Medial Exposure

Medial exposure of the peroneal artery is easily accomplished in its most proximal portion through the identical approach used for exposure of the TP trunk, as previously described. The artery is easily identified at the bifurcation of the TP trunk, and dissection continues along the anterior surface of the

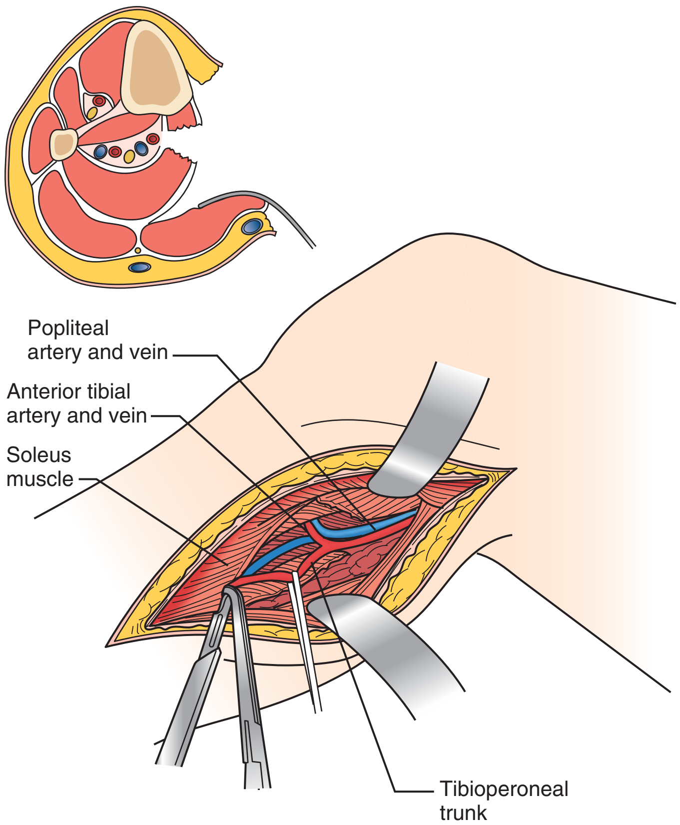


Figure 58.10 Exposure of the posterior tibial artery begins with an incision one to two fingers' breadth posterior to the edge of the tibia. The deep fascia is incised, and the soleus is detached from the tibia to enter the deep posterior compartment. The posterior tibial vessels are then encountered. (Figure 18.34 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:501.)

artery deep to the location of the posterior tibial artery and vein. The peroneal artery can also be exposed in its middle and distal portion through medial incision by detaching the soleus muscle from the tibia, as previously described. In general, a more lengthy incision should be used than is generally required for the posterior tibial artery due to the deep location of the peroneal artery, especially in individuals with large calf muscles. Once the posterior tibial neurovascular bundle has been identified, dissection is deepened either anterior or posterior to the posterior tibial structures (Fig. 58.12). Deepening the dissection anterior to the posterior tibial neurovascular bundle is probably the more traditional approach. This dissection can occasionally be quite tedious if there are numerous venous connections between the posterior tibial and peroneal veins. As one approaches the peroneal artery posterior to the posterior tibial neurovascular bundle there are fewer veins, but care must be taken to avoid injury to the peroneal nerve, which must also be retracted superiorly. Both approaches are useful in the authors' experience. The peroneal artery is first located by palpating the medial side of the fibula in the depths of the dissection. A continuous-wave Doppler probe can be used to identify the location of the artery more precisely. The peroneal vascular structures are often covered by muscular fibers of the flexor hallucis muscle, which may have to be divided to expose the artery and vein. Unfortunately the vein is often

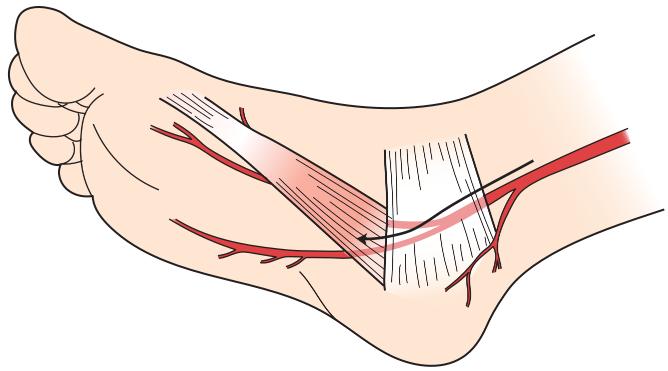


Figure 58.11 The distal posterior tibial artery is exposed through an incision posterior to the tibia and anterior to the Achilles tendon. After dividing the fascia, the posterior tibial artery and vein are identified in an investing layer of fatty tissue. (Figure 85 from Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposure*. Philadelphia: WB Saunders; 1993:166.)

encountered first and the artery is generally found behind the vein from this approach, which involves multiple small crossing venous branches. These must also be divided to expose the artery. Self-retaining retractors are a must during this exposure. The peroneal artery is often heavily calcified, which can make the creation of an anastomosis most challenging, particularly in its midportion in heavily muscled individuals. Tourniquet control can be very useful in this circumstance.

Lateral Exposure

Many vascular surgeons prefer to approach the peroneal artery from the lateral side of the calf to avoid the often difficult and challenging dissection required from the medial approach. A longitudinal incision is placed directly over the fibula. Once the fibula has been exposed, a periosteal elevator is used to free its muscular attachments on all surfaces. Careful dissection is important in freeing posterior attachments to the fibula to avoid injury to the underlying peroneal vein. Once the appropriate length of fibula has been dissected free of soft tissue, it can be divided with a rib shear or double-action bone cutter. Some authors recommend drilling small holes in the fibula to avoid shattering it. Alternatively, a small oscillating power saw can be used (authors' preference). Once the bone segment has been removed, the underlying fascia is incised longitudinally. The artery is then encountered superficial to the vein and dissected free with minimal difficulty (Fig. 58.13). This approach is particularly useful when exposing the peroneal artery in the distal half of the lower leg. Grafts can be tunneled subcutaneously and laterally as previously described for the anterior tibial artery or medially through the rent in the interosseous membrane created by removal of the fibula.

EXPOSURE OF THE ARTERIES OF THE FOOT

Distal anterior tibial and posterior tibial artery exposures are essential for distal bypass targets, especially in patients with diabetes. They are also useful for thrombectomy in cases of

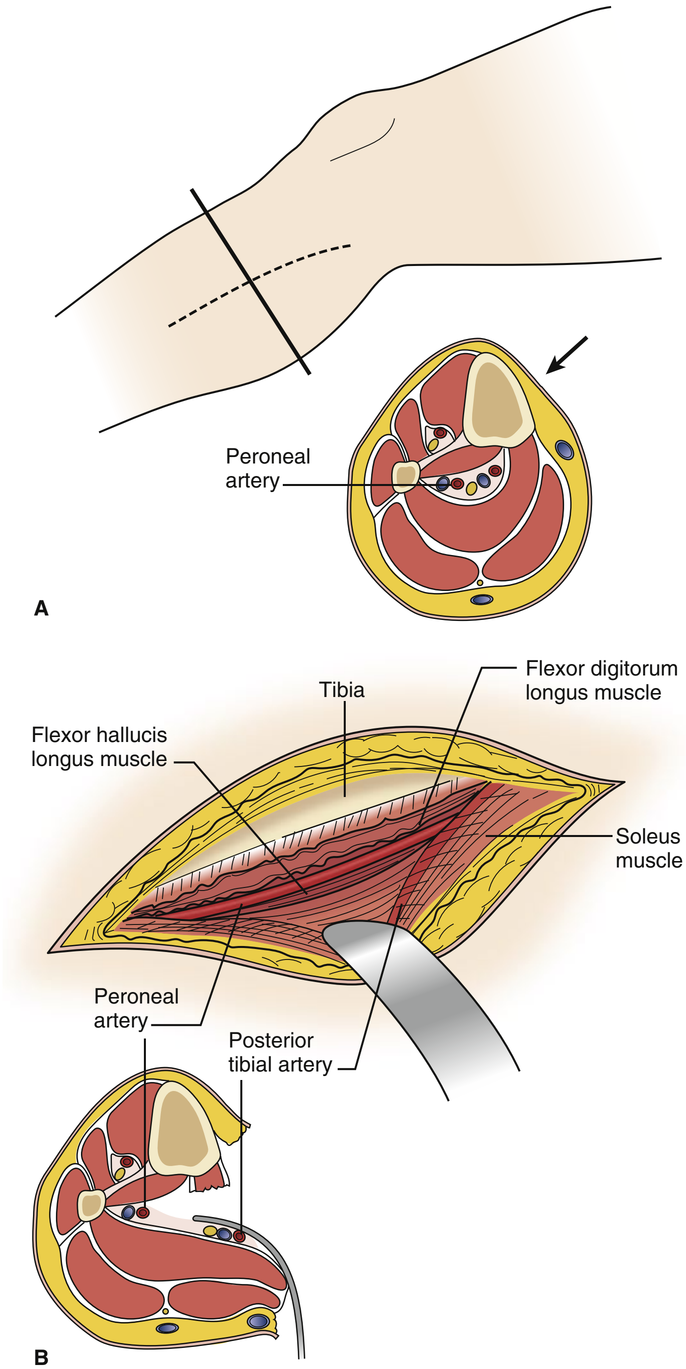


Figure 58.12 **(A)** Anatomical relationships. **(B)** The proximal and mid-peroneal artery can be exposed through a medial incision as previously described for the posterior tibial artery. The posterior tibial neurovascular bundle is identified, and the dissection is performed anterior or posterior to the posterior tibial vessels and peroneal nerve. The peroneal artery is located deep in the incision in close proximity to the medial side of the fibula, which is a useful landmark. (B, Figure 18.46 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:513.)

acute limb ischemia, and access for complex hybrid open and endovascular revascularization.

Exposure of the pedal arteries is generally straightforward due to their superficial location. However, their small caliber, often being calcified, and requiring long venous conduits, can make for a challenging procedure that is lengthy, tedious, and unforgiving. Fortunately, when these procedures are performed well, the rates of graft patency and limb salvage are comparable to more proximal reconstructions.[11] Although both the dorsalis pedis and posterior tibial arteries and their branches are suitable targets for bypass, in the authors' experience the dorsalis pedis arterial segment is more commonly spared of significant disease. Unlike the tibial and peroneal arteries, the vessels of the foot taper significantly as they run their course. Consequently, it is advantageous to place the anastomosis as proximal as possible on the target artery. The dorsalis pedis and inframalleolar posterior tibial artery segments are connected through anastomoses of the tarsal and plantar arches of the distal foot. Successful bypass to either will often result in the healing of lesions even in angiosomes typically supplied by the other artery.

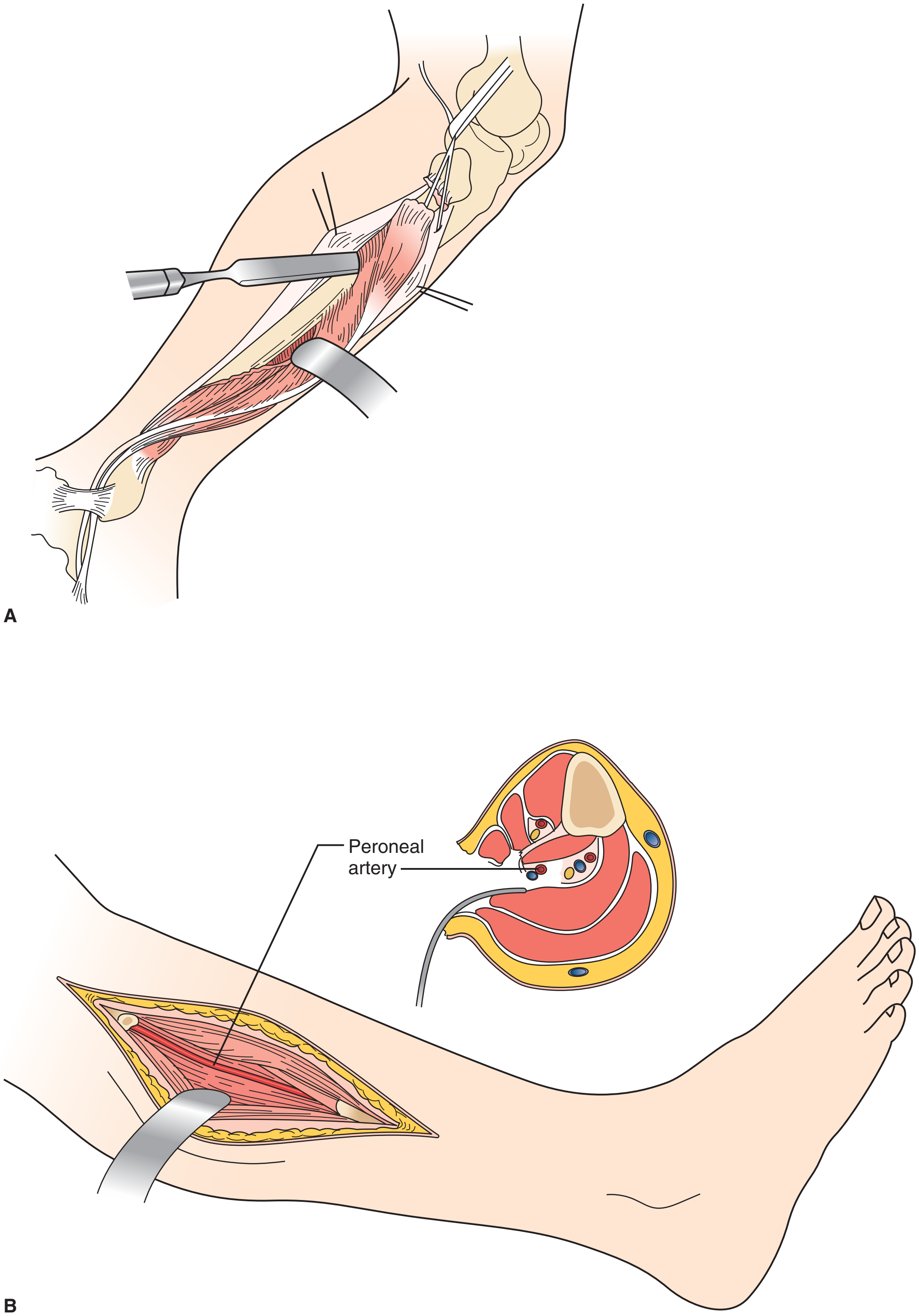
The anterior tibial (AT) artery runs along the lateral border of the extensor hallucis longus muscle and passes beneath the inferior extensor retinaculum to become the dorsalis pedis artery, which runs parallel and immediately lateral to the extensor hallucis longus tendon between the first and second metatarsals. It gives off a deep plantar branch between the heads of the first interosseous muscles, connecting with the lateral plantar branch of the posterior tibial artery and forming the plantar arterial arch. The posterior tibial artery is found between the flexor digitorum longus and the flexor hallucis longus muscles and enters the foot after coursing beneath the flexor retinaculum. It travels in a neurovascular bundle with the tibial nerve and accompanying veins. It subsequently divides into medial and lateral plantar arteries, terminating in the anastomotic loop created by the tarsal and plantar arches, as previously described.

In contrast to open bypass, AT and PT access for retrograde endovascular intervention is best achieved at the supramalleolar posterior tibial artery and proximal to the flexor retinaculum that encompasses the anterior tibial artery. Distally, as described above, the arteries taper, making access more difficult. Furthermore, the medial malleolus and dorsal aspect of the foot increases wire angulation creating poor ergonomi and increasing difficulty. In select cases, open exposure is preferable over percutaneous retrograde access, and the typical 4 French site can be closed with a single 7-O polypropylene suture.

These areas of access are also the authors' preferred cut down sites for Fogarty embolectomy in the setting of calf and foot thrombosis rather than the below-knee popliteal artery. Access of the distal AT and PT allow for passage of a 2 French Fogarty embolectomy balloon proximally to the popliteal artery, and distally through the pedal arch, with less risk of further embolization to the foot and avoids popliteal fossa hematoma in an anticoagulated patient. The transverse arteriotomy is easily controlled using vessel loops and closed with interrupted 7-0 polypropylene suture.

Dorsalis Pedis Artery Exposure

The dorsalis pedis (DP) artery is found on the dorsum of the foot as the continuation of the AT artery once it crosses under the inferior extensor retinaculum of the ankle.[12] The foot



A

B

Figure 58.13 The lateral approach to the peroneal artery is especially useful in the distal half of the lower leg. (**A**) The incision is made directly over the fibula, and the muscular attachments are divided on all sides using a periosteal elevator. (**B**) A segment of fibula is removed, and the underlying fascia is incised to reveal the peroneal artery and vein. (Figures 18.48 and 18.49 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:515 and 516.)

should be supported in a relaxed position with the operating table in reverse Trendelenburg position. Very small Weitlaner retractors are very useful. Both good lighting and the use of magnification with surgical loupes are essential. A longitudinal incision should be placed directly over the DP just distal to the retinaculum. When the DP has an audible Doppler signal, its precise course can be marked on the foot prior to making the incision. When no signal is present, the incision should be placed parallel and immediately lateral to the extensor hallucis longus tendon. The location of the artery can also be mapped by duplex ultrasound when preoperative vein mapping is performed. This allows direct access to the artery without creating skins flaps. The dorsal branch of the peroneal nerve is often encountered and can be retracted or divided with no consequence. The artery and its corresponding vein lie under a layer of deep fascia and are often palpable and visible. The length of the DP is variable; it bifurcates into the medial and lateral tarsal arteries, which should both be preserved. Small side branches are always present and should also be preserved. If the artery is heavily calcified, the segment under the retinaculum is often found to be softer due to flexion of the ankle; it is a good place for proximal control.

Inframalleolar Posterior Tibial and Plantar Artery Exposure

The patient's knee should be slightly flexed with the foot elevated on towels or a pad behind the lateral malleolus. This will widen the space between the calcaneus and the medial malleolus, aiding in exposure. A curvilinear skin incision is made between the medial malleolus and the calcaneus, deepening the tissue down to the flexor retinaculum. Marking the course of the artery with a Doppler prior to making an incision is helpful. An investing layer of fat is encountered that occasionally contains small veins; these should be divided and ligated. The artery is invariably calcified and easily palpable beneath the deep fascia, which is incised to expose the distal PT, which is bound by the flexor digitorum longus superiorly and the flexor hallucis inferiorly. The artery is dissected distally until its bifurcation into the medial and lateral plantar arteries. Crossing veins are often present. The calcaneal branch of the PT should always be preserved. The abductor hallucis is then divided for additional exposure of the lateral plantar artery.[13,14]

EXPOSURE FOR OBTURATOR BYPASS

The obturator bypass is most commonly used to treat a severe arterial infection involving the CFA.[15,16] The inflow artery is typically the common or external iliac artery, which is exposed through a retroperitoneal approach. The obturator foramen is exposed through this same retroperitoneal approach. The dissection is performed medial to external iliac vein and posterior to the pubic ramus. The obturator internus muscle is then bluntly dissected to reveal the obturator membrane. Grafts should be tunneled through the anterior medial portion of the membrane to avoid injury to the obturator artery and nerve, which pass through its posterior lateral portion.

The distal target of the obturator bypass is the popliteal or distal SFA. The tunnel between the inflow and target arteries is made in the medial compartment of the thigh in the space between the adductor longus and brevis muscles anteriorly and the adductor magnus muscle posteriorly, which leads directly to the obturator foramen. The SFA is easily identified and controlled in the plane of the tunnel anterior to the adductor magnus muscle (Fig. 58.14). If the popliteal artery is the target, the graft must be either tunneled through the adductor hiatus or brought around the adductor tendon. The proximal and distal anastomoses are then performed in the standard fashion. After completion of the bypass, the surgical incisions are closed and excluded before the groin is explored to remove any infected prosthetic or native material in order to prevent contamination of the obturator bypass.

EXPOSURE OF THE LOWER EXTREMITY VEINS

Great Saphenous Vein

Anatomy

The great saphenous vein arises from the medial aspect of the dorsal pedal venous arch and ascends anterior to the medial malleolus, crossing the tibia at the junction of the distal and middle third of the calf to pass posteromedial to femoral condyle at the knee. The vein then ascends medially in the thigh, remaining parallel to the medial edge of the sartorius muscle. It then perforates the deep fascia and joins the common femoral vein approximately 4 cm below the inguinal ligament. The saphenous nerve lies anterior to the great saphenous vein in the calf and may be injured by procedures extended into the calf. The great saphenous vein usually lies directly on the muscular fascia in the saphenous compartment, a subcompartment of the superficial compartment that is bordered superficially by the saphenous fascia and deeply by the muscular fascia. This compartment is readily visualized in the thigh with ultrasound.

Exposure of the Great Saphenous Vein

If the upper portion of the great saphenous vein is to be used for bypass, the vein harvest typically begins in the groin. A 30- to 45-degree oblique incision is made starting at the femoral pulse at the groin crease. Preoperative evaluation of the saphenous vein with duplex ultrasonography and skin marking of its location may help in better placing the incision. Care must be taken to ensure the ultrasound probe, and incision, are perpendicular to the skin when marking its course and ultimately harvesting the vein, as parallax can lead to large skin flaps, increasing wound infection rates. It may also help to identify any issues with the quality of the vein preoperatively. The skin is incised sharply and the subcutaneous tissue is divided with electrocautery. The skin incision can be performed with either a continuous technique or using skip incisions based on the surgeon's preference. Comparison of vein harvest techniques using skip incisions versus continuous incisions from the Vascular Quality Initiative shows no difference in the rates of surgical site infection or in graft patency at 1 year.[17] Once the vein has been identified, the anterior aspect is dissected sharply with Metzenbaum scissors and the subcutaneous tissue is undermined distally over the vein. The skin and subcutaneous tissue are then divided over an instrument superior to the vein. This process is continued until sufficient length of the great saphenous vein is exposed. The authors prefer a modified no-touch technique to remove the vein. The vein is first encircled with a vessel loop to apply gentle countertraction as sharp dissection at a slight distance from the adventitia is used to separate it from adjacent tissues. The vein is not grasped

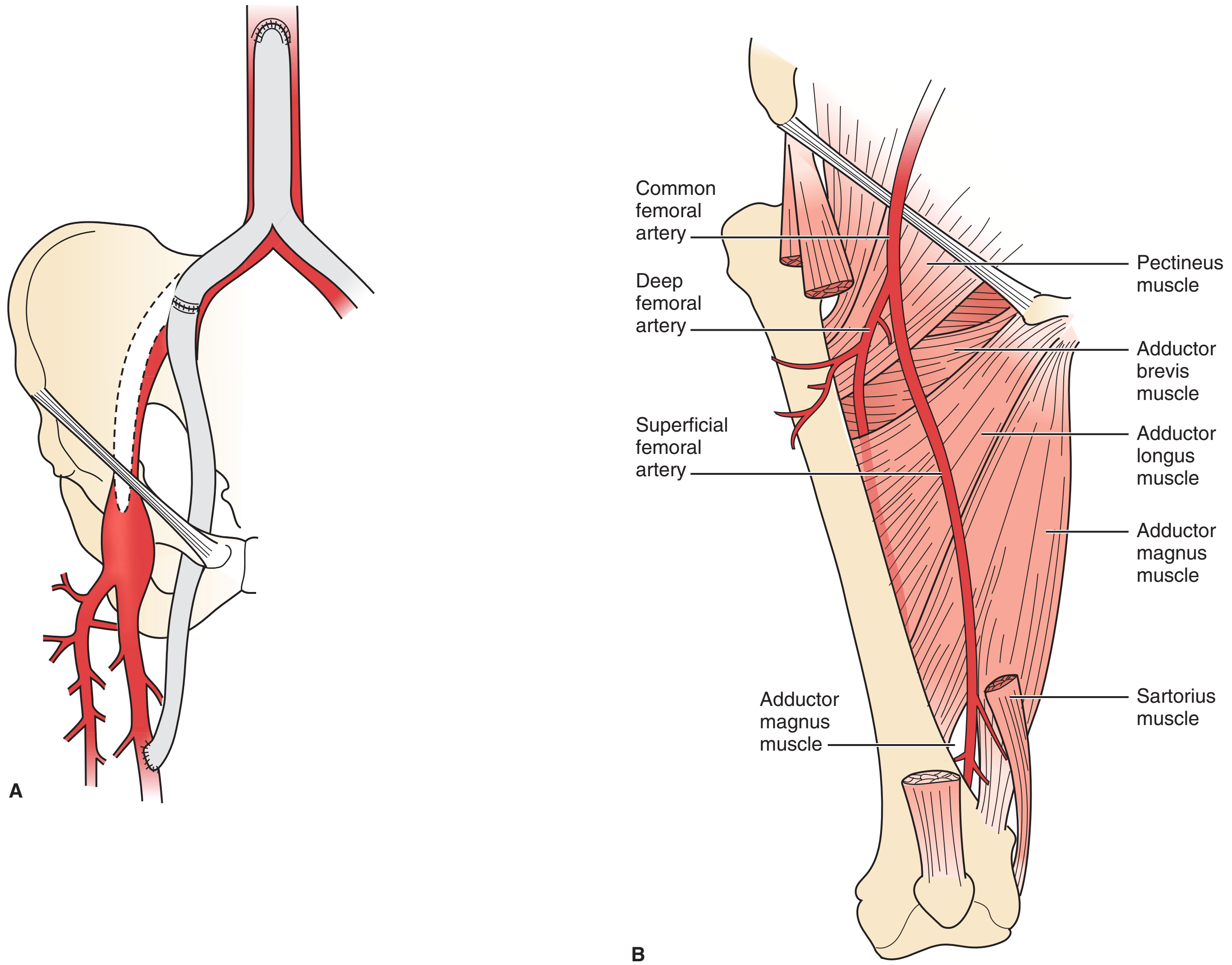


Figure 58.14 (**A**) The obturator bypass is tunneled through the obturator foramen via a retroperitoneal approach. Dissection is performed medial to the external iliac vein and posterior to the pubic ramus. The obturator foramen is identified by bluntly dissecting the obturator internus muscle. The tunnel is made through the anterior medial portion of the membrane to avoid the obturator artery and nerve. (**B**) The tunnel through the obturator foramen leads into the medial compartment of the thigh anterior to the adductor magnus muscle, where the superficial femoral artery is easily identified. (A, Figure 35.3 from Chaikof EL, Cambria RP. *Atlas of Vascular Surgery and Endovascular Therapy: Anatomy and Technique*. Philadelphia: Elsevier Saunders; 2014:431. B, Figure 16.8 from Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003:418.)

with forceps to minimize the potential for injury to the intima. Branches are ligated with silk ties. The vein is not removed until all arterial dissections and tunnels are completed in order to minimize ischemic time. The distal vein is divided first and gently dilated with a mixture of heparinized saline and papaverine instilled with an olive-tip needle to distend the vein gently and identify any untied branches. The proximal aspect of the vein is then clamped at the saphenofemoral junction, often with a 1 mm cuff of common femoral vein, which makes a large hood when the vein is used in nonreversed fashion (our most common configuration). Valve lysis is done with a Mills valvulotome under direct imaging with an angioscope. If the vein from the lower leg is to be used, the incision is made just anterior to the medial malleolus and the dissection is continued proximally as described earlier.

An alternative to open saphenectomy is endovascular saphenous vein harvest. In most cases, this is performed by an experienced operating room technician beginning distally in the lower leg and working toward the saphenofemoral junction. This modality decreases wound infection rates, and while some single-center studies have shown non-inferiority,[18] the majority of literature demonstrates compromised long-term graft patency.[19,20]

Small Saphenous Vein

Anatomy

The small saphenous vein arises from the dorsal pedal arch and ascends posterolaterally from behind the lateral malleolus to a variable termination in the popliteal vein. The small saphenous vein usually has 7 to 10 valves, which are closely spaced along its length. The sural nerve ascends immediately lateral to the vein, beneath the muscular fascia prior to its junction with the popliteal vein. Approximately 75% of small saphenous veins join the popliteal vein, while as many as 25% ascend more proximally into the thigh, with no connection to the popliteal vein.[21] Recognition of this anatomic variant is important in harvesting the vein for bypass. The proximal extension of the small saphenous vein, often referred to as the vein of Giacomini,[22] may ascend in the posterior thigh to communicate with the great saphenous vein through the circumflex vein of the posterior thigh.

Exposure of the Small Saphenous Vein

The small saphenous vein harvest is begun in the lower leg with a vertical incision just posterior to the lateral malleolus. The authors will typically use ultrasound preoperatively just prior to the procedure to mark the location of the vein and facilitate its identification. Dissection of the vein is performed with the modified no-touch technique, as outlined previously. The distal vein is clamped and divided, and the vein is distended as described. The saphenopopliteal junction is then clamped and oversewn and the vein is prepared in a reversed or non-reversed fashion per surgeon preference.

Femoral Vein of the Thigh

Anatomy

The femoral vein of the thigh (referred to as the *femoral vein* in the following section) is an excellent conduit for arterial reconstruction. Due to its sturdy structure and large caliber, it is commonly used for reconstruction after removal of infected prosthetic grafts of the abdominal aorta or iliac and common femoral arteries. It is the authors' preferred conduit for abdominal oncologic reconstructions, and may also be used in venous reconstruction procedures (see Ch. 195, Vascular Reconstruction in Oncologic Surgery). The deep venous system of the leg is made up of the paired tibial and peroneal veins, the popliteal vein, the femoral vein of the thigh, the deep femoral vein, and the common femoral vein.[1] After passing through the adductor canal, the popliteal vein becomes the femoral vein, lying posterior and lateral to the artery. The vein is generally large in caliber and quite sturdy, making an excellent conduit where a larger-caliber graft than the typical saphenous vein is required. Harvesting of the femoral vein can be a tedious exercise in some patients owing to its typical location somewhat posterior to the SFA and the multiple crossing branches of the SFA that are usually encountered. The femoral vein and the deep femoral vein join together to form the common femoral vein approximately 4 to 12 cm below the inguinal ligament. The deep femoral vein is a critical collateral pathway that must be preserved in harvesting the femoral vein to avoid the significant lower leg edema, which would occur if it were removed.

Harvest Technique

The patient is positioned with a bump under the knee to facilitate external rotation at the hip with a flexed knee. A longitudinal incision is then made in the thigh along the border of the sartorius muscle. The sartorius muscle is then reflected laterally and the fascia overlying the abductors is incised to expose the SFA and femoral vein. Branches of the SFA are often encountered, which may cross over the femoral vein and can be divided. Distal SFA branches are best preserved if the popliteal artery is occluded, as these are important collaterals around the knee. Branches of the femoral vein are relatively large and should be either doubly ligated or suture-ligated to avoid bleeding when pressurized with arterial blood flow. Proximally, the junction of the femoral vein and deep femoral vein should always be fully exposed. When removing the femoral vein of the thigh, it is critical to preserve the deep femoral vein to prevent severe leg swelling. The femoral vein should be transected at its junction with the common femoral vein and the resulting defect closed with a running continuous polypropylene suture in a manner to both preserve the inflow of the deep femoral vein while not leaving a proximal stump of the femoral vein, which may result in thrombus formation. The distal end of the remaining vein should be suture-ligated or oversewn. The harvested femoral vein can then be used in a reversed orientation or the valves can be cut with a valvulotome to facilitate its use in a nonreversed orientation. A closed-suction subfascial drain is left at the harvest site, as the area is prone to seroma formation. The fascia is then reapproximated using a running technique followed by the subcutaneous tissue and the skin.[23]

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Rutherford RB. *Atlas of Vascular Surgery*. Philadelphia: W.B. Saunders; 1993.

This classic atlas takes a "how to do it" approach to the surgical exposures used throughout the circulatory system in vascular surgery. The text is written in Dr. Rutherford's typically clear and concise style and contains many personal observations based on his enormous clinical experience. The illustrations are well drawn and accurate, including many highly useful cross-sectional depictions of the anatomic relationships between the blood vessels and adjacent structures in the lower extremity.

Valentine JR, Wind GG. *Anatomic Exposures in Vascular Surgery*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003.

Created by an expert vascular surgeon and anatomist, this well-written text contains a level of anatomic detail not often seen in surgical atlases and provides a unique perspective on the surgical anatomy of the lower extremity circulation. The late Charles Rob said it best in his Foreword: "The illustrations are the strong part of this excellent book." They are beautifully done with a three-dimensional quality that depicts the anatomy from the perspective of the surgeon. It should be required reading for all vascular surgical trainees.

A complete reference list can be found online at www.expertconsult.com.

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59 CHAPTER

Upper Extremity Vascular Exposure

KARL A. ILLIG

INTRODUCTION

Vascular surgeons who treat thoracic outlet syndrome and perform arteriovenous (AV) access obviously regularly operate in the upper extremities, but expeditious and safe upper extremity exposure is required for the treatment of trauma, complex aortic endograft repair of aortic diseases, and many other conditions.

For purposes of planning exposure, it is convenient to divide the relevant upper extremity vessels into three zones (Fig. 59.1). The intrathoracic zone contains the aortic arch, innominate artery, subclavian arteries on both sides, innominate veins, and superior vena cava. The importance of this classification is that exposure, although straightforward, requires more time than in the limb (see Ch. 55, Thoracic and Thoracoabdominal Vascular Exposure). The sternum must be divided or the thorax opened. Therefore, in trauma cases, because it takes more time to expose the arteries, planning ahead and perhaps a more conservative and safer approach for proximal control should be considered. For venous reconstruction, although usually less emergent, somewhat complex exposure strategies are likewise needed. The next zone is essentially the thoracic outlet, extending from the base of the neck to the axilla, which contains the subclavian, proximal vertebral, and proximal axillary arteries and veins. This area contains critical nerves, which must be preserved, and the clavicle and to a lesser extent deltoid muscle can block access to certain parts of the vessels. Finally, the third zone is the arm itself, extending from the axilla to the fingers. Vascular exposure in the arm is usually much more straightforward, especially if the operative field is sufficiently distal so that a tourniquet may be used.

EXPOSURE OF ARTERIES WITHIN THE THORAX

In patients with normal anatomy, the first branch of the aortic arch after the coronary arteries is the innominate artery, which then bifurcates into the right subclavian and right common carotid arteries. Approximately 13% of patients have a “bovine arch,” somewhat inaccurately but commonly used to describe the situation where the left common carotid artery arises from the innominate itself or a common ostium; in most patients the left common carotid artery is the next separate branch from the arch, followed by the left subclavian artery. There are two critical variants. The first is an aberrant right subclavian artery. This situation, occurring in up to 2% of patients, is variable but most typically creates a situation where the innominate artery simply becomes the right common carotid artery, and the right subclavian artery arises as the last branch (usually from the descending aorta, now on the left side), passing behind the esophagus to supply the right arm. Although often asymptomatic, this abnormal artery is sometimes associated with aneurysmal degeneration (diverticulum of Kommerell) and/or can produce dysphagia via a mass effect (dysphagia lusoria) (see Ch. 78, Thoracic and Thoracoabdominal Aortic Aneurysms: Etiology, Epidemiology, Natural History, Medical Management, and Decision Making). A second important variant is origination of the left vertebral artery from the aortic arch, occurring in 2%–5% of patients. Although this should specifically be identified ahead of time if direct intervention on this vessel is planned,

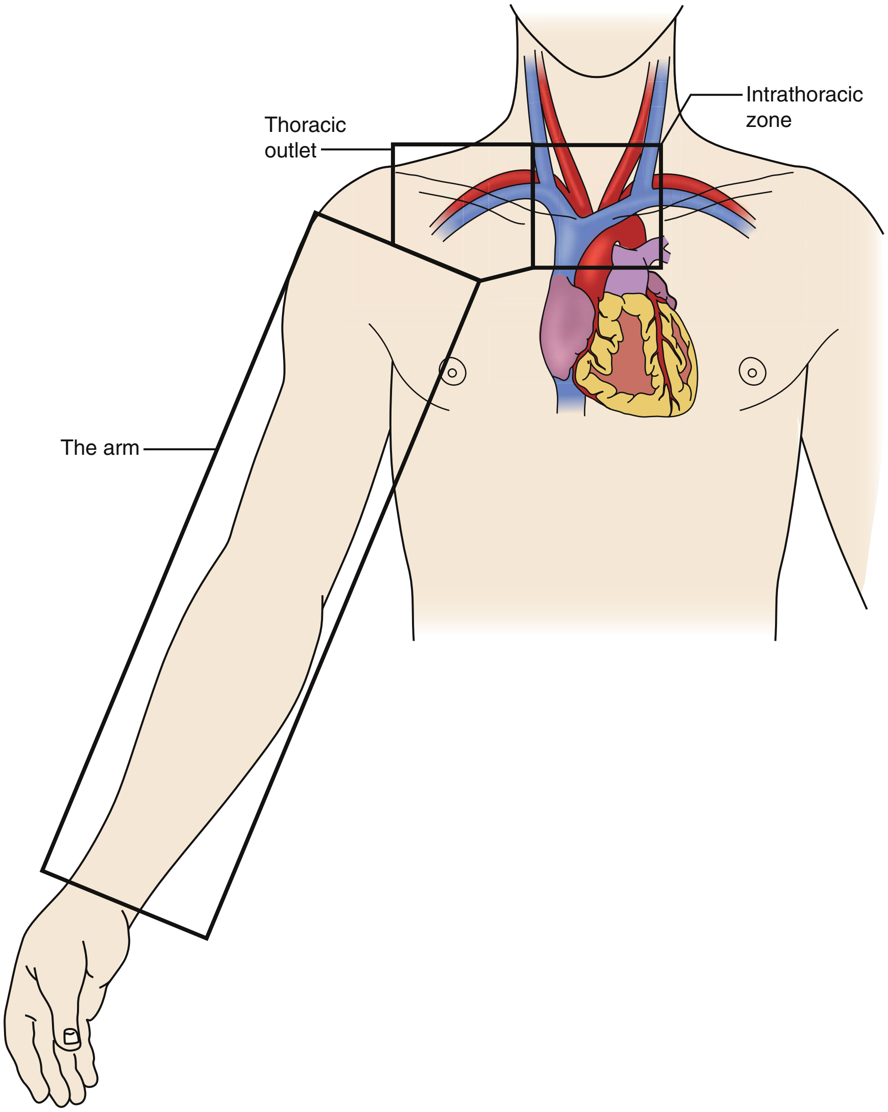

Figure 59.1 The chest and arms (right-side shown) illustrating the three general zones described. The intrathoracic vessels almost always require bony division, hence more thorough preplanning. The vessels in the thoracic outlet are easier to expose, but technical challenges exist. Finally, the vessels of the arm are relatively straightforward to expose.

its major significance lies in planning thoracic endovascular aneurysm repair, to avoid covering this vessel inadvertently.[1,2]

As described previously, especially with regard to trauma, control of intrathoracic vessels takes more time than elsewhere, and thus a slightly more conservative approach may be considered. Exposure of most extremity vessel injuries directly is straightforward because proximal control is not difficult, although if a supraclavicular injury occurs that is constrained, proximal control may not be possible at the site of injury itself. Although endovascular approaches can be used, surgical control will take much longer than in the arm itself. The implication of this is that if there is any question that control may be needed within the thorax (again, classically an injury to the subclavian artery with a supraclavicular hematoma), it is prudent to obtain this control first, before the injury is approached directly.

Exposure of the arch and proximal great vessels is required for debranching, aortosubclavian and carotid bypass for atherosclerosis or Takayasu arteritis, or occasionally complex AV access and in some trauma cases. In general, exposure of the innominate, proximal right subclavian, and proximal left carotid arteries should always be performed by means of median sternotomy. The proximal left subclavian artery can be reached via median sternotomy, although not quickly, so if such exposure is needed urgently an anterolateral third interspace thoracotomy is the preferred approach.

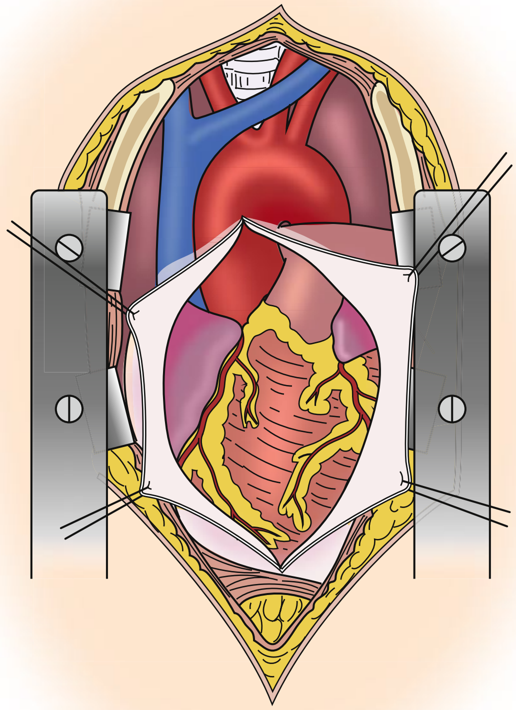

Figure 59.2 Open median sternotomy with arch vessel exposure.

Innominate, Right Subclavian, and Left Common Carotid Arteries, and Proximal Left Subclavian Artery: Elective Situation

Median sternotomy provides superb exposure to these vessels, as well as to the ascending aorta. If the aorta does not need to be used, the sternotomy can be limited to the third interspace (Fig. 59.2). Following sternotomy, the anatomy will be very well delineated. The left innominate vein is superficial and should be preserved but can be sacrificed in an emergency. Two nerves are critical to protect. The right recurrent laryngeal nerve loops around the right subclavian artery just as it arises from the innominate artery, and the phrenic nerve passes behind the jugular and right innominate vein and anterior to the right subclavian artery and anterolateral to the innominate artery. Both should be easy to identify, but both can be in jeopardy if indiscriminate circumferential dissection of the vessels is carried out without caution.

After teasing away fatty tissue and mobilization and retraction of the overlying veins, this approach yields ideal exposure to the orifice of the innominate and left common carotid arteries, the proximal portions of these arteries themselves, and, by extending the incision onto either side of the neck or the right supraclavicular area, the rest of both common carotid arteries and the right subclavian artery into the thoracic outlet, respectively (Fig. 59.3). Exposure of the subclavian arteries will be limited by the sternocleidomastoid muscles (which can be partially divided, but ideally not fully transected) and anterior scalene muscle which can be fully divided (see later), but the vertebral arteries usually arise proximal to this and this approach can be excellent for proximal vertebral exposure. Finally, with further dissection, the proximal portion of the left subclavian artery (and left vertebral artery, if normal) can be reached through this incision. Again, caution should be taken with regard to the left recurrent laryngeal nerve; after looping around the aorta in the region of the ligamentum arteriosum, it ascends anterior to the arteries and can be within the surgical field.

Left Subclavian Artery: Emergent Situation

In emergent situations (trauma with active bleeding) a more immediate need for proximal control may be present. In this situation an anterolateral limited third space thoracotomy,

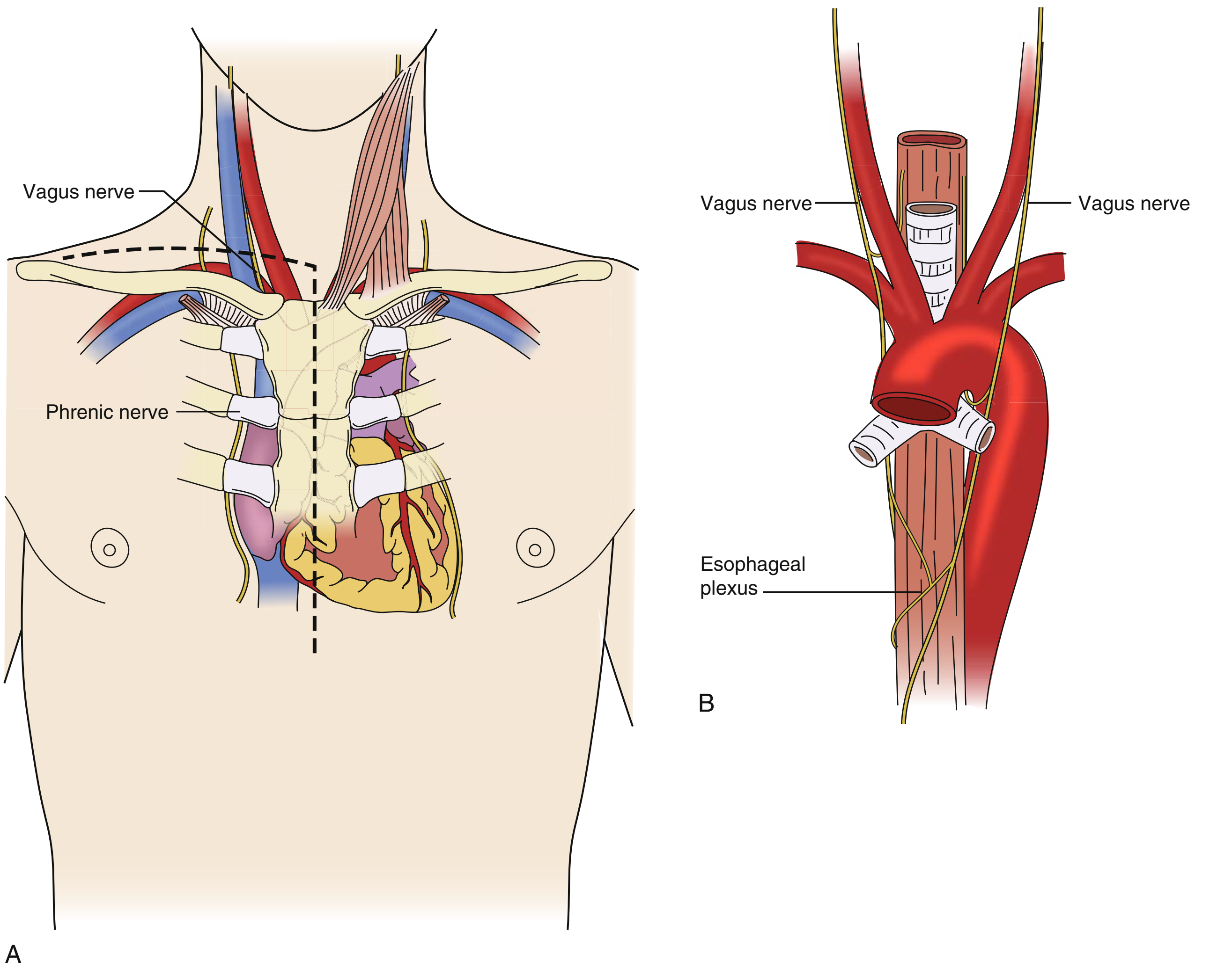

Figure 59.3 Median sternotomy extended to the (right) side, for better exposure of the innominate vessels, proximal subclavian artery and vein, and jugular vein. The sternocleidomastoid muscle can be divided in an emergency but is probably better left intact if possible (**A**). Note that the phrenic and vagus nerves both pass anterior to the arteries and posterior to the veins; both should be preserved (**B**).

with the patient supine, allows expeditious proximal left subclavian artery control (Fig. 59.4). This approach usually does not permit extensive repair or other work in this area, but once bleeding has been controlled, definitive wide exposure can be obtained. When third space sternotomy and a supraclavicular incision is combined with the thoracotomy, this is termed a "trap-door" exposure (Fig. 59.5).

EXPOSURE OF VEINS WITHIN THE THORAX

Traumatic venous injuries are very often associated with concomitant arterial injury, and the previously described exposure concepts apply. Exposure of the superior vena cava requires formal sternotomy. However, other techniques can be used for exposure of the central (medial) portion of the subclavian vein as it joins the jugular vein and/or the innominate veins on either side and are useful adjuncts in the treatment of venous thoracic outlet syndrome. The venous thoracic outlet is essentially the junction of the clavicle and sternum anteriorly, with the subclavius muscle and tendon and the ligamentous structures attaching the two bones playing a major role in venous obstruction. Over time these structures, especially in those who are muscular and/or participate in activities with arms overhead, can chronically injure the vein in this location. The decision to reconstruct this area is complex and exposure is critical. The injury to the vein is usually fairly central, and it is sometimes difficult to get sufficiently central enough (defined as normal endothelium) from an infraclavicular approach. Molina has described an excellent technique for exposure of either innominate vein to the level of the cava.[3] The patient is supine, and the first rib is resected using either an infraclavicular or paraclavicular approach. At this point a first interspace median sternotomy is performed (Fig. 59.6A). After the deeper tissues have been incised, the entire sternoclavicular complex (leaving

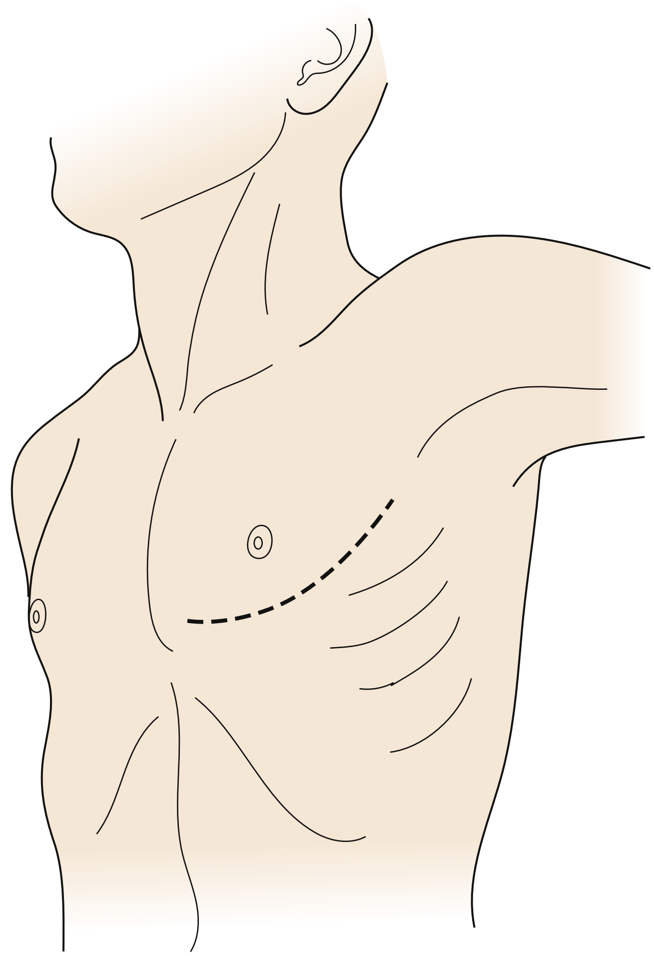

Figure 59.4 Left third interspace thoracotomy is ideal for emergent exposure of the proximal left subclavian artery when a patient is in the supine position. Be aware that the vagus nerve is anterior to the proximal portion of the artery and, after looping around the aorta near the ligamentum arteriosum, the recurrent laryngeal posterior (not shown).

the sternoclavicular junction intact) is then rotated upward, which provides superb visualization of this area. Finally, after the operation is completed, the sternal fragment is reattached to the main portion of the bone, using two sternal wires oriented at right angles to each other (Fig. 59.6B).

Finally, although technically not a vein, the right atrial appendage can be used as outflow for complex venous occlusive disease (including patients with threatened AV access). This can be accessed fairly easily by means of a limited anterior third interspace thoracotomy (with the patient supine). The pericardial sac must be entered, but then the appendage is immediately accessible and easily clampable with a Satinsky-type clamp.[4]

EXPOSURE OF VESSELS WITHIN THE THORACIC OUTLET

The thoracic outlet broadly includes the neurovascular area from the scalene triangle to the axilla. This chapter considers arterial exposures from the point at which they pass beyond the sternum to the deltoid to lie within this area. Barring anomalies, the anatomy is symmetric on each side, making descriptions easier.

As described previously, exposure of the vessels from the arch to the supraclavicular fossa, including the proximal vertebral arteries, is best performed by means of limited sternotomy and supraclavicular extension of the incisions. Direct access to the subclavian arteries will be limited by the sternocleidomastoid muscle medially and the anterior scalene muscle deep to it, the latter forming the anterior border of the scalene triangle. Through this triangle run the brachial plexus and subclavian artery, with the artery passing over the top of the first rib (the base of the triangle) (Fig. 59.7).

Subclavian Arteries

De novo exposure in this area can most easily be performed by means of a supraclavicular incision (however, it should again be stressed that in traumatic situations when a supraclavicular hematoma [or suspected subclavian artery injury] is present, strong consideration should be made of conservative, proximal control as described previously). Such a supraclavicular incision can essentially be placed anywhere; we use a convenient skin crease for best cosmetic results. This approach, in addition to being used for carotid–subclavian bypass, is also commonly used for treatment of neurogenic and arterial thoracic outlet syndrome and has been very well described (see Ch. 124, Thoracic Outlet Syndrome: Neurogenic; and Ch. 125, Thoracic Outlet Syndrome: Arterial).[5] After division of the platysma and clavicular head of the sternocleidomastoid muscle, there is a fat pad of varying thickness, containing the omohyoid muscle. This should be divided and the fat pad teased superiorly or laterally. At this point the anterior scalene muscle will be exposed medially, with the phrenic nerve running in its characteristic (and unique) lateral to medial direction (Fig. 59.8). It is very important to identify and protect this nerve; complete injury can result in significant disability even for sedentary people. If it is not immediately visible, it should be looked for superficially directly anterior to the muscle or medially. If it is still not found, dissection of the muscle should be slow and careful because it may be intramuscular. Note that it is not uncommon to have bifid or duplicated nerves. The nerve can also be identified by first dissecting free the upper nerve roots (C5 and C6), then following them until the nerve is found.

Full division of the anterior scalene muscle is advised if carotid subclavian bypass is to be performed. Not all clinicians do this, and although we believe no data exist, essentially all failures we have treated are in patients whose muscle has been left intact (affecting both length and angles of the resultant bypass). This muscle should be divided as close as possible to the first rib then subtotally removed after the phrenic nerve is identified and protected; in theory, this prevents reattachment and scarring. After this is performed, the entire subclavian artery from beneath the sternocleidomastoid to the rib is nicely exposed. The vertebral arteries are more medial than one would expect. They generally lie beneath the SCM itself and can be reached by retracting this muscle. It should be noted

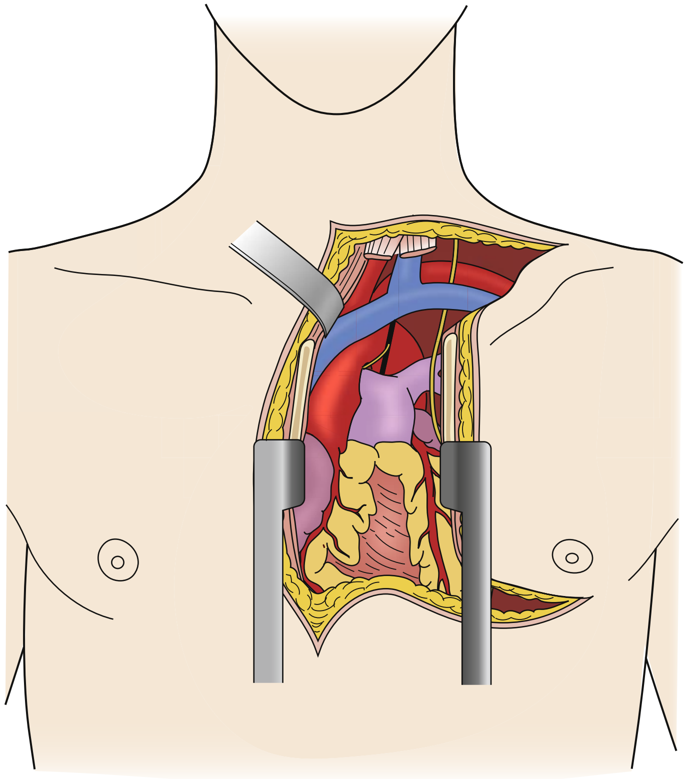

Figure 59.5 By adding median sternotomy and extending the incision to the left, the anterior thoracotomy is converted to a "trap-door" extension, nicely exposing the proximal left-sided great vessels. The sternocleidomastoid is divided in this figure.

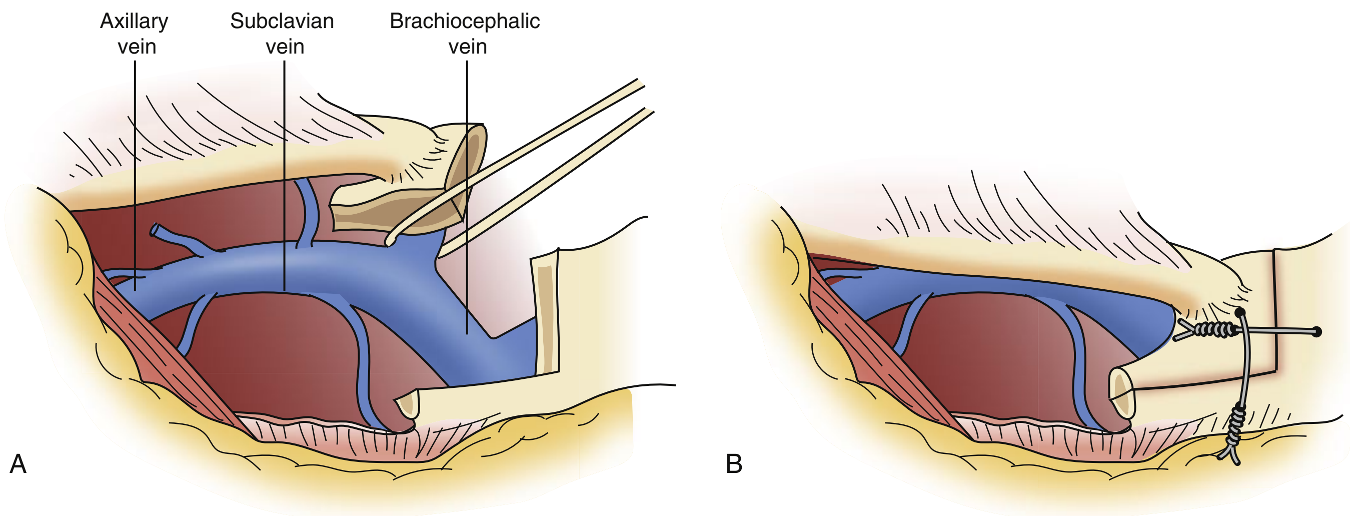

Figure 59.6 After anterior first rib resection, a first interspace sternotomy can be performed, leaving the sternoclavicular joint intact. (**A**) Initial exposure obtained by rotating this complex upward. (**B**) Repair using two perpendicularly oriented sternal wires. (From Molina JE. A new surgical approach to the subclavian and innominate veins. *J Vasc Surg*. 1998;27:576–581.)

that the clavicular head of the SCM can and may be sacrificed without consequence; in extenuating circumstances the entire muscle can be divided for full exposure from the sternum to the deltoid.

The subclavian arteries technically become the axillary arteries as they cross over the lateral border of the first ribs but obviously structurally are the same vessel. They arch over the first rib then pass beneath the clavicle, cephalad to the vein. The area underneath the clavicle itself is difficult to approach,

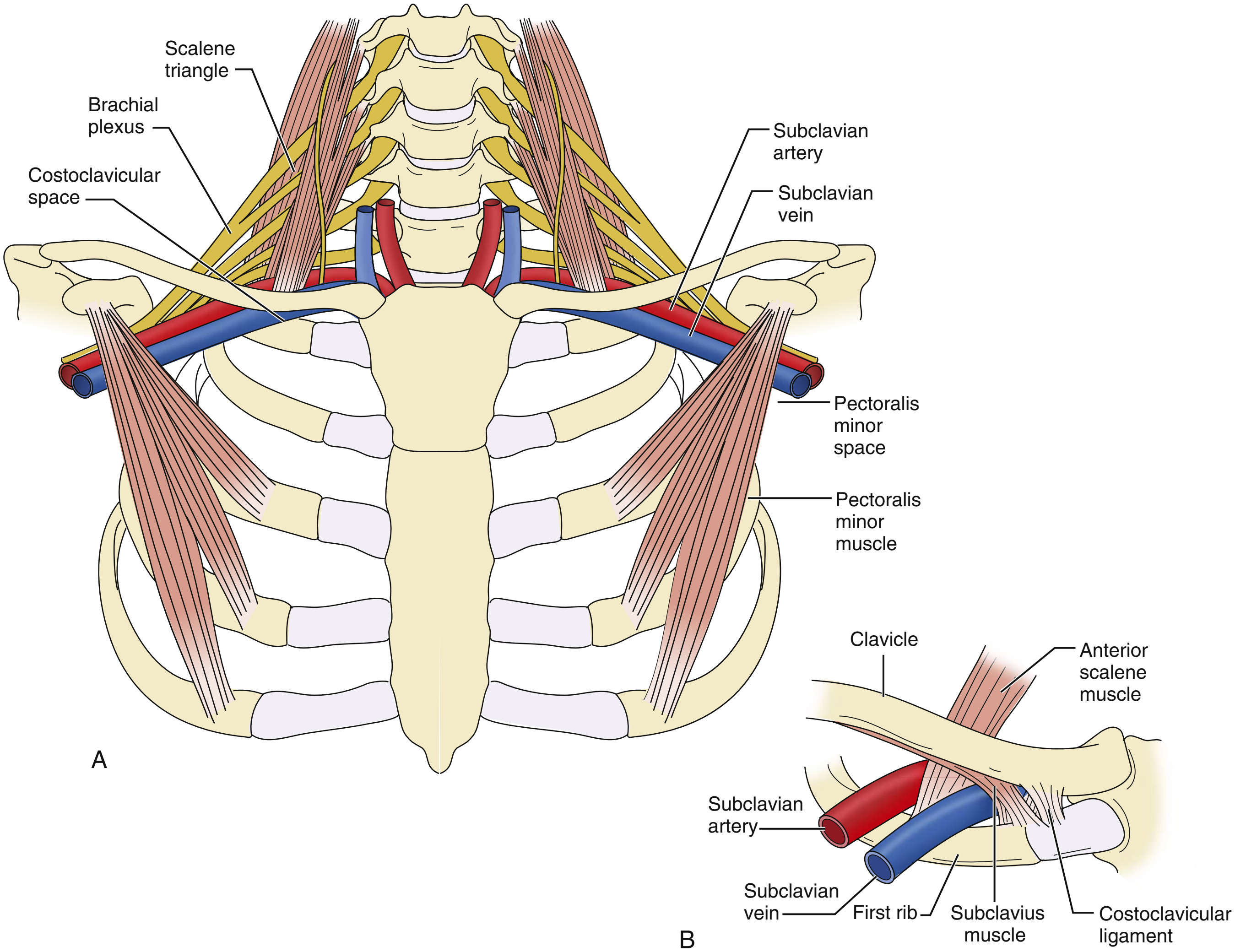

Figure 59.7 The Vessels and Nerves of the Thoracic Outlet. (**A**) Subclavian artery from its takeoff from the innominate to the pectoralis minor. The vertebral artery, internal mammary artery, and thyrocervical trunk arise proximal to the anterior scalene muscle; the latter two can be sacrificed. The phrenic nerve (and vagus nerve medially) runs anterior to the muscle (and thus artery) but behind the vein; this should not be sacrificed. (**B**) The anteromedial aspect of the thoracic outlet on the right side showing the subclavian vein running past the junction of the first rib and sternum, potentially compressed by the subclavius muscle, subclavius tendon, and fibrotic costoclavicular ligament.

although claviculectomy is very well tolerated[6] and will afford excellent and expeditious exposure of both artery and vein. The axillary artery is easily accessible inferior to the clavicle, although it lies cephalad to the vein and is not always immediately visible (Fig. 59.9). The optimal approach to vessels in this area depends upon the indication. If the problem is a subclavian/axillary artery aneurysm (usually secondary to a bony abnormality: arterial thoracic outlet syndrome), a paraclavicular approach with control of the subclavian artery above the clavicle and axillary artery below, as described, allows bypass with a wide-open tunnel after the cervical rib, Roos band, and/or first rib have been resected. Conversely, if the lesion needs to be addressed directly, the clavicle can be resected with minimal morbidity. For axillary artery exposure inferior to the clavicle for an axillofemoral bypass, most advocate exposure as medially as possible (first part of the axillary artery), with tunneling of the graft deep to the pectoralis minor muscle and a very gradually diverging end-to-side anastomosis, to reduce the risk of axillary pullout syndrome. Again, the pectoralis minor muscle can be resected with impunity to expose the second part of the artery, and, if arterial inflow for an AV graft is needed, this allows excellent exposure.

Subclavian Veins

The veins lie inferior (caudal) and superficial to the arteries and are most often exposed for treatment of venous TOS. Although supraclavicular exposure is occasionally used, in the vast majority of cases the veins are very difficult to adequately expose from this direction. In addition, they obviously continue inferior to the clavicle as they move laterally, so the author prefers an infraclavicular approach, usually

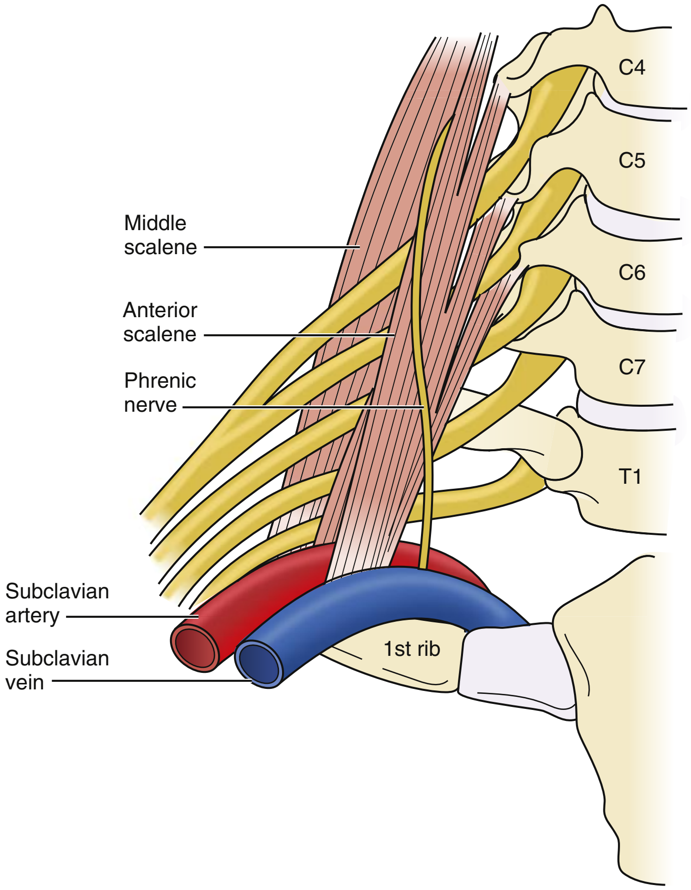

Figure 59.8 Anterior scalene muscle (right side) with phrenic nerve running lateral to medial as it descends (the only nerve in the body to do so).

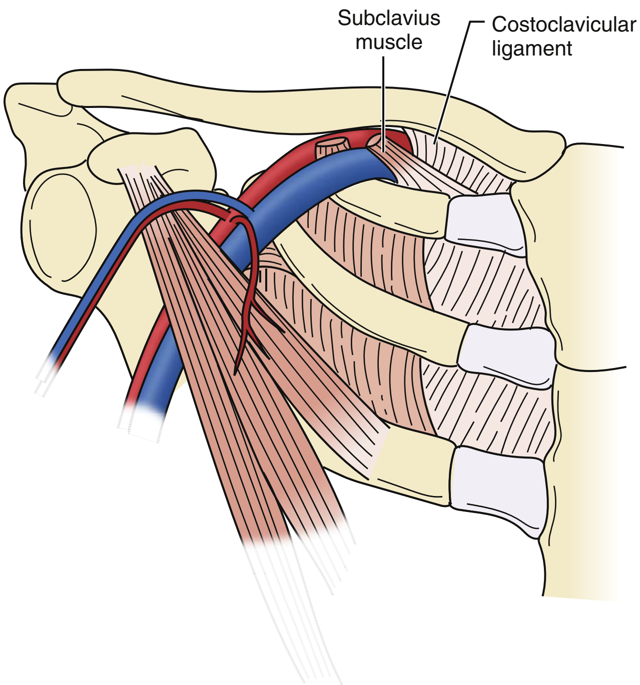

Figure 59.9 **The Axillary Artery and Vein Just Distal to the Clavicle.** These are relatively easily exposed.

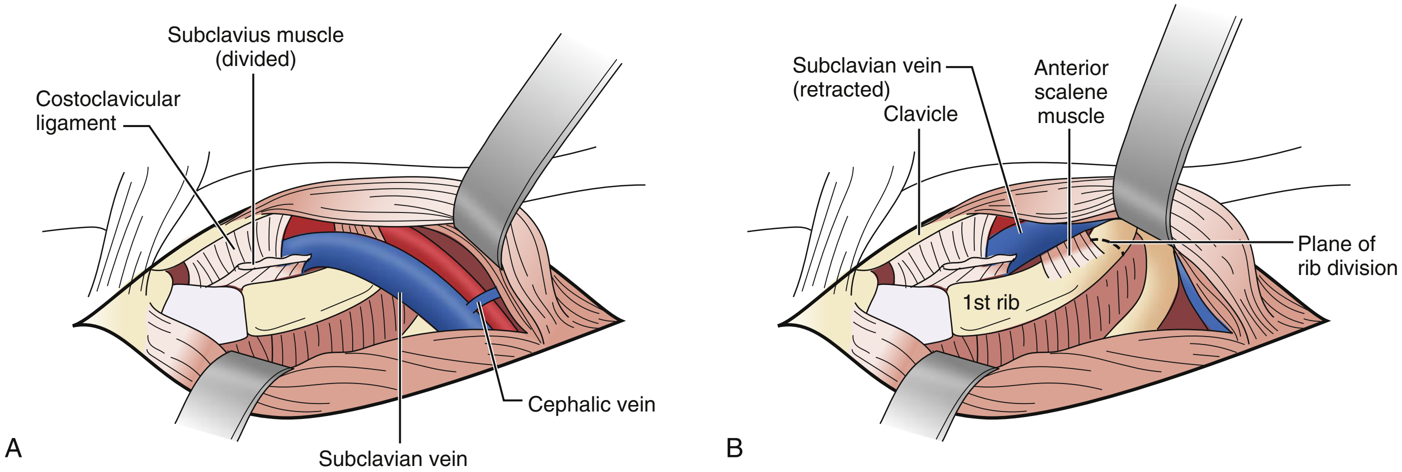

Figure 59.10 Infraclavicular exposure of the subclavian vein, most often used for treatment of venous thoracic outlet syndrome. (**A**) The intercostal muscle has been incised, exposing the anterior/inferior border of the first rib, and the subclavius muscle (laterally) and tendon (medially) and medial costoclavicular ligamentous structures exposed. The vein has been exposed laterally by resecting fatty tissue and then followed medially, at which point, all nonbony structures medially are resected. (**B**) The vein is then elevated upward; the anterior scalene muscle is exposed and divided. The phrenic nerve is well medial at this point and not in the surgical field, the medial border of the rib exposed, and the rib divided several centimeters deep to the vein.

combined with rib resection if venous TOS is the indication (see Ch. 126: Thoracic Outlet Syndrome: Venous). The patient is supine, so imaging (for lysis, venoplasty, or AV access intervention) can easily be combined with surgery. An incision is made over the usually palpable first rib, extending to varying lengths laterally as the specific indication requires. The upper fibers of the pectoralis major are separated or divided, exposing a lateral fat pad. After this is retracted or resected, the inferior border of the rib can be identified and developed, although it is futile to explore the cephalomedial border at this point. We then identify the vein lateral to the rib and follow it medially; if a bulky subclavius muscle is present, it is resected off the clavicle, again moving laterally to medially. At this point the fibrotic tissue medially, made up to varying degrees of subclavius tendon and costoclavicular ligament, will be very obvious. Rather than incising this only, we advocate full resection from clavicle to rib (Fig. 59.10). At this point the cephalomedial border is exposed and can be developed to the level of the anterior scalene muscle. This muscle is then divided, and the mid- to posterior rib then developed by reflecting the fibers of the middle scalene muscle off of it. The rib is divided as posterior as possible and anteriorly within the cartilaginous segment and removed, after which a rongeur is used to pare back any bony or cartilaginous tissue impinging upon the vein. The vein can be freed at this point. There is often a fibrotic external cicatrix which, when removed, leaves behind surprisingly normal venous adventitia. If more proximal exposure is needed, sternoclavicular rotation, as described previously (see Fig. 59.6), can be used; distal exposure requires division of soft tissue only and is relatively trivial.

Ultimately, exposure of the axillary vessels is limited laterally by the deltoid muscle. In an emergency this can obviously be excised, but other than in trauma, there is essentially no indication for exposure of the artery in the area deep to the deltoid itself.

EXPOSURE OF THE ARM VESSELS

Exposure of the vessels in the arm is relatively straightforward. Traumatic injuries can usually be approached directly by an experienced vascular or trauma surgeon. Even if hemorrhage is unroofed, direct pressure is usually trivial, and a tourniquet can be placed without problems (see Ch. 183, Extremity Vascular Trauma). The brachial artery in the upper arm is most commonly used as inflow for an upper arm AV graft or as inflow for distal revascularization interval ligation (DRIL), whereas the vein is commonly exposed for the venous anastomosis of an upper arm AV graft (see Ch. 174, General Considerations and Strategies to Optimize Access Placement). Parenthetically, although some have described DRIL as being performed with a short bypass component, there is no evidence to support this and solid hemodynamic evidence exists to support as long a segment of interposed native artery as possible,[7] and therefore the recommendation for exposure as proximally as possible. A longitudinal incision is made in the upper arm distal to the deltoid muscle, and the neurovascular bundle is located just below (medial to) the biceps. The artery is usually deep to the vein (variably paired at this level) and nerve, but exposure is straightforward (Fig. 59.11). Although the median nerve must obviously be preserved, the superficial nerves in this area, some quite large, are all sensory and patients do not typically have significant symptoms after division. Of note, unlike in the leg, the deep brachial vein can be sacrificed without problems; this can be helpful to increase length and eliminate problems caused by tethering at the swing point of a transposed brachiobasilic AV fistula.

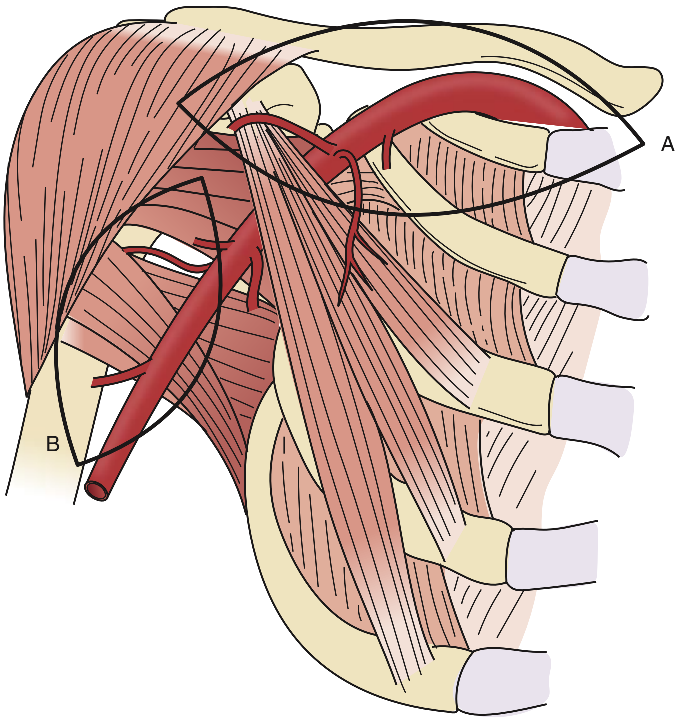

Figure 59.11 **Exposure of the Axillary Artery.** *A* Between the clavicle and pectoralis minor. *B* Distal to the pectoralis minor. Note that this muscle can be divided with impunity.

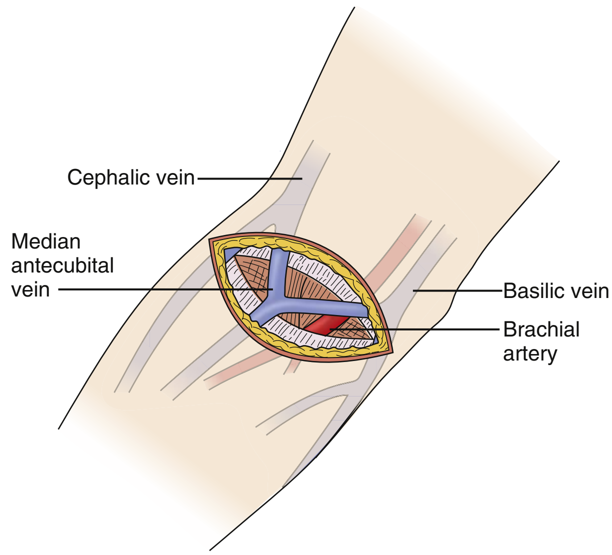

Figure 59.12 Exposure of the brachial artery and vein(s) at the antecubital fossa.

More distally, the brachial artery at the antecubital fossa is obviously the most commonly exposed upper extremity artery; it serves as the inflow vessel for approximately 80% of upper extremity AV access cases, as well as the access vessel for upper extremity imaging and intervention for many thoracic cases. For brachiocephalic fistula creation, a transverse incision is best. It is tempting to stay slightly proximal to the antecubital crease to avoid bending the vein, but as exposure moves proximally the cephalic vein is located more laterally, increasing the distance between the vein and the artery. The author finds that an incision slightly distal to the crease allows the best fistula to be created. In addition to the cephalic vein itself lying close to the artery, various anatomic variants (antecubital vein, perforating veins) can most easily be used for access. A longitudinal incision is most convenient if the antecubital fossa is not crossed; if so, a transverse or "lazy-S" incision will reduce the risk of stricture. The longitudinal incision also provides excellent exposure of the proximal radial artery just distal to its takeoff from the brachial artery. Constructing the AV anastomosis at this level may decrease the likelihood of developing a steal syndrome. Like many superficial arteries, an overlying tendinous band (the bicipital aponeurosis) tends to protect it. The artery is easily palpable; dividing the fibrotic tissue very easily exposes it (Fig. 59.12). Finally, although venous exposure in this area is relatively straightforward, knowledge of which vein is exposed is important for successful AV access. The cephalic vein can be used itself, or the variably located antecubital vein or deep perforating veins can be used to lengthen a brachiocephalic fistula. Similarly, if a first-stage (nontransposed) brachiobasilic fistula is to be constructed, usually a branch traveling into the antecubital fossa can be found. If this branch is not present or usable, the true basilic vein in this location is quite medial.

The artery just distal to this is commonly exposed for the distal anastomosis of a DRIL. The benefit of this operation is to fully perfuse the forearm (distal revascularization) while eliminating all retrograde flow into the fistula (interval ligation); it is thus critical to ensure that the brachial artery itself (above the bifurcation) is ligated. We prefer a longitudinal incision just distal to the takeoff of the AV fistula; formal landmarks are sparse, but the artery should be accessible with minimal exploration (Fig. 59.13). If the artery is not immediately localized, occlusion of the fistula with localization by palpation or a Doppler probe can help. Once the artery is exposed, attention should be paid to ensure that the brachial artery itself (proximal to the bifurcation) is ligated (the anastomosis can be performed to any site on the vessels as long as continuity between the radial and ulnar arteries is maintained).

The radial artery and cephalic vein are most commonly exposed at the wrist for creation of a radiocephalic fistula. Most prefer a longitudinal incision; the pulse is followed to the artery (which lies between the flexor carpi radialis and brachioradialis tendons). No special precautions are followed, other than preservation of the radial sensory nerve; division or injury of this nerve leads to a surprising amount of disability. The cephalic vein is likewise easy to expose, although usually the lateral branch, "deep" with regard to this exposure, is best to use (Fig. 59.14). There is evidence that decreasing manipulation of this vessel improves early AV access patency, but extensive manipulation allows the vein to lie without tension at the "swing point" where it transitions from "loose" to fixed

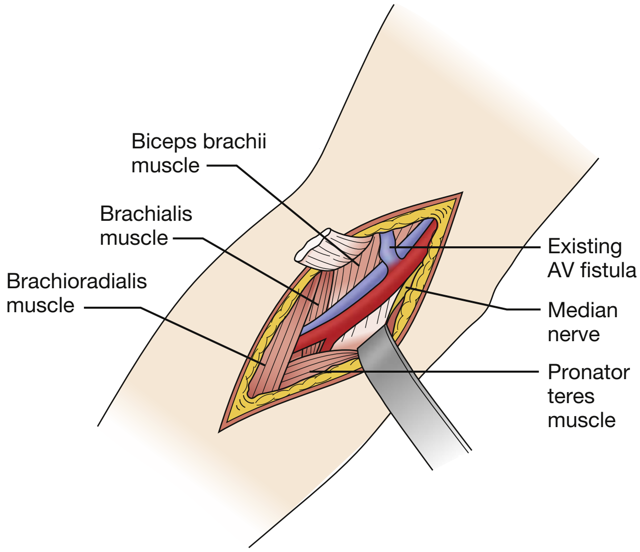

Figure 59.13 Exposure of the brachial artery distal to the antecubital fossa for distal revascularization interval ligation (DRIL) or embolectomy. In both cases the ulnar and radial artery takeoffs should be exposed and controlled. *AV*, arteriovenous.

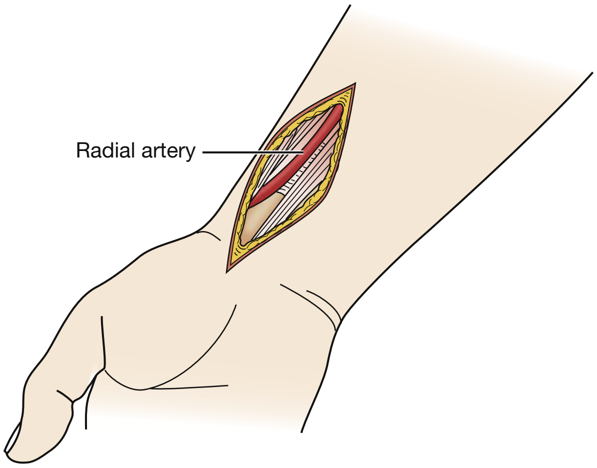

Figure 59.14 Exposure of the radial artery at the wrist.

by tissue. The radial artery can be exposed in the anatomic snuff-box quite easily for a snuff-box fistula, and is quite large in this area (Fig. 59.15).

The ulnar artery is very seldom exposed. Most avoid using this for access because it is the dominant artery to the hand. It is unclear whether this attitude is supported by evidence, but if exposure is needed, the pulse can simply be followed to the artery.

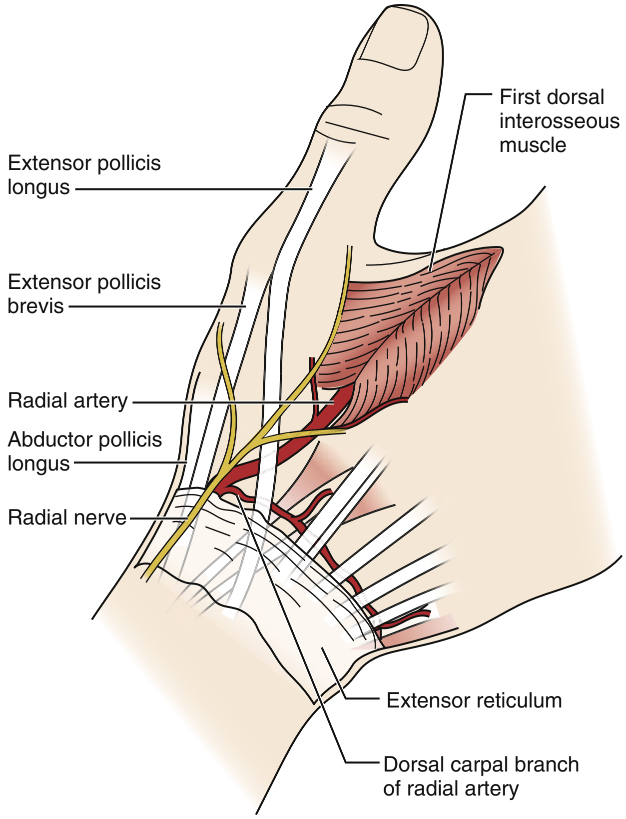

Figure 59.15 Exposure of the radial artery just medial to the extensor pollicis longus tendon for a snuff-box fistula.

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CHAPTER 60

Spinal Operative Exposure

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CHRISTOPHER J. ABULARRAGE

Spinal disorders, such as degenerative disc disease and spondylolistheses, are treated with interbody fusion. To accomplish this, the spine can be exposed through anterior, transforaminal, oblique, lateral, and posterior approaches. The vascular surgeon becomes critical, however, to the success of the orthopedist or neurosurgeon for the anterior approach to the spinal column,[1,2] which was first described in the 1930s.[3–5] While there is controversy regarding when to intervene on back pain,[6–8] what pathology is most amenable to an anterior approach,[9] and whether one approach offers substantial postoperative benefits over others,[10–14] the anterior approach is generally considered less invasive than the posterior approach. Specifically, anterior spine exposure obviates the need for paraspinal muscle dissection and encountering the spinal cord and cauda equina. As compared to the posterior approach, the anterior approach is associated with less blood loss, fewer transfusions, and shorter operative times.[15]

Anterior spine exposure takes advantage of the potential space between the peritoneal contents and kidney, and the quadratus lumbar and psoas muscles. From the vascular surgeon's perspective, the goal is to provide the spine surgeon with adequate vertebral side-to-side exposure so that discectomy, decompression, and/or partial corpectomy can be safely performed and implants accurately inserted on the basis of the disc space midpoint. Given that there is potential for major vessel injury, most centers have adopted a two-team (vascular and spine surgeon) approach to minimize morbidity and to maximize optimal operative exposure for reconstructive spinal surgery. These vascular surgeons, functioning as "access surgeons," have improved patient outcomes, with vascular co-surgeons being associated with decreased intraoperative blood loss, operative time, and length of stay.[16]

In the United States, the incidence of spinal disorders, such as degenerative disc disease, disc herniation, and slipped discs, and subsequent operative management is increasing over time. Therefore, it is possible that the demand for vascular surgeons may increase. This chapter explores anterior spine exposure from a vascular surgeon's perspective.

CLINICAL PRESENTATION, DIAGNOSTIC EVALUATION, AND RISK ASSESSMENT

Patients present to their spine surgeons with complaints of low back pain, and often have failed pharmacologic and nonpharmacologic (e.g. acupuncture, massage, cognitive behavioral therapy) management, and procedural interventions (e.g. glucocorticoid injections). These surgical candidates will also often have severe or progressive neurologic deficits, and experience decreased health-related quality of life and increased physical disability and depression.[17] In contrast to the patients that the vascular surgeon commonly encounters, patients requiring spine surgery infrequently have atherosclerotic disease. Patients with spine disorders are generally 50 to 70 years of age, female and normal weight.[18] About 40% of the population will be overweight or obese, which is sometimes the result of inactivity secondary to pain. However, as compared to patients undergoing posterior fusion, the patient undergoing anterior fusion is relatively younger and healthier,[19] which may be partly due to a selection bias towards candidates suitable for abdominal surgery.

Despite the low prevalence of atherosclerotic disease, the diagnostic evaluation still includes a peripheral vascular history and physical since anterior spine exposure involves extensive mobilization of major arteries and veins within the abdomen/pelvis. As usual, a history of claudication or any abnormality in the peripheral pulse findings should prompt noninvasive testing. Routine noncontrast imaging of the spine frequently shows aortic calcification or aneurysmal changes. Occasionally, further testing such as duplex ultrasonography and/or computed tomography angiography is required for severe aortoiliac occlusive disease or aortic aneurysmal disease. Knowledge of peripheral pulses is also important as open retroperitoneal anterior spine exposure sometimes leads to temporary vessel occlusion from retraction, which for some may result in thromboembolic events (see Ch. 22, Vascular Laboratory: Arterial Duplex Scanning and Ch. 29, Computed Tomography).

Diagnostic evaluation also includes an examination of the patient's thorax, abdomen, and flank for signs of previous chest or abdominal procedures, the presence of which may influence incision placement. For instance, the lower lumbosacral spine can be well exposed via a right retroperitoneal approach for reoperation at similar disc level, or if there has been prior abdominal surgery with a lower quadrant incision. Lastly, it is wise to anticipate significant anterior spinal scarring with an increased incidence of complications if the procedure is done in the setting of discitis, previous posterior spinal surgery, or if the exposure is one disc level proximal or distal to one that has been previously exposed.

Fortunately, the overwhelming majority of patients needing anterior spine exposure are relatively healthy and do not require any other preoperative testing except as mentioned previously. However, older patients may need preoperative cardiac stress testing or pulmonary function studies, particularly if the procedure requires thoracic spine exposure. It is also paramount to counsel patients regarding the complications of this vascular exposure, which include injury to vasculature, bowel or ureter, deep venous thrombosis, surgical site infection, hematoma, seroma, lymphedema, vein stenosis, incisional hernia, nerve injury, and retrograde ejaculation.

SURGICAL TREATMENT

It is beyond the scope of this chapter to discuss the indications for and contraindications to interbody fusion from the perspective of spine surgeons. Rarely the vascular surgeon may advise against surgery if the patient is morbidly obese, or has a history of multiple prior abdominal surgeries, dense aortoiliac calcification, acute/subacute iliofemoral deep vein thrombosis, or solitary kidney.[20] A consistent finding across studies is that morbid obesity is associated with an increased risk of complications, and in these unusual cases, the risks of surgery may exceed the benefits until significant weight loss has been addressed.

Operative Planning and Surgical Exposure Options

Anterior spine exposure for interbody fusion is performed with the patient in either the supine or lateral decubitus position, depending upon disc level(s) of interest. Sometimes, the patient is proned intraoperatively to combine anterior fixation with posterior fixation (i.e. circumferential fixation). In the majority of procedures, the disc space(s) of interest is exposed by dissection and mobilization of the overlying vessels from left to right across the midline via a left thoracotomy for thoracic spine procedures or via the left retroperitoneal space for lumbosacral spine procedures. No single approach lends itself to all circumstances; therefore, it is wise to become comfortable with the relationship of the target disc level(s) to overlying skin and bony structures such as ribs, costal margin, and anterior superior iliac spine. Further, an appropriately placed incision will minimize soft tissue dissection and extent of vessel mobilization. Palpation of pedal pulses before and after the procedure is also prudent because temporary arterial retraction that accompanies disc exposure and spinal instrumentation may result in arterial injury and thrombosis.

Thoracic Spine Exposure

Thoracic spine exposure requires the least amount of vessel dissection because the interbody implants are designed to be placed from a more lateral position, unlike lumbosacral spine exposures in which the implants are usually positioned from a true anterior approach. Therefore, a left (occasionally right) thoracotomy with the lung deflated is employed for thoracic spine procedures. Very proximal thoracic spine procedures that involve disc pathology from T1 to T3 are usually approached posteriorly except in unusual circumstances that may require medial claviculectomy or mini-sternotomy. A right thoracotomy facilitates T3 to T6 exposure, and a left thoracotomy is utilized for procedures that involve T7 to T12 disc pathology. It is also possible to obtain spine exposure through the L2 vertebra from a low thoracotomy if needed.

Thoracolumbar (T12–L2), lumbar (L2–L5), and lumbosacral (L5–S1) spine exposures necessitate more extensive mobilization of major abdominal and pelvic vessels and risk injury to other vital structures within the operative field.[5] Various surgical approaches including open retroperitoneal, laparoscopic transperitoneal, endoscopic retroperitoneal, and endoscopic lateral trans-psoas have been used for anterior interbody fusion to minimize vessel dissection and surgical morbidity without compromising anterior spine exposure. No matter the approach, the key advantages of anterior spine exposure are direct access to and superb visualization of the intervertebral disc level of surgical interest.

Lumbosacral Spine Exposure

The surgical approach for anterior interbody fusion of the lumbosacral spine can pass either through the abdominal cavity or outside the peritoneal contents in an extraperitoneal plane of dissection (see Ch. 56, Abdominal Vascular Exposures). Abdominal approaches include transperitoneal, transperitoneal laparoscopic, and anterior retroperitoneal.

Transperitoneal exposure

Transperitoneal lumbosacral spine exposure requires extensive mobilization of the midgut and hindgut out of the operative field. This can be a demanding exercise, particularly in obese patients or in those who have dense adhesions as a result of a prior abdominal procedure or inflammatory process. Furthermore, the transperitoneal approach is associated with prolonged postoperative ileus, third-space fluid sequestration, and an increased risk of retrograde ejaculation in male patients.[21]

Transperitoneal laparoscopic exposure

Transperitoneal laparoscopic interbody spine fusion has been evaluated as a method to minimize abdominal wall vascular and urologic complications. However, studies have shown that the approach offers minimal to no benefit above open anterior retroperitoneal exposure.[22,23] In a prospective, nonrandomized study that directly compared laparoscopic L4–L5 interbody fusion to an open approach, there was no difference in operating time, blood loss, or length of hospital stay for single-level fusions.[24] However, for multi-level fusions, laparoscopic procedures took 25 minutes longer and were associated with more complications. For 16% of patients the laparoscopic approach offered inadequate spine exposure. Many of the perceived advantages of a laparoscopic approach have not been realized in clinical practice and vascular anatomy variability significantly limits its applicability. Another minimally invasive technique, the endoscopic lateral trans-psoas approach, does minimize vessel dissection, but similarly has poor postoperative outcomes with an increased risk of groin/thigh numbness and pain from manipulation of the genitofemoral nerve coursing along the psoas muscle.

Anterior retroperitoneal exposure

Despite a working knowledge of laparoscopic techniques, the open approach via anterior retroperitoneal lumbosacral spine exposure is favored. Open anterior retroperitoneal approach for lumbosacral spine exposure has advantages similar to those that have been described for retroperitoneal aortoiliac vascular procedures. Single-level or multilevel disc exposure can be performed in an expeditious manner with minimal intraoperative complications. Vital structures can be thoroughly mobilized out of harm's way to facilitate complete discectomy and, in theory, better interbody fusion.

Relevant Surgical Anatomy

Thoracic Spine Exposure

Patient positioning for exposure of the thoracic spine is similar to the position that is often used for open thoracoabdominal aortic aneurysm repair (see Ch. 55, Thoracic and Thoracoabdominal Vascular Exposure). After central venous and radial arterial line placement and dual-lumen endotracheal intubation, the patient is placed in a true right or left lateral decubitus position. A beanbag device, or anterior/posterior padded bolster, is helpful to support the patient's position on the operating table. The free upper extremity can be passed across the upper chest and supported on a cushioned Mayo stand. Care should be taken to ensure that padding of the lower extremities is appropriate and that there is no external pressure on the feet or that the feet are severely plantar-flexed. Transcranial motor evoked potential (TCMEP) monitoring and somatosensory evoked potential (SSEP) monitoring of the posterior tibial nerve, with the ulnar nerve as control, is used.

The rib interspace to be entered after the lung is deflated depends primarily on the extent of thoracic spine that is to be exposed. There is no need to divide the costal margin in the vast majority of cases. In general, the best operating exposure for the spine surgeon is afforded by entering the chest two intercostal levels proximal to the disc level of interest. Sometimes, one can remove the lower rib to facilitate access at multiple disc levels and then morselize the rib for use as bone graft during the procedure. However, removal of the rib facilitates spine visualization at the potential cost of increased postoperative pain, which can be relieved with a multilevel intercostal block. Intraoperative fluoroscopy is vital to identify the appropriate disc space(s) and to limit the extent of surgical dissection. For proximal thoracic spine exposure via a right thoracotomy, incision of the parietal pleura along the lateral aspect of the thoracic vertebra and limited division of ipsilateral intercostal arteries/veins facilitates exposure of the disc space(s) as needed. Venous tributaries coursing into the azygos vein should be divided as needed to prevent injury and troublesome bleeding. These maneuvers are generally all that is needed for proximal thoracic spine exposure, and it is a rare circumstance that one would encounter the esophagus or the vagus nerve, which courses parallel and medial to the azygos vein in the proximal chest.

From the left side, for mid-to-distal thoracic spine exposure, the approach is similar to that already described, except that the descending thoracic aorta is encountered as one dissects across the anterior surface of the thoracic vertebra and disc space. After limited division of ipsilateral intercostal arteries/veins, the descending thoracic aorta can be retracted medially with Omni-Tract (Integra Lifesciences, Minneapolis, MN) renal vein retractors to minimize the risk of arterial injury. Preservation of the blood supply to the spinal cord is critical; therefore, it is wise to ligate intercostal arteries close to the aorta to preserve potential collateral vessels. Brockstein et al. have stressed the importance of the arteria radicularis magna (artery of Adamkiewicz) in providing circulation to the anterior spinal artery. This vessel is a branch of either a distal intercostal or a proximal lumbar artery. It has been identified as proximal as T5 and as distal as L4. However, the artery generally arises between the T8 and L1 vertebral levels. Therefore, it is unwise to ligate any large intercostal or proximal lumbar artery unless it is absolutely necessary to do so for adequate disc space exposure. Finally, the diaphragm can be divided in a limited fashion just lateral to its central tendinous portion to extend the dissection distally to facilitate exposure through the L1 to L2 disc space. Alternatively, these disc spaces can be exposed from the chest by "hooking" the central tendinous portion of the diaphragm with a renal vein retractor, pulling caudad, and performing very limited dissection of the diaphragmatic attachments to the proximal lumbar vertebral bodies.

T12 to L2 Exposure

For thoracolumbar (T12–L2) spine exposure, the patient is placed in the right lateral decubitus position on the operating table with the kidney rest at waist level. If needed, the kidney rest can be elevated and the operating table gently flexed to open the space between the left anterior superior iliac spine and the costal margin. The free left upper extremity is positioned as described earlier. A limited flank incision is made over the anterior extent of the 12th rib. This step decreases the chance of injury to the main trunk of the intercostal nerve within the 11th intercostal space. Abdominal/flank muscle fibers should be split in their respective orientations as opposed to transected. Resection of the 12th rib facilitates safe entry into the retroperitoneal space, as well as an extraperitoneal plane of dissection. Alternatively, this limited thoracolumbar spine exposure can be obtained through the 10th or 11th intercostal space as mentioned previously, with dissection just lateral to the central tendinous portion of the diaphragm, rather than inferior to the diaphragm as described here.

Extraperitoneal entry into the upper left retroperitoneal space exposes Gerota's fascia with contained left kidney as well as the spleen, which can then be rotated inferomedially off the diaphragm and proximal psoas muscle. This maneuver facilitates exposure of the left diaphragmatic crus, which will be divided to reveal the underlying vertebra and abdominal aorta. Once again, limited ligation and division of intercostal/lumbar arteries as needed should be performed to preserve spinal blood flow. The Omni-Tract retraction system (Integra Lifesciences), with its multiple and varied blades, is critical for maintaining this exposure. The previously mentioned thoracolumbar spine exposure can also be performed from a right flank approach, requires mobilization of the right lobe of the liver and, in some cases, the vena cava. Thoracolumbar spine exposure can also be achieved via a left upper quadrant paramedian incision, which affords the spine surgeon superb anterior spine exposure.

L2 to S1 Exposure

More distal lumbosacral spine exposures (typically from L2 to S1) are usually performed with the patient supine and via small oblique or longitudinal left (occasionally right) paramedian incisions. The preoperative lateral lumbar spine radiograph can be useful to determine appropriate position of the incision for optimal disc space exposure. The relationship of the palpable iliac wing, which is easily visualized on the lateral radiograph, with the lower lumbar disc levels, provides an excellent landmark to determine incision placement. Oblique/transverse incisions that are centered over (or just between) the target disc(s) are useful for one- or two-level disc exposures, and longitudinal paramedian incisions facilitate multilevel disc exposure. Electromyography in addition to somatosensory-evoked potential monitoring is used for these cases. A reduction in somatosensory-evoked potential amplitude may signal diminished blood flow and ischemia to the affected limb.

In either orientation, the incision is carried through the anterior layer of the rectus sheath to expose the rectus abdominis muscle. Flaps can be created between the anterior rectus sheath and the muscle itself in order to maximize retraction and exposure. The muscle belly is encircled with a Penrose drain and retracted medially to expose the posterior layer of the rectus sheath and/or the transversalis fascia. Muscle fibers are not sharply transected to reduce the incidence of muscle laxity that might predispose one to abdominal wall hernias. The posterior rectus sheath/transversalis fascia is incised to develop an extraperitoneal plane of dissection. The muscle is then retracted laterally, after which rotation of the peritoneal contents from left inferolateral to right superomedial opens the left lower retroperitoneal space and exposes the major arteries and veins that overlie the distal lumbosacral spine. For higher levels of thoracolumbar spine exposure (T12–L1), a retro-nephric, extraperitoneal plane of dissection is created by rotating the kidney and left ureter, as well as the peritoneal contents, medially off the psoas muscle. However, in most patients, particularly the morbidly obese patient, it is often easier to obtain proximal (L1–L3) lumbar spine exposure if the dissection plane to the anterior spine is developed between the left colon and Gerota's fascia, leaving the left kidney and ureter in place. In this circumstance, care must be taken to protect the left ureter, which will remain *in situ* and lateral to the spine. It is also important not to injure the very vascular tissue that is medial to the kidney hilum and adjacent to the adrenal gland. Occasionally, the spleen also requires medial mobilization away from the psoas muscle and diaphragm to facilitate some extended thoracolumbar spine exposures.

The maneuvers described previously, depending on their extent, facilitate exposure of the entire abdominal aorta and left common iliac artery with accompanying left common iliac vein (Fig. 60.1). Mobilization of these vessels from left to right across the midline is usually required to anteriorly expose the spine and disc space from side to side. The left ureter is generally swept medially with the posterior peritoneum out of harm's way; however, if the ureter appears to be under too much stretch and at risk for injury, it should be gently dissected away from the medially rotated posterior peritoneum. The ipsilateral vas deferens and testicular/ovarian vessels are gently dissected away from the posterior peritoneum to maintain their normal anatomic positions, and occasionally, division of the round ligament in women facilitates medial rotation of the peritoneal contents and exposure of the distal lumbosacral spine. The vestigial ipsilateral umbilical artery that courses into the internal iliac artery can be divided with impunity. Finally, and particularly in males, a concerted effort is made to protect the condensation of nerve elements (inter-mesenteric nerve plexus and superior hypogastric nerve plexus) that course over the left common iliac artery origin (Figs. 60.2 and 60.3). The use of bipolar cautery in this area for any small paraspinal and periarterial bleeders also helps decrease inadvertent nerve injury.

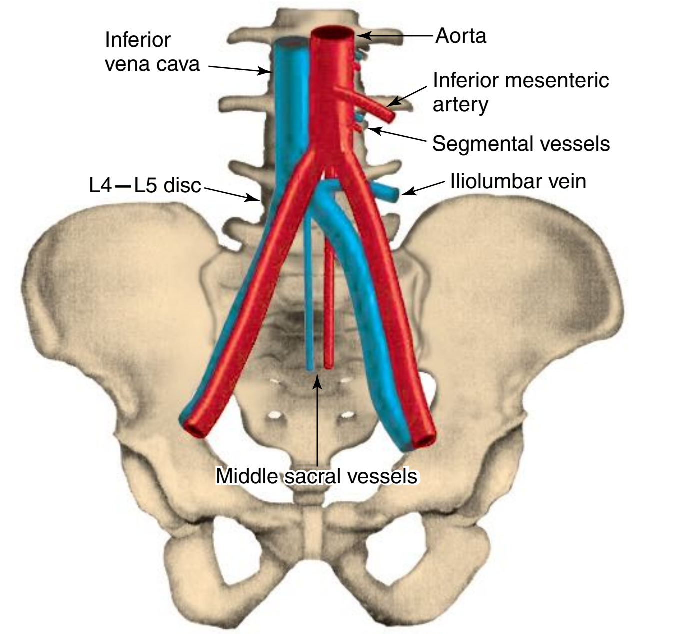

Figure 60.1 Arterial and venous anatomy that is typical for lumbosacral spine exposure. Note that in this case the L4 to L5 disc is just above the aortic and caval bifurcation.

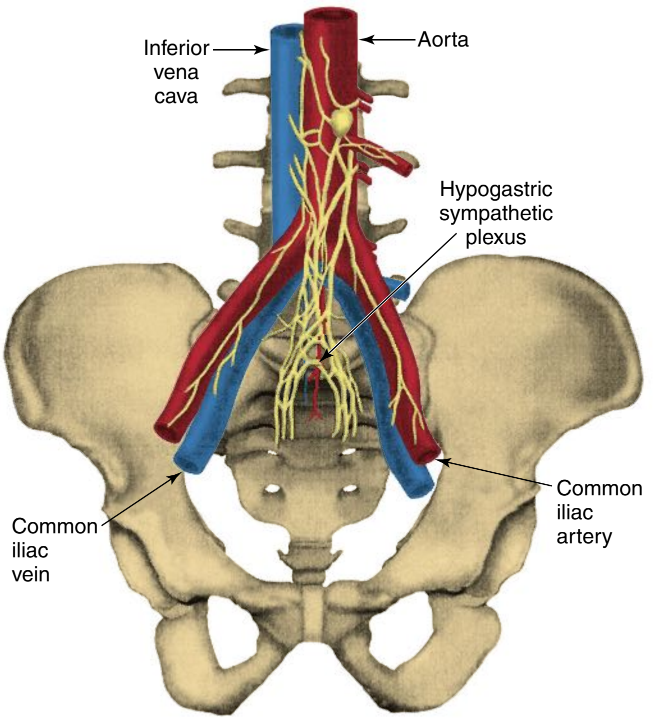

Figure 60.2 Relationship of the infrarenal sympathetic nerves to the aorta and iliac arteries.

L4 to L5 and L5 to S1 Exposures

Exposure of the L5 to S1 disc space is relatively straightforward compared with other levels, because once the rectosigmoid bowel is swept across the midline from left to right, the disc space is readily exposed between the left common iliac vein and the right common iliac artery after division of the middle sacral artery and vein (Figs. 60.3–60.5). Various incisions can be used

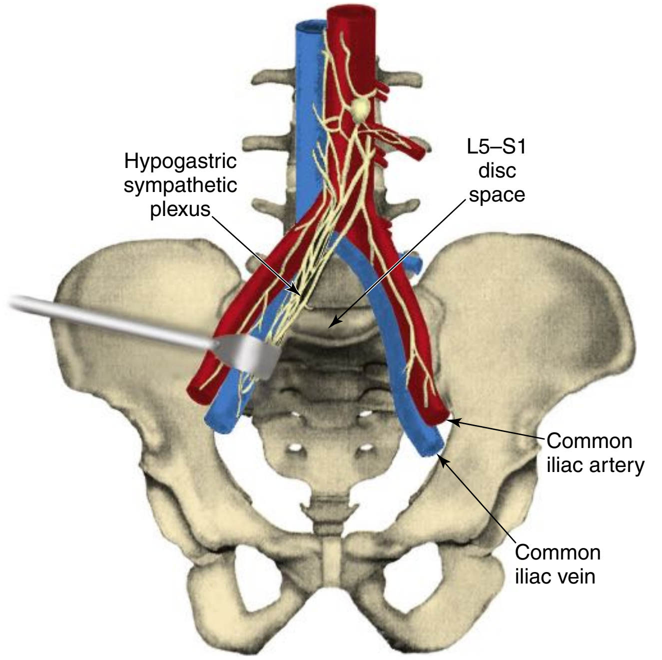

Figure 60.3 To approach the L5 to S1 disc and to protect the sympathetic nerves, it is wise to begin dissection along the medial aspect of the left common iliac vein and then to retract the soft tissue overlying the disc toward the right common iliac artery.

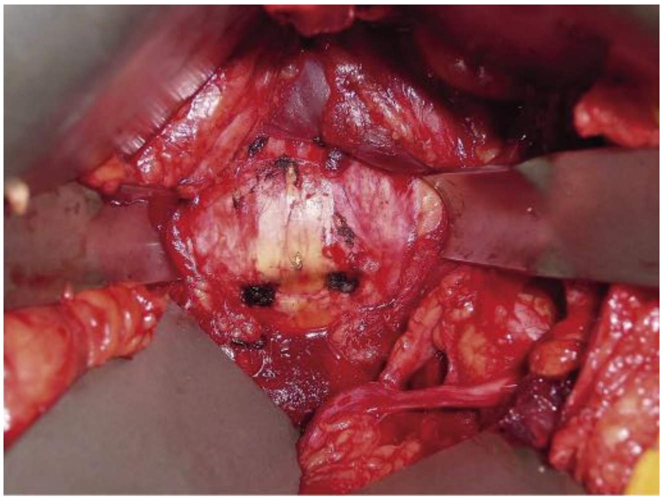

Figure 60.4 Intraoperative photo of the exposed L5 to S1 disc. Note the positioning of the Omni-Tract renal vein retractors (Integra Lifesciences, Minneapolis, MN) as described in the text.

for this single-level exposure, including left lower quadrant oblique, transverse, and, occasionally, midline.

Exposure of the L4 to L5 disc space can be technically demanding, particularly if there is significant spondylolisthesis at this disc level because the "tethered" left common iliac vein stretches and flattens out across the lower edge of the disc space, inviting inadvertent injury. L4 to L5 disc space exposure should always be accompanied by division of the iliolumbar vein(s), which course toward the posterolateral aspect of the left common iliac vein (Fig. 60.6). Failure to divide this vein can result in a significant tear at this venous junction with bleeding that can be difficult to control. In other more proximal procedures,

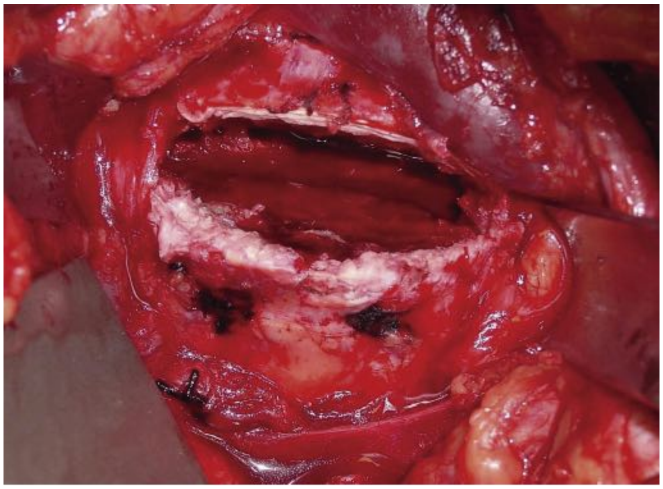

Figure 60.5 Intraoperative photo following discectomy at the L5 to S1 disc level; subsequent insertion of allograft bone or a synthetic prosthesis to promote spine fusion completes the procedure.

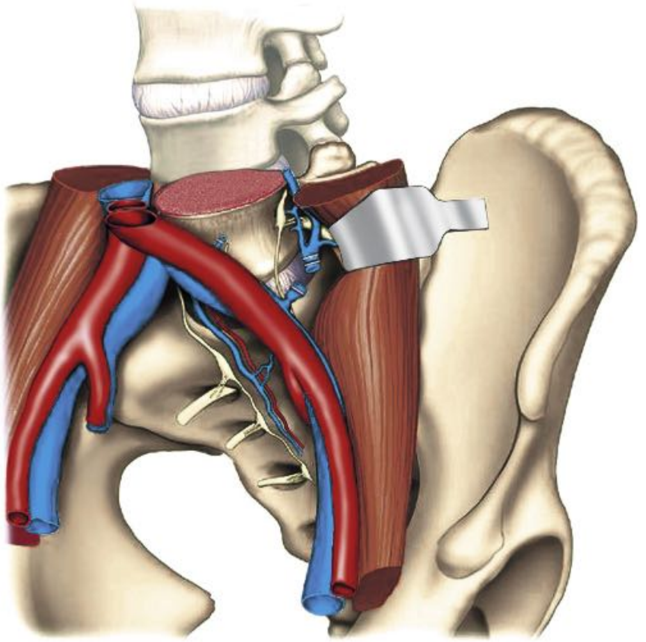

Figure 60.6 Division of the iliolumbar vein (or veins) is key for safe exposure of midlumbar and lumbosacral disc levels.

appropriate disc level exposure requires meticulous left-to-right dissection and mobilization of some portion of the abdominal aorta. Additional dissection of the common iliac arteries and/or iliac veins may also be required to fully expose the natural width of the desired disc space(s). Lumbar arteries and unnamed venous tributaries should be individually ligated and divided to facilitate the spine exposure. One particular advantage of this left-to-right dissection/mobilization plane is that the vena cava remains well protected throughout the procedure.

Exposure of More than One Disc Space

Although tempting in some cases, it is unwise to perform discectomy and spinal instrumentation at multiple disc levels simultaneously if this extended exposure occludes the aorta/

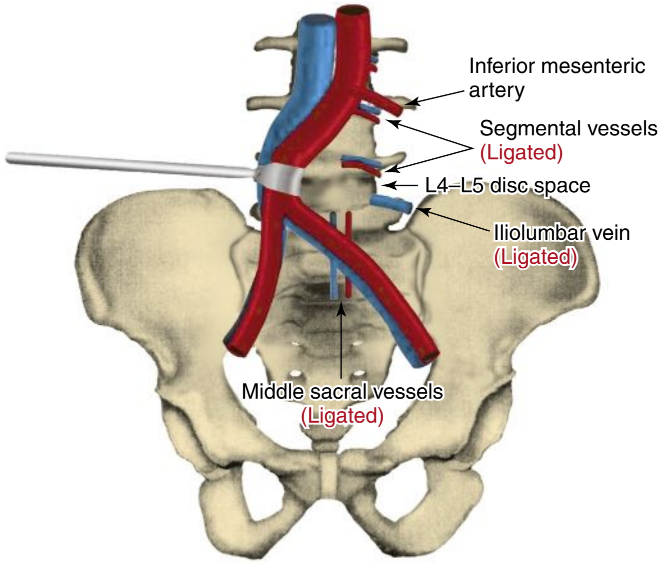

Figure 60.7 L4 to L5 disc exposure when aortic and caval bifurcations are distal to the disc level.

common iliac artery or risks significant damage to the confluence of the common iliac veins and the vena cava. This is particularly true when the L4 to L5 disc space is involved, because there can be significant variability in the arterial and venous anatomy. However, for non-diseased iliac arteries, well-positioned retractors can allow for simultaneous exposure and operation on multiple disc spaces from L1 to L5. The retractors are then repositioned to expose the L5 to S1 disc space if discectomy/decompression is also required at this disc level.

Figure 60.7 depicts the usual scenario in which the disc is exposed following left-to-right mobilization of the aorta and left common iliac artery across the anterior spine. However, the left common iliac artery and vein occasionally need to be separated and retracted away from each other to fully expose the disc space without prolonged arterial occlusion or arterial injury (Fig. 60.8). Figures 60.9 and 60.10 depict other, less common dissections used to expose the L4 to L5 disc space, in the patient with a high aortic bifurcation, for instance. These alternate dissection schemes are particularly helpful for redo anterior procedures, in which the major overlying arteries and iliac veins may be densely adherent to the anterior surface of the spine, or in dissection being performed after previous posterior lumbosacral spine surgery, in which significant scarring of the anterior spine surface may occur.

Right-Sided Exposure

Spine exposures performed from a right-sided mini-open retroperitoneal approach necessitate mobilization of the vena cava and, to some extent, the right common iliac vein for lower lumbosacral spine procedures. Medial retraction of the vena cava all the way across the anterior surface of the spine often occludes the vessel and may result in significantly decreased preload, which may not be tolerated in older persons. Therefore, depending on arterial/venous anatomy, the disc space(s) may be better exposed by dissecting between the vena cava and abdominal aorta. This alternative causes less compression of each vessel with lateral retraction away from the midline.

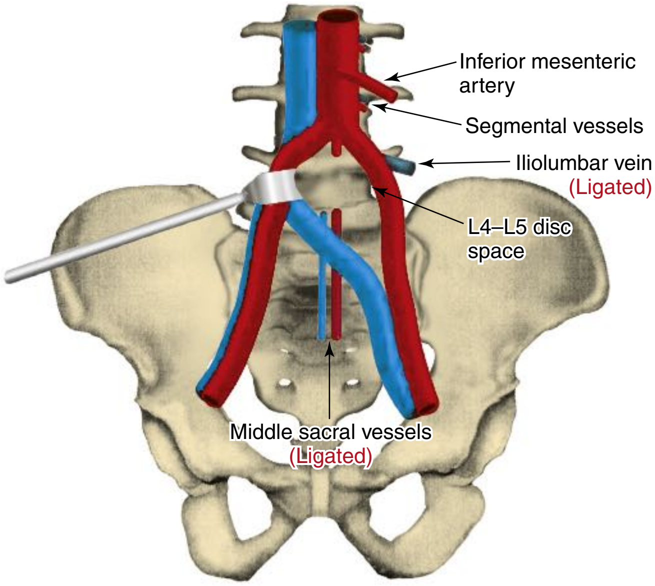

Figure 60.8 L4 to L5 disc exposure between the left iliac artery and vein.

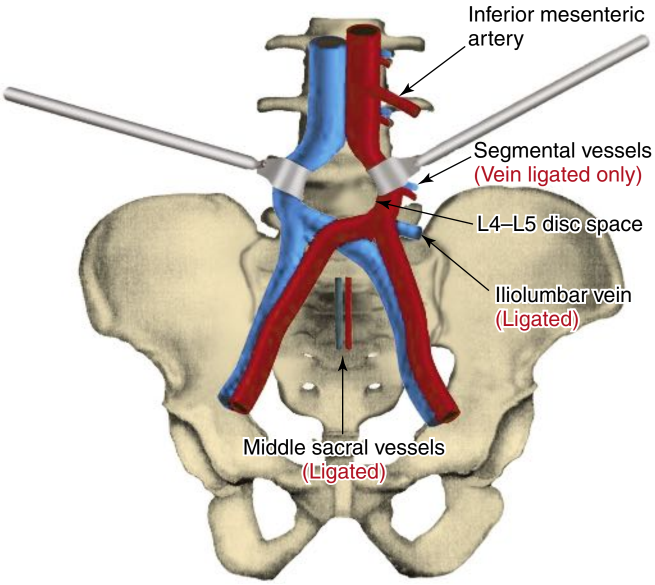

Figure 60.9 L4 to L5 disc exposure between the aorta and the vena cava.

Self-Retaining Retractors

Self-retaining renal vein retractors (Omni-Tract Surgical) are typically employed to maintain each exposed disc space and to protect the adjacent vessels/peritoneal contents. These particular retractors are slightly angled backward at their tips, and this angled portion can usually be positioned to hug the disc space laterally, thus protecting encroaching vital structures from the disc space and giving the spine surgeon just enough room to operate even in very large patients (see Fig. 60.6). These retractors should be placed with care to avoid excessive traction on the mobilized structures and should be positioned just medial to the sympathetic chains that course along the lateral aspects of the vertebra, to protect them from inadvertent injury. It is also recommended to intermittently release retraction intraoperatively, as increased duration of retraction

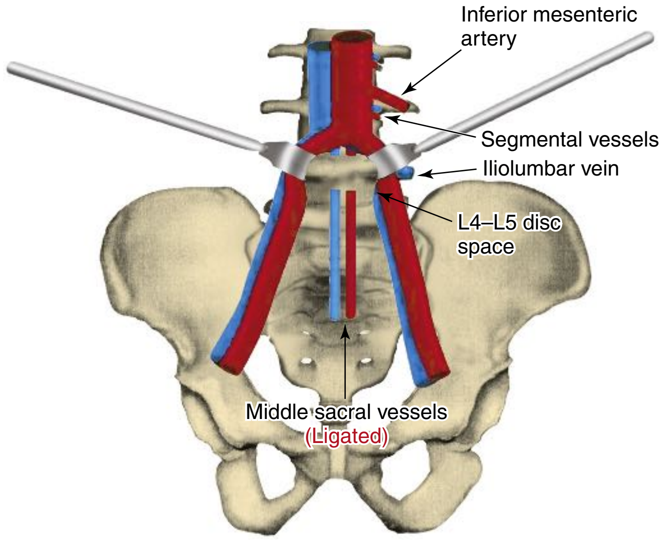

Figure 60.10 L4 to L5 disc exposure when aortic and vena caval bifurcations are proximal to the disc level.

is associated with increased thromboembolic events,[25] especially in patients with dense aortoiliac calcification.

To achieve hemostasis and decrease anterior spine adhesions, some surgeons elect to apply fibrin sealant (Evicel, Ethicon US, LLC.). The peritoneal contents are rotated back into place after confirming a palpable pulse in each common iliac artery. Pedal pulses are confirmed to be unchanged from preoperative before the patient transfers to the recovery room.

Special Considerations

Reoperation

Reoperation is associated with scarring and vital organ fixation to the anterior spine, increasing the risk of injury.[26] This is particularly true when artificial discs or hardware are being removed for displacement or component failure. If anticipated scarring is insurmountable, an alternative exposure to the spine might be recommended. In any event, it is wise to prepare for dissection difficulties and potential bleeding. Arteriorrhaphy or venorrhaphy with pledgetted nonabsorbable polypropylene (e.g. Prolene) suture is recommended because the vessels tend to be friable when re-dissected off the anterior spine. Large venous rents are best controlled with a side-biting vascular clamp or multiple Allis-type clamps because it may not be possible to completely occlude the vein proximal and distal to the injury site without risking further injury. On rare occasions, transection (or even segmental resection) of the overlying iliac artery may be required to adequately expose a major pelvic venous injury. Standard arterial reconstruction techniques can be used after ensuring an intact vein repair or vein ligation as the case dictates.

Calcified Arteries

Significant aortoiliac artery calcification increases the potential risk of arterial injury or dissection, especially with significant retraction. Even pliable vessels are frequently retracted at rather acute angles to decrease the amount of operative field dissection needed, but also to afford complete disc space exposure. The best way to avoid injury to a calcified vessel is to mobilize more length of the artery proximal and distal to the disc level(s) of interest, even if doing so requires extension of the incision and/or more mobilization of adjacent structures. While significant arterial injury during anterior interbody fusion is rare, appropriate arterial reconstruction should be employed as needed, as opposed to risking acute arterial occlusion by applying multiple blindly directed sutures and pledgets to an injured vessel.

SURGICAL RESULTS AND COMPLICATIONS

There are rare intraoperative and few postoperative complications related to anterior spine exposure.[27,28] Only about 2%–4% of patients have intraoperative vascular injury. Intraoperative hemorrhage is usually due to venous bleeding from iliac branch avulsions or small lacerations,[1,25,29–33] but rarely venous injury can be a cause of mortality, particularly in patients with comorbidities that are exacerbated by rapid changes in volume.[27] The most commonly injured vessel is the left common iliac vein, and relatively higher rates of vascular injury are associated with exposures involving L4–L5 and L5–S1.[31,34] Arterial injuries are rare, occurring in less than 2% of these cases. Arterial injuries are more common in patients with variant vascular anatomy secondary to spine pathology or prior instrumentation.[35,36] There are also a few case reports of iliac artery occlusion in patients with known atherosclerotic disease,[37–39] which have been partly attributed to prolonged compression of the iliac artery from retractors.[40,41] Patients who have intraoperative vascular injuries are also more likely to have postoperative thromboembolic events than those who do not.[42] Nonvascular intraoperative complications include ureteral injury, bowel enterotomy and retained foreign objects.[43] Importantly, complications can occur during spinal instrumentation rather than during the anterior spine exposure.[44] Major vascular injuries may occur when sharp curettes, rongeurs, and drill bits are being used. Therefore, it is prudent for the vascular surgeon to be available for the duration of the operation to ensure swift recognition and repair of inadvertent injury to a vital structure.

Postoperative complications following anterior spine exposure include prolonged ileus,[45] hernias, thromboembolic events, retrograde ejaculation, transient unilateral lower extremity paresis, seroma/hematoma, lymphedema, and chylo-retroperitoneum. Erectile dysfunction occurs secondary to the disruption of the intermesenteric nerve plexus and superior hypogastric nerve plexus, which course over the left common iliac artery origin. For women, there is no association between anterior interbody fusion and sexual and urinary function.[46] In a retrospective study of 735 patients who underwent anterior spine exposure at a single institution, 2.7% developed paramedial incisional hernias, which were large (13.5 cm) on average.[47] Risk factors for paramedial incisional hernia included a higher American Society of Anesthesiologist class, history of abdominal surgery, and postoperative intensive care unit admission.[47] Operative technique has also been found to be associated with postoperative hernias. Specifically, unaddressed peritoneal defects have also been found to lead to retroperitoneal hernias with incarcerated bowel.[48] Therefore, peritoneal defects recognized during anterior spine exposure should be primarily repaired.

In general, higher complication rates are associated with obesity,[31,34,49] increased number of prior abdominal surgeries,[50] exposure of multiple disc levels,[20,34,42] reoperation, and removal of old hardware.[26] In addition, intraoperative risk factors, such as increased operative blood loss and an extended paramedian incision, were also associated with a higher risk of perioperative complications.

POSTOPERATIVE MANAGEMENT AND FOLLOW-UP

While the highlight of postoperative management is rehabilitation of the spine, inpatient postoperative management under the purview of the vascular surgeon includes waiting for return of bowel function and performing frequent peripheral vascular examinations (especially if the patient has a history of atherosclerotic disease). For patients with prior endovascular aneurysm repair, some surgeons recommend postoperative duplex to confirm endograft patency and assess for endoleak.[51] Outpatient postoperative needs are rare. However chronic vascular problems requiring continued care include deep vein thrombosis, severe lymphedema, and surgical site infection. Symptomatic common iliac vein stenosis is a long-term sequela (an average of 5 years later) of spine instrumentation that may require venoplasty and stenting.[52] Therefore, patients who present with venous stasis and have a history of lumbar interbody fusion should be referred for a pelvic ultrasound to evaluate the pelvic veins.

CONCLUSION

The vascular surgeon provides exposure to the anterior spine needed to treat prevalent and increasing spinal disorders in the general population. The vascular surgeon is critical to the success of the operation and improves patient outcomes. Anterior spine exposure provides access to the spine via a retroperitoneal approach. From the vascular surgeon's perspective, the goal is to provide the spine surgeon with adequate vertebra side-to-side surgical exposure so that discectomy, decompression, and/or partial corpectomy can be safely performed and implants accurately inserted on the basis of the disc space midpoint. Intraoperative vascular complications are rare but, when they occur, tend to be venous injuries that can be repaired primarily. Patients have both inpatient and outpatient postoperative management needs. Lastly, knowledge of prior spine instrumentation is critical to the assessment and treatment of patients presenting with vascular complaints.

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61 CHAPTER

Open Surgical Technique

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INTRODUCTION

As trainees and practicing vascular surgeons perform fewer open procedures, it becomes increasingly important to understand and become familiar with the established principles of open surgical technique. With advances in catheter-based technology, endovascular therapy is now the first option in many, if not most, clinical scenarios. However, open vascular surgery has traditionally been the "gold standard" with respect to durability and efficacy. Hybrid procedures which combine open surgery and endovascular techniques have been performed to achieve revascularization with limited exposures. Similarly, debranching procedures (i.e., iliorenal and iliomesenteric bypasses) in patients with suprarenal aortic aneurysms or carotid–subclavian and carotid–carotid bypasses in patients with thoracic aortic aneurysms can provide a landing zone during the endovascular treatment of a thoracoabdominal or thoracic aortic aneurysm. However, there remain clinical scenarios where open bypass may serve as the optimal mode of limb revascularization. Factors affecting this decision include life expectancy, degree of tissue loss, arterial anatomy, availability of autogenous conduit, and failed prior endovascular intervention. Despite advances in endovascular technology and the increase in the number of endovascular interventions, open vascular reconstructions will continue to play a significant role in the management of patients with vascular disease for the foreseeable future.

BASIC PRINICPLES

The key elements of a successful open vascular reconstruction involve choosing the optimal procedure at the optimal time point while selecting the appropriate method of vascular exposure and executing the selected procedure carefully and expeditiously. Appropriate choices of inflow, outflow, and bypass conduit are critical for the success of open revascularization. This success also requires the appropriate instruments, grafts, and suture materials. Exposure to the skin should be avoided while suturing and tunneling grafts, especially prosthetic conduits. The skin can be isolated with impregnated drapes or moistened laparotomy pads (see Ch. 49, Graft Infection). All open vascular procedures should be performed under excellent lighting aided by magnifying loupes in most cases. Often overlooked, maintaining good ergonomic position during the reconstruction is essential for the surgeon to not only prevent significant work-related discomfort in the neck, shoulders, and back, but to also to allow the efficient execution of surgical maneuvers in awkward angles and limited spaces as is routine in open reconstructions.

Vascular Instruments and Retractors

A vascular instrument tray typically includes vascular clamps, needle holders, forceps, scissors, and various retractors. Depending on the size of the vessel and the location of the surgical reconstruction, the instruments used will vary.

Clamps

Vascular clamps typically have jaws with rows of fine interdigitating serrations that allow clamping of the vessel without slippage or significant crush injury. Although vascular clamps are considered atraumatic, a vascular clamp applied inappropriately can cause significant intimal damage or may tear the artery if placed over a plaque in an inappropriate manner. Even in a soft, minimally diseased artery, a clamp applied with excessive force can damage the arterial wall and intima. Palpation of the artery to locate the orientation of the plaque can be very helpful in proper placement of the clamp in the best geometric plane. Clamps vary in shape and angulation to fit into specific anatomic locations and for arteries of different sizes and can be used to fully or partially occlude the vessel. Clamps with special soft, atraumatic inserts (e.g., Fogarty soft jaw) are also available and especially important to allow clamping of prosthetic grafts without damaging the graft material. Types of vascular clamps and their suggested uses are outlined in Table 61.1. For smaller vessels and branches, various sizes of bulldog clamps or intracranial aneurysm clips, such as the Yasargil or Heifitz clips, are available (eFigs. 61.1–61.12).

Needle Holders, Forceps, and Scissors

The choice of needle holder is often dictated by the size of the needle used; a Mayo–Hegar needle holder is typically used with large needles, and Castroviejo needle holders are typically used with small, fine needles (eFig. 61.13). The forceps used during vascular procedures typically have very fine, non-crushing jaws, exemplified by the DeBakey or Gerald forceps. However, similar to clamps, vascular forceps can crush a vessel wall if they are not used appropriately and delicately. Fine-tip ring forceps, Jarrell forceps, are useful during the construction of vein bypasses to infrapopliteal vessels. Metzenbaum and Church scissors are used for the dissection of blood vessels while Stevens tenotomy scissors with sharp tips are used for dissecting smaller, tibial vessels. Potts scissors with various angulations are used to enlarge and shape arteriotomies and venotomies. Right-angle clamps with various tip sizes are used to encircle blood vessels and branches (eFigs. 61.14–61.19).

Retractor Systems

Self-retaining retractors should be used when possible for stability and consistency without excessive pressure on retracted tissues. The Omni-Flex vascular retractor (Omni-Tract Surgical, St. Paul, MN) is frequently used for open aortic surgery, whether transabdominal or retroperitoneal (eFig. 61.20). This retractor system consists of a wishbone that attaches to a post mounted on the operating room table rail, and it typically offers a selection of blades with different depths, widths, and shapes that can be clamped to the wishbone. Shallow, wide blades are typically used to retract the abdominal walls, whereas deeper splanchnic blades may be used to retract the splenic flexure and other parts of the colon. A wide, fence-shaped blade is typically used to retract the small bowel during aortic dissection, and a narrow, deep blade with a "lip" may be used to carefully retract the left renal vein cephalad. This retractor system is useful during abdominal and thoracoabdominal aortic aneurysm repair. Modifications of this retractor have also been designed for inguinal, carotid, and spine exposures.

Another self-retaining abdominal retractor is the Bookwalter retractor (Codman Johnson & Johnson, Raynham, MA) (eFig. 61.21). This retractor is often used when conducting abdominal aortic and iliac exposures especially through minilaparotomy incisions. The retracting blades in the Bookwalter retractor attach to an oval metal ring placed around the abdominal incision instead of a wishbone. Several single-instrument self-retaining retractors are available for neck and extremity procedures (eFigs. 61.22–61.24). The Weitlaner retractor is commonly used for inguinal, cervical, and popliteal incisions. Available with either sharp or dull retraction jaws, the sharp variety tends to hold its position in a more secure manner, thus requiring fewer adjustments than the dull version. The Adson cerebellar retractor is angled such that it can also be very useful in cervical, groin and below-knee exposures. In obese patients with significant inguinal pannus, a Miskimon retractor can be especially useful because of its deeper and wider blades, which provide a larger retracting area. Spring retractors are extremely useful when conducting infrageniculate vessel exposure because they tend to occupy little space. The Gelpi retractor is

eFigure 61.1 DeBakey–Bahnson aortic aneurysm clamp.

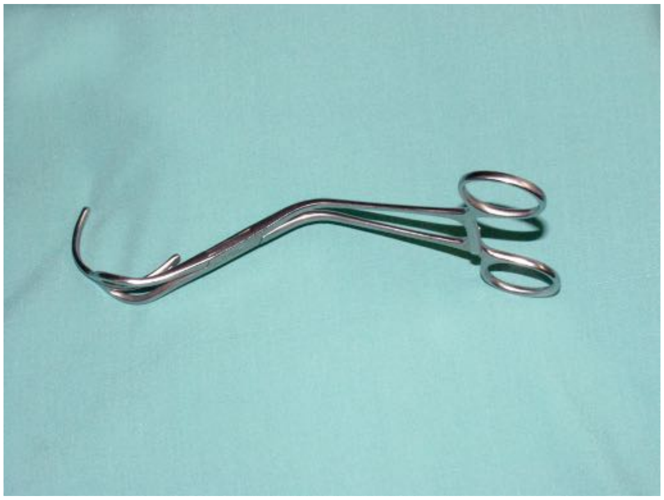
eFigure 61.2 Fogarty aortic clamp.

eFigure 61.3 Lambert–Kay aortic clamp.

eFigure 61.4 Wylie hypogastric clamp.

eFigure 61.5 DeBakey peripheral vascular clamp (angled handle).

eFigure 61.6 Henly subclavian clamp.

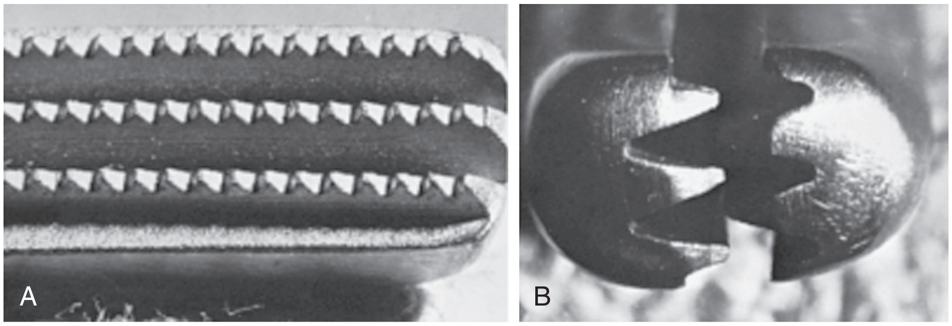


eFigure 61.7 Lemole–Strong aortic clamp.

eFigure 61.9 Cooley pediatric clamp.

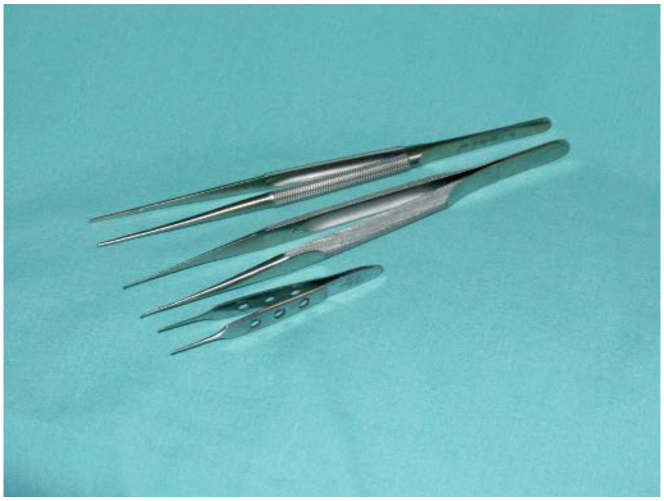
eFigure 61.8 Satinsky clamp.

eFigure 61.10 Jaw of Fogarty clamp.



eFigure 61.11 (**A** and **B**) Jaw of DeBakey vascular clamp.

eFigure 61.12 Yasargil aneurysm clips with clip applicator.

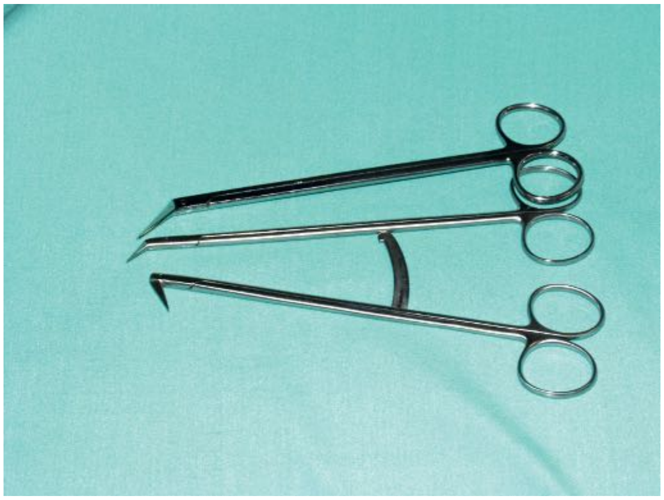


eFigure 61.14 *Bottom to top,* Bishop–Harmon forceps, microsuture ring-tip forceps, and fine DeBakey forceps.

eFigure 61.13 *Bottom to top,* Castroviejo, Ryder, and Mayo–Hegar needle holders.

eFigure 61.15 *Top to bottom,* Tips of DeBakey and ring-tip forceps.

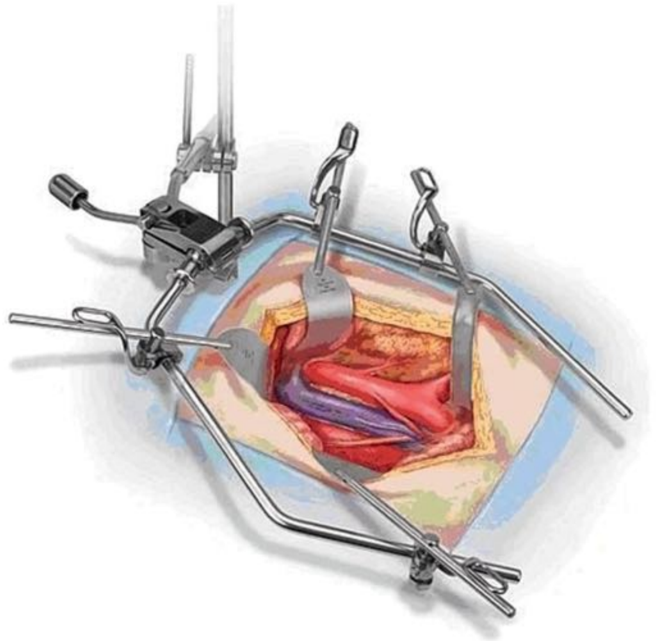
eFigure 61.16 *Top to bottom,* Church and Metzenbaum scissors.



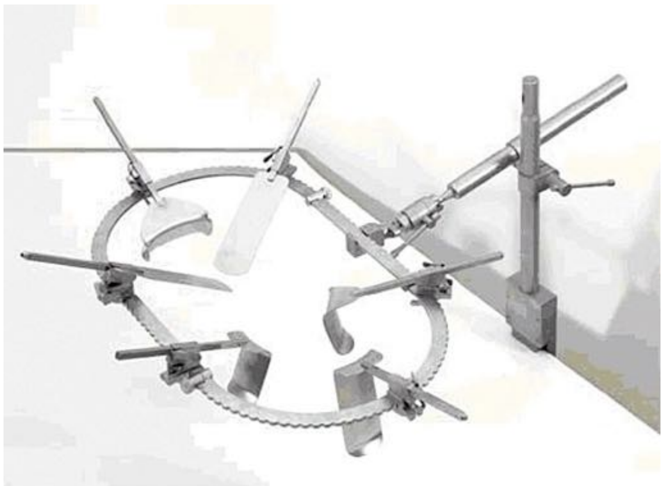
eFigure 61.17 Potts scissors.

eFigure 61.18 Castroviejo scissors.

eFigure 61.19 Right-angle clamps.



eFigure 61.20 Omni-Tract retractor.



eFigure 61.21 Bookwalter retractor.

eFigure 61.22 Weitlaner retractor.

eFigure 61.24 Gelpi retractor.

eFigure 61.23 Miskimon retractor.

TABLE 61.1 Vascular Clamps and Target Vessels

Clamp Type	Vessel
Totally Occluding	
DeBakey aortic aneurysm clamp (side-to-side apposition of aortic wall)	Supraceliac, infrarenal aorta
DeBakey–Bahnson aortic aneurysm clamp	Infrarenal aorta
Howard–DeBakey aortic aneurysm clamp with reverse curve shafts (side-to-side apposition of aortic wall)	Infrarenal aorta
Fogarty aortic clamp (side-to-side apposition of aortic wall)	Infrarenal aorta; aortic grafts, calcified aorta
DeBakey aortic aneurysm clamp (apposition of anterior and posterior walls together)	Infrarenal aorta
Lambert–Kay aortic clamp (apposition of anterior and posterior walls together)	Infrarenal aorta
Wylie hypogastric clamp	Iliac arteries, especially hypogastric arteries
DeBakey peripheral vascular clamp (angled handle)	Iliac arteries
DeBakey peripheral vascular clamp (angled jaw, 45 degrees)	Iliac and common carotid arteries
Henley subclavian clamp	Subclavian and common femoral arteries
Partially Occluding (Side-Biting)	
Lemole–Strong aortic clamp	Aorta; aortic grafts
Satinsky clamp	Aorta, vena cava
Cooley anastomosis clamp	Aorta; aortic grafts
Cooley–Derra clamp	Graft limbs
Cooley pediatric clamp	Common femoral artery, saphenofemoral junction
Self-Compressing (No Applicator Required)	
Gregory carotid “soft” bulldog	Small vessels
Potts bulldog – straight and angled jaw	Small vessels
DeBakey bulldog	Small vessels
Dietrich bulldog	Small vessels
Self-Compressing (Applicator Required)	
Yasargil aneurysm clip	Small vessels and branches
Heifitz clip	Small vessels and branches
Kleinert–Kutz clip – straight, angled, curved	Microvascular anastomoses
Louisville microvessel approximator	Microvascular anastomoses

Adapted from Hoballah JJ. *Vascular Reconstructions: Anatomy, Exposures, and Techniques*. New York: Springer-Verlag; 2000.

typically helpful when conducting a first rib resection through a transaxillary approach for thoracic outlet obstruction.

Vascular Sutures and Grafts

Sutures

Nonabsorbable sutures are used for vascular anastomoses and repairs. These sutures typically provide the tensile strength necessary to juxtapose and secure the vessels together until healing occurs. When prosthetic conduits are used in vascular reconstruction, the tensile strength provided by the sutures is needed indefinitely to maintain vascular integrity. Monofilament sutures are used for vascular reconstructions, although braided silk or polyester multifilament sutures can be used for ligation of vessels. Vascular sutures are usually double armed with a needle on each end to allow continuous suturing in both directions from the initial knot. Commonly used monofilament sutures include polypropylene, polybutester, and polytetrafluoroethylene (PTFE). Polypropylene sutures (Prolene, Ethicon Inc., Somerville, NJ; Surgipro and Surgilene, Covidien, Mansfield, MA) are made of a monofilament strand of synthetic linear polyolefin. These sutures tend to maintain their tensile strength over time. Prolene has little friction and good handling characteristics, becoming widely popular and probably the most commonly used suture material for vascular reconstructions. It is important to moisten the suture and surgical gloves with saline prior to tying the suture in order to avoid microscopic tears and fraying of the material, and prevent suture breakage. Polybutester is another monofilament made of a copolymer of polyglycol terephthalate and polytrimethylene terephthalate coated with polytribolate to reduce drag and improve tissue passage. PTFE sutures were developed to minimize needle hole bleeding associated with suturing PTFE grafts or patches by optimizing the diameters of the needle and the suture to plug the needle hole with a slightly oversized suture diameter. This material has excellent handling characteristics

TABLE 61.2 Suggested Needle Sizes

	NEEDLE BRAND AND SIZE			
Vessel Size[a]	Ethicon	USSC	Davis and Geck	Gore-Tex
Small (calcified tibial)	CC	DV-1	CV-311/DTE-10	PT-9
Small (tibial, internal carotid)	BV-1	CV-1	CV-310/TE-10, 11	TT-9
Small (tibial)	BV	CV	CV-309/TE-9	TT-12
Medium (common carotid, femoral, popliteal)	C-1	CV-11	CV-301/TE-1	TT-13
Large (common iliac)	RB-1	CV-23	CV-331/T31	TH-18
Large (aorta)	V7	V-20	DV-305/T-5	TH-26
Large (posterior wall of aorta)	MH	V26	CV-C00/T-10	TH-35

[a]For arterial anastomoses, the following suture and needle sizes are recommended: 2-0 or 3-0, aorta; 4-0, iliac arteries; 5-0, axillary, common carotid, common femoral, and superficial femoral arteries; 5-0 or 6-0, internal carotid, popliteal, and brachial arteries; 7-0 or 8-0, tibial and inframalleolar arteries.
Adapted from Hoballah JJ. *Vascular Reconstructions: Anatomy, Exposures, and Techniques*. New York: Springer-Verlag; 2000.

with low friction and drag coefficient, but must be securely tied to with multiple throws of the knot to avoid slippage. The needle and suture sizes vary, depending on the vessel. Suggestions are provided in Table 61.2.

Grafts

Selection of a graft type is an integral part of any vascular reconstruction. Polyester grafts of different shapes and structures are available to replace the thoracic aorta. Polyester and PTFE grafts are available as conduits for the abdominal aorta and infrainguinal vessels. Autogenous vein grafts are favored in many small arterial reconstructions. These grafts are discussed in further detail in Chapter 66 (Prosthetic Grafts).

BASIC VASCULAR TECHNIQUES

Open vascular surgery is conducted using the general principles of blood vessel exposure with proximal and distal control, along with the basic techniques of vascular reconstruction. These basic vascular techniques include thromboembolectomy, endarterectomy, creation and closure of an arteriotomy, and construction of bypasses or in-line graft replacement using end-to-side or end-to-end anastomoses.

Vascular Exposure and Dissection

Several excellent resources are available that describe the vascular anatomy and the variety of exposures available to the vascular surgeon[1–4] (see Ch. 55, Thoracic and Thoracoabdominal Vascular Exposure; Ch. 56, Abdominal Vascular Exposures; Ch. 57, Cerebrovascular Exposure; Ch. 58, Lower Extremity Arterial Exposure; and Ch. 59: Upper Extremity Vascular Exposure).

Initial Vessel Exposure

A basic concept of vascular exposure and dissection is to approach and expose the vessel by the most direct and expeditious route possible. Anatomic landmarks, skin characteristics, and location of a pulse are factors used to guide placement of the initial skin incision. For infrainguinal bypasses a palpable inflow pulse should always be prepped within the surgical field allowing for the possibility of a retroperitoneal extension. In most dissections, the vascular structures can be exposed between existing muscle bellies. If extensive muscle transection is required during dissection, the approach to the vascular structures should be reconsidered as an errant plane may have been encountered.

Following the incision, proper handling of the skin and soft tissue overlying the vessels is essential to prevent significant wound complications. Lymphatics are typically ligated and divided to avoid lymphorrhea and lymphocele. Use of electrocautery through lymph nodes should be avoided to prevent significant lymph leak or the need to excise larger lymph nodes, leaving dead space in the wound. Once the vascular sheath is identified and incised, the adventitia is retracted in one direction with dissection carried out in the tissue adjacent to the edge of the blood vessel wall. Maintaining intimate proximity to the arterial adventitia during dissection usually ensures an appropriate anatomic plane, thus enabling the vessel to be circumferentially skeletonized and encircled with a Silastic loop or umbilical tape (Dow Corning Corporation, Midland, MI). The basic surgical technique of gentle traction with counter traction is essential in vascular exposure. Traction on a vessel loop can be used to retract a vessel during dissection or mobilization. Gentle tension on the vessel loop is recommended to prevent injury to the intima.

Reoperative Vessel Exposure

Reoperative vascular exposure often poses a challenge, given the fibrous obliteration of the normal anatomic vascular planes. Sharp dissection is important with identification of side branches. When the surgeon is faced with a difficult "redo" operation, sharp dissection with a no. 15 knife blade may allow better management of the scar tissue than scissors and allow the surgeon to stay in the appropriate dissection plane. The belly of the blade can be angled away from the vessel at approximately 45 degrees to "carve" the scar away from the arterial wall. The principle of dissecting from "known to unknown" can also be useful in preventing vessel injury during re-exposure with proximal control of the artery outside of the scarred area – an important consideration should an inadvertent injury occur.

A significant concern with a reoperative femoral artery exposure is injury to the profunda femoris artery. To avoid this occurrence, the superficial femoral artery can be exposed in the distal part of the dissection, where minimal scarring exists. The dissection is then carried along the medial aspect of the superficial femoral artery and progresses proximally. Typically, the common femoral vein is identified during the process, revealing an important dissection plane. Once the inguinal ligament is reached, the common femoral artery is encircled with a loop. The direction of the dissection is then reversed and continued back distally toward the superficial femoral artery. The area of size transition between the common and superficial femoral arteries often identifies the location of the profunda femoris artery. The profunda femoris artery can be controlled at its origin by passing a vessel loop underneath the superficial femoral artery and then retrieving it just proximal to the common femoral bifurcation by passing a right angle above and below the profunda femoris from the same side (lateral) in order to avoid injury to deeper branches with a circumferential passing of the right angle. In cases of extensive scarring, the profunda femoral branch can be controlled with a balloon occlusion catheter after common femoral arteriotomy, to avoid potential injury during profunda dissection.

Anticoagulation

Before interrupting blood flow, the patient may be anticoagulated to prevent thrombosis or embolization due to a static column of blood created between the clamp and first major collateral branch. Unfractionated heparin at 75 to 100 U/kg is typically administered intravenously, approximately 3–5 minutes before blood flow interruption. Anticoagulation may be monitored by measuring the activated clotting time (ACT), aiming for a value of more than 250 seconds. While distal limb ischemia following aortic reconstruction often may result from distal embolization, unrecognized suboptimal anticoagulation may also be responsible. In patients with known heparin-induced thrombocytopenia, anticoagulation may be achieved with intravenous thrombin inhibitors such as argatroban (see Ch. 41, Anticoagulant Therapy).

Blood Vessel Control

Blood vessel control can be achieved using vascular clamps, balloon occlusion, vessel loops, pneumatic tourniquet, Rumel tourniquet, or internal occluders.

Vascular Clamping

Ideally, vascular clamps should be applied to a disease-free segment of the artery. Palpating the artery against a right-angle clamp can help determine the presence and extent of atherosclerotic plaque, which is often in a posterior location. In the presence of significant plaque, the artery should be dissected more proximally to identify a less diseased site for clamping. This situation is often encountered when clamping the common femoral artery, where plaque often extends to the level of the inguinal ligament. Further dissection proximal to the external iliac circumflex and inferior epigastric branches, however, usually reveals an external iliac artery that is more amenable to clamp placement. If clamping is necessary across an area of diseased artery, the clamp should be applied in a manner that opposes the soft part of the artery against the plaque without causing plaque fracture or vessel tear. Occasionally the plaque burden and calcification are so extensive that the only option is to identify a more proximal location for safe clamp placement. One example is supraceliac aortic control through the lesser sac, when clamping in the infrarenal or suprarenal location is not possible because of extensive calcification or scarring from previous surgery or an inflammatory process.

Balloon Occlusion

If plaque is circumferential or occupies more than 50% of the circumference, vascular clamps can fracture the plaque or tear the wall and may not provide adequate vascular control. This can be managed by occluding the artery from within using a compliant balloon occlusion catheter, such as the Fogarty catheter normally used to perform embolectomy, or a noncompliant balloon catheter used for angioplasty. There are also several compliant occlusion balloons that can be used to occlude the aorta during ruptured aneurysm repair, including Reliant (Medtronic, Minneapolis, MN), Coda (Cook, Bloomington, IN), and Equalizer (Boston Scientific, Natick, MA). Balloon occlusion can be used to control the external iliac artery in the presence of extensive calcification that extends beyond the most proximal part of the exposure. It is also useful for controlling the right common iliac artery during a left retroperitoneal abdominal aortic aneurysm repair, the profunda femoris artery during repair of a pseudoaneurysm of a femoral anastomosis, or the renal or visceral vessels during a thoracoabdominal aortic aneurysm repair.

Vessel Loops

Vessel loops are ideal for controlling small- to medium-sized vessels, such as the profunda femoris or popliteal arteries, and arterial side branches. Silastic vessel loops can be traumatic, however, if excessive tension is applied to them. A double loop, or Potts technique, can be helpful in the use of vessel loops by minimizing the tension required to obtain vascular control of small- or medium-sized arteries. Further, excessive tension on Silastic vessel loops for simultaneous proximal and distal control of a vessel may make an anastomosis or repair more difficult to perform properly. One way to avoid excessive tension on the artery in two opposing directions is to apply a vessel loop on the proximal side of the artery and a small Yasargil aneurysm clamp or bulldog clamp on the distal end of the artery (Fig. 61.25).

Pneumatic Tourniquet

A pneumatic tourniquet can be used for vascular control in the extremities and is ideal for infrapopliteal reconstructions. It allows for minimal exposure, dissection, and handling of the arteries, and may decrease the risk of spasm or injury caused by clamping of the tibial vessels. The tourniquet can be placed around the thigh or below the knee; usually a soft roll is applied

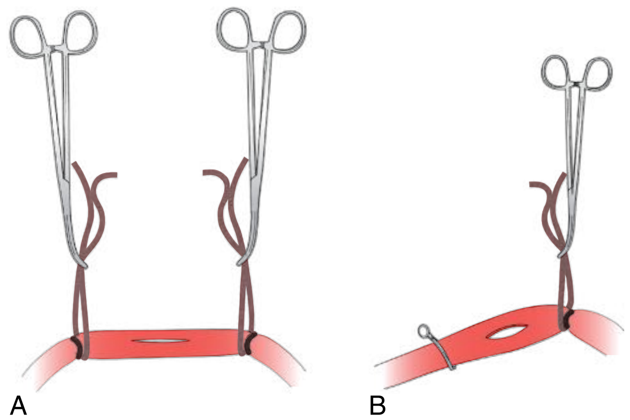


Figure 61.25 A vessel loop on the proximal side of the artery and a small Yasargil aneurysm clamp or bulldog clamp on the distal side of the artery can minimize tension on the anastomosis. (**A**) Pulling on both loops can result in tension on the arteriotomy. (**B**) Tension on the anastomosis is minimized when one loop is pulled and the other replaced with a bulldog clamp.

first, followed by the tourniquet. The leg is elevated, and an Esmarch compression wrap is used to wrap the leg from the foot in a cephalad direction expelling the venous blood from the leg. The tourniquet is then inflated to a pressure of about 250 mm Hg or 100 mm Hg above systolic pressure. It is essential to make sure the graft is well aligned and to mark the graft orientation before inflating the tourniquet. Bleeding occasionally occurs despite the tourniquet, and this can sometimes be controlled by increasing the pressure in the tourniquet. An additional clamp on the profunda femoris artery can also help control persistent bleeding. Sometimes calcified and incompressible arteries at the tourniquet site prevent this technique from completely controlling bleeding at the distal arteriotomy.

Other Techniques

Rumel tourniquets can be used for vascular control, but they can cause arterial wall damage in the presence of significant plaque. The Rumel tourniquet may be most useful during an endovascular aortic aneurysm procedure when there is a large sheath in an artery and persistent bleeding from the arteriotomy around the sheath. Pediatric Rumel tourniquets are useful to atraumatically secure carotid intraluminal shunts to control blood leak around the shunt, keeping blood flow to the brain while carotid endarterectomy is being performed. The use of internal coronary artery occluders can be useful to achieve vessel control in smaller, heavily calcified arteries. Florester internal vessel plastic tip occluders (Biovascular, St. Paul, MN) are available in various sizes. However, the surgeon must be comfortable using such occluders, and oversizing should be avoided to prevent intimal damage during insertion.

THROMBECTOMY AND THROMBOEMBOLECTOMY

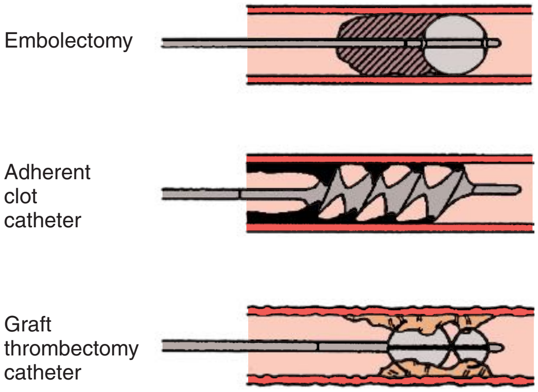
Basic Considerations

Surgical thrombectomy and thromboembolectomy must be mastered by every vascular surgeon because the need to perform these procedures to treat acute ischemia is not uncommon. Balloon thrombectomy also allows for the removal, inspection, and pathologic examination of the occlusive clot while restoring blood flow expeditiously. A vessel may become acutely occluded because of a thrombotic or embolic process. Thrombosis frequently occurs proximally and distally to an embolus because of resulting stagnant flow, hence the term *thromboembolectomy*. Balloon embolectomy is often paired with thrombectomy to remove the thrombus. Several issues need to be addressed during the performance of a thromboembolectomy procedure, including the location and shape of the arteriotomy used to extract the thrombus, selection of the thrombectomy catheter, and performance of the procedure with minimal blood loss and injury to the arterial system. In addition, steering the catheter into the appropriate location and extracting all the offending thrombi are essential to the success of the procedure.

Thromboembolectomy Catheters

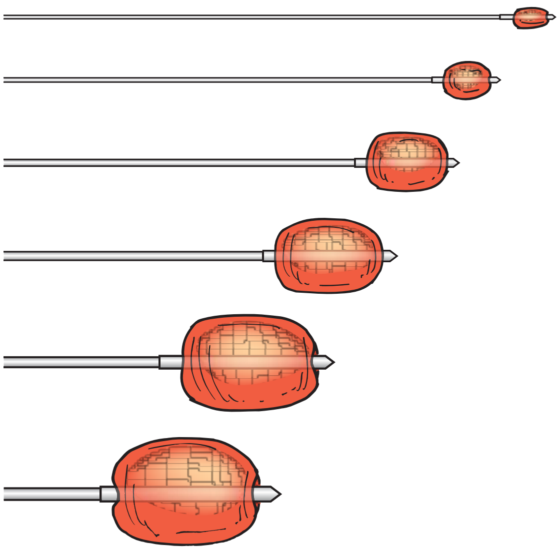
A wide variety of thromboembolectomy catheters are available (eFigs. 61.26 and 61.27). The standard ones are balloon catheters that vary in size, length, and maximal balloon inflation. These catheters are typically available in sizes from 2 to 7F. Saline solution is used to inflate the balloon, except for the 2F balloon, which requires air insufflation for easy deflation. The diameter of the fully inflated balloon is 4 mm for the 2F catheter, 5 mm for the 3F, 9 mm for the 4F, 11 mm for the 5F, 13 mm for the 6F, and 14 mm for the 7F. Size 2F catheters are typically used for very small pedal or hand vessels. The most commonly used catheters are 3 to 5F. A 3F Fogarty catheter is typically used for tibial vessels, a 4F Fogarty catheter is used for vessels the size of the superficial femoral and popliteal arteries; it can also be used initially for external iliac arteries. A 5F Fogarty catheter is typically used for external iliac or common iliac arteries. Size 6F and size 7F catheters can be used for thrombectomy of an aortic femoral graft or a saddle aortic embolus. A venous thrombectomy catheter with a large, lower pressure balloon is also available.

Standard balloons are made of latex; however, latex-free embolectomy catheters are available for patients with latex allergies. In addition, balloon catheters that can be introduced over guide wires for fluoroscopically assisted thromboembolectomy are also available in sizes 3, 4, 5.5, 6, and 7F. Special catheters have been devised for adherent clots. The Fogarty adherent clot catheter (Edwards Life Sciences, Irvine, CA) features a spiral-shaped, latex-covered stainless-steel cable that assumes a corkscrew shape when retracted, thus expanding the surface area to entrap fibrous material. It is marketed for adherent clots resistant to removal by standard elastomeric balloons in both native arteries and synthetic grafts. The Fogarty graft thrombectomy catheter (Edwards Life Sciences) is designed to remove tough thrombus from synthetic grafts; it has a flexible wire coil at the distal end and expands when retracted to form a double-helix ring that acts as stripper, forming a plane between the graft and the adherent material. This catheter is not intended for native vessels and is marketed for use in PTFE dialysis grafts and aortobifemoral grafts (eFig. 61.28).



eFigure 61.26 Thromboembolectomy catheters – diagram.

eFigure 61.27 Thromboembolectomy catheters.



eFigure 61.28 Fogarty catheters.

Technique

Arteriotomy Location and Shape

The arteriotomy for clot extraction can be performed in a location proximal or distal to the embolic or thrombotic process. Site selection depends on the ease of exposure, anticipated location of the thrombus, and ease of arteriotomy closure. In patients with acute lower extremity ischemia, the common femoral artery is an ideal site for clot extraction. A patient with an aortic saddle embolus or a popliteal embolus can be managed by thromboembolectomy through the common femoral artery. The common femoral artery and its bifurcation are easy to expose, and closure of the arteriotomy is easily accomplished in this relatively large artery. Further, the procedure can be performed under local anesthesia. If thromboembolectomy proves to be inadequate, a site closer to the location of the thrombus may be required. Before performing the thrombectomy, it is important to ensure that the patient is adequately anticoagulated.

The selection of a transverse versus longitudinal arteriotomy for catheter access is influenced by the size of the vessel, the cause of the embolus or thrombus, and the presence of plaque in the vessel. A transverse arteriotomy is less likely to narrow the vessel upon closure and may be preferred when dealing with an embolic process, and can be easily closed with interrupted sutures to avoid purse-stringing and narrowing of the lumen of the artery at the site. When the occlusive pathology is due to an atherosclerotic and thrombotic process, or when significant arterial plaque is present, a longitudinal arteriotomy should be considered. This allows endarterectomy and patch angioplasty of the diseased artery after thromboembolectomy with the option to incorporate the longitudinal arteriotomy into a bypass anastomosis if additional revascularization is required. A patch may be indicated to close a longitudinal arteriotomy to avoid significant narrowing of the vessel lumen.

Minimizing Blood Loss

During the process of establishing inflow, a balloon catheter is passed proximally for the estimated distance just short of the culprit lesion to remove as much thrombus as possible prior to crossing and removing the offending process, inflated, and withdrawn through the arteriotomy (Fig. 61.29). This may also allow better facility in crossing the culprit lesion with smaller catheters. After crossing the culprit lesion, allow brief but unrestricted bleeding to flush any debris or thrombi that may still be present in the proximal part of the vessel or the graft. This step can be repeated until strong pulsatile flow is established, and at least two successive embolectomy passes yield no remnants of clot remaining in the artery. Blood loss can be minimized by applying Silastic vessel loops in "Potts" fashion around the artery and gently pulling on the loop to snug around the catheter while it is being advanced proximally or distally.

When performing thromboembolectomy of a prosthetic bypass or the limb of an aortobifemoral bypass, vessel loops are not adequate to control bleeding. The surgeon can often control bleeding manually by squeezing the arterial wall between the index finger and thumb with one hand and withdrawing

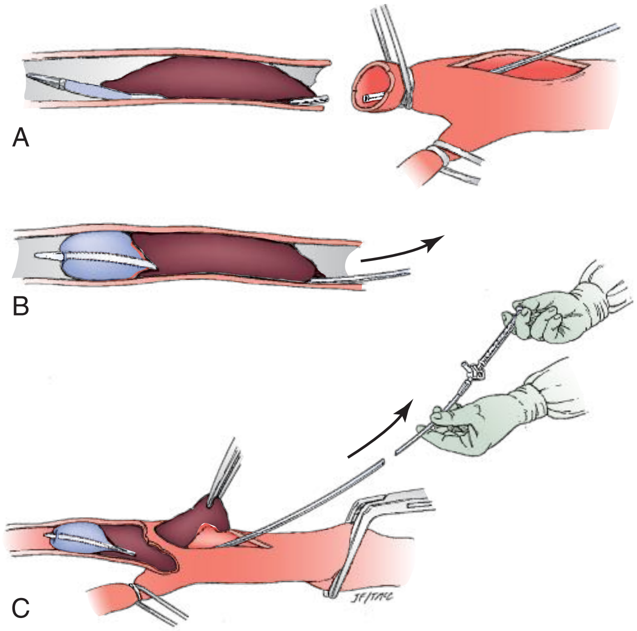


Figure 61.29 A balloon thromboembolectomy catheter is passed proximally for an estimated distance (**A**), inflated (**B**), and withdrawn through the arteriotomy, with bleeding controlled by double-looped Silastic tape (**C**).

the inflated catheter with the other hand. Depending on the anatomy and the presence of scarring, bleeding may be excessive if finger control is used while passing the Fogarty catheter through the proximal artery. In such situations, use of a Fogarty soft-jaw clamp is recommended (Fig. 61.30). The soft jaws are intended to oppose the blood vessel walls just enough to prevent bleeding and still allow the thromboembolectomy catheter to be advanced or withdrawn. The jaws are then opened as the inflated thromboembolectomy catheter is being withdrawn. The clamp is reapplied once the balloon catheter is pulled out of the vessel and vigorous blood flushing has occurred.

Minimizing Vascular Injury

Vascular injury can occur from thromboembolectomy and manipulation of the balloon catheter, inadvertent placement of the balloon tip, or from over-inflation of the balloon. Injury can also occur during insertion, advancement, or withdrawal of the thromboembolectomy catheter. During insertion, it is important to ensure that the catheter is being advanced intraluminally. The catheter can inadvertently pass into a subintimal plane, and inflation and withdrawal of the catheter in that situation can cause arterial dissection or disruption. Hence it is very important to perform the procedure gently and be cognizant of any resistance during passage of the catheter. If the catheter does not advance freely, it may be in a side branch or abutting a curve in the artery. Further forceful advancement can result in either perforation or penetration into the subintimal plane. Another cause of injury is over-inflation of the balloon catheter and its withdrawal; this can result in significant shearing of the intima, with intimal disruption and damage. Balloon over-inflation can also result in rupture of the vessel or pseudoaneurysm formation.

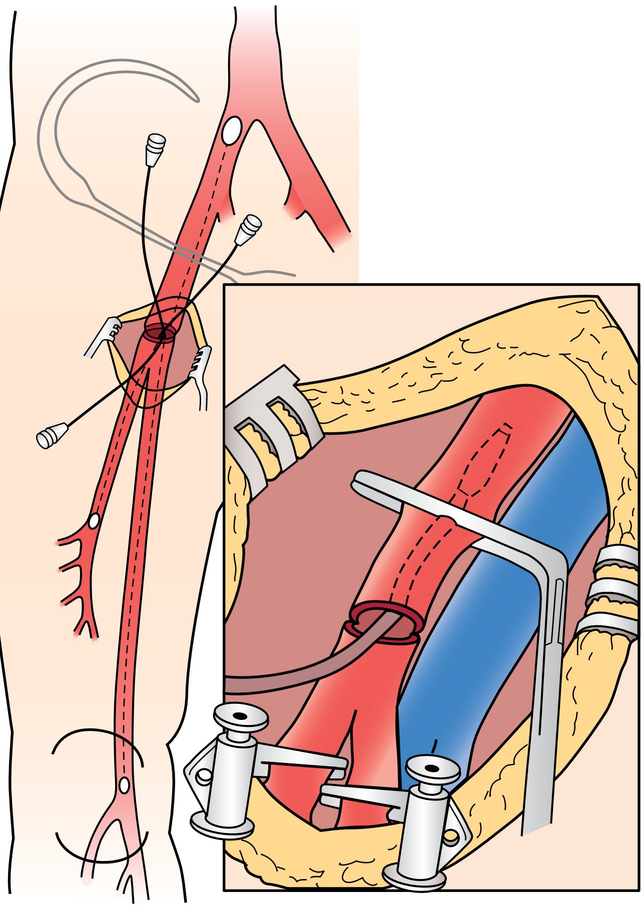


Figure 61.30 The Fogarty soft-jaw clamp may be able to appose the blood vessel walls just enough to prevent bleeding and still allow manipulation of the thromboembolectomy catheter.

Several steps are helpful to minimize vascular injury during balloon thromboembolectomy. Selection of an appropriately sized thromboembolectomy catheter is important. Before inserting a thromboembolectomy catheter, test the balloon, visualize its size, and get a feel for its inflation characteristics. It is a good practice to limit the fluid used in the syringe to the minimum amount needed for full inflation. This protects against over-inflation of the balloon when it deployed in the vessel. Another helpful maneuver is to externally measure the distance from the arteriotomy to the location of the thrombus. This helps determine whether the catheter has reached its desired destination and limit unnecessary insertion of the catheter beyond the thrombus. Once the catheter has reached its maximal advancement or the desired location, the balloon is gently inflated while the catheter is slowly withdrawn until tactile friction is sensed by the surgeon. At that point, the balloon should not be further inflated. The catheter is then retrieved, maintaining the same amount of friction and tension. The balloon may have to be further inflated as the catheter is being pulled into a more proximal location, where the artery's caliber may increase. The inflation, deflation, and withdrawal of the balloon should be a dynamic and variable process to accommodate changes in vessel caliber.

The presence of "back bleeding" does not ensure complete thromboembolectomy. An intraluminal thrombus burden may still exist despite multiple balloon passes and resulting back bleeding. This is especially true when performing thromboembolectomy of the infrapopliteal vessels. For example, the catheter may repeatedly pass into the peroneal artery, while significant thrombus remains in the anterior and posterior tibial arteries. To avoid leaving residual thrombus, the reperfused limb or organ should be carefully examined following arteriotomy closure. An intraoperative angiogram may be obtained if the perfusion does not appear satisfactory. It may also be obtained before closing the arteriotomy to assess the completeness of the thromboembolectomy.

Fluoroscopy-Guided Thromboembolectomy

Another option is to perform the thromboembolectomy procedure under fluoroscopic guidance.[5] Fluoroscopy can be used from the start of the procedure, or it can be used selectively to retrieve thrombi that cannot be extracted with non-image-guided thromboembolectomy. The balloon is first tested under fluoroscopy to appreciate its shape when inflated and deflated, and an angiogram through the arteriotomy can be performed before passing the catheter. This may allow a better understanding of the anatomy and the location of the thrombus. Visualizing the catheter as it travels down the leg provides significant information about its location and course. When the balloon is inflated under fluoroscopy, the surgeon can appreciate the degree of inflation required. To best image the balloon, it should be inflated using contrast material diluted to 25% as a greater contrast concentration prevents rapid deflation of the balloon due to excessive viscosity. Over-inflation can be avoided, and inadvertent positioning of the catheter into a side branch before balloon inflation can be detected and corrected. Further, if the catheter passes through an area of stenosis, a change in the shape of the inflated catheter indicates the location of the stenosis.

When performing an infrapopliteal thromboembolectomy, the catheter can be directed into the desired tibial vessel by bending its tip and rotating it into the desired location. One approach is to use two balloon catheters; one is inflated at the origin of the tibioperoneal trunk, forcing the second one toward the anterior tibial artery (Fig. 61.31). Another technique is to use a 7 or 8F multipurpose guiding catheter and park the catheter tip at the level of the popliteal trifurcation. The balloon catheter is introduced through the guiding catheter, and using the curve of the guiding catheter, the balloon catheter is directed into the desired location. The balloon is inflated and withdrawn together with the guiding catheter. Another approach is to use over-the-wire balloon embolectomy catheters. Standard endovascular techniques are used to introduce a wire into the desired vessel, followed by advancement of the thromboembolectomy balloon over the wire. The 5.5F catheter can be advanced over a 0.035-inch wire; the 3F catheter, which is typically the size needed for tibial vessels, is passed over a 0.018-inch wire. The process of withdrawing the catheter over the wire may be frustrating if an 0.018-inch wire is used, because often the wire dislodges and retracts simultaneously with the catheter. This difficulty rarely occurs if a stiff 0.035-inch hydrophilic wire is used.

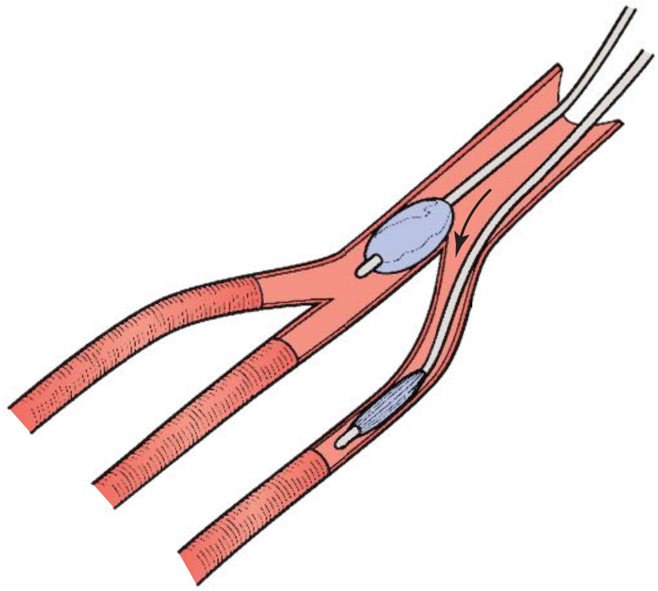


Figure 61.31 One approach to guide the thromboembolectomy catheter into the anterior tibial artery is to use two balloon catheters, inflating one at the origin of the tibioperoneal trunk and thus forcing the second one toward the anterior tibial artery.

The advantages of fluoroscopy include the performance of a controlled thromboembolectomy with visualization of postprocedure success. There is also the opportunity for endovascular intervention when appropriate, such as balloon angioplasty and stenting of a dialysis graft venous stenosis, distal anastomosis of a femoropopliteal bypass, or occlusive iliac pathology.

ENDARTERECTOMY

Basic Considerations

Endarterectomy involves the removal of atherosclerotic plaques compromising the arterial lumen. Carotid endarterectomy is often the sole intervention for occlusive disease at the carotid bifurcation. Similarly, endarterectomy of the common femoral and profunda femoris arteries may be the sole procedure to treat lower extremity occlusive disease, or can be combined with a proximal or distal endovascular intervention thereby performing multilevel revascularization through limited access. Endarterectomy can also be incorporated into the construction of the proximal anastomosis of an infrainguinal bypass. Similarly, a common femoral endarterectomy can be performed while the common femoral artery is used as an access to perform an endovascular repair of an abdominal aortic aneurysm. Endarterectomy results in removal of the thickened intima and inner media, leaving behind the outer part of the media and the adventitia and should achieve a smooth transition at the endpoint of the endarterectomy plane in the direction of arterial flow. “Tacking sutures” can be considered to secure such an endpoint. It should not be performed in an aneurysmal artery because the remaining adventitial layer is too weak and degenerated to withhold suturing or arterial pressure. Several methods of endarterectomy have been described; open, semi-closed, eversion, orificial, and extraction endarterectomy.

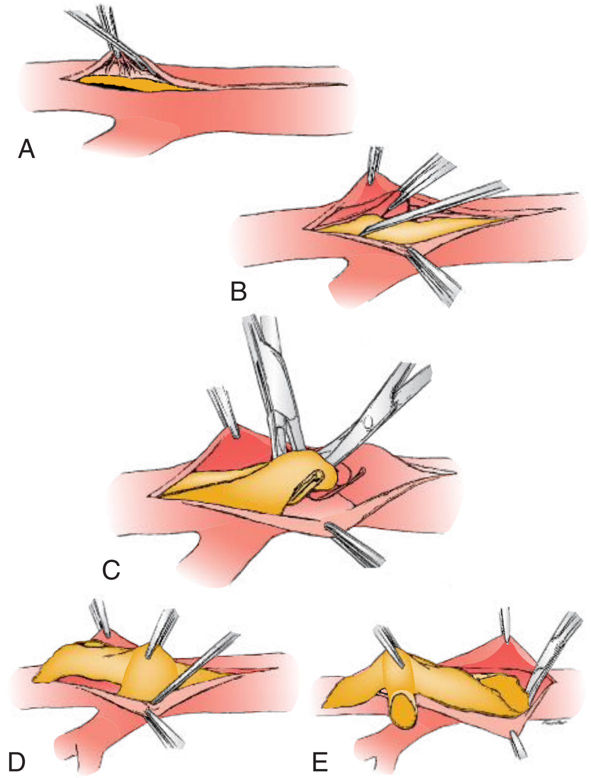


Figure 61.32 (**A–E**) In the open endarterectomy technique, the vessel is opened longitudinally at the site of disease. The plaque is then separated from the vessel wall in the direction of the arteriotomy and removed.

Open Endarterectomy

In the open endarterectomy technique, the artery is opened longitudinally at the site of disease. The plaque is then separated from the artery wall in the direction of the arteriotomy and removed (Fig. 61.32). The arteriotomy can be closed primarily or often with patch angioplasty. Being in the right anatomic plane is essential to performing an adequate endarterectomy. This can be accomplished by holding the edge of the adventitia with forceps and pulling it away from the plaque. A plane is then developed between the plaque and the outer media or adventitia. Using a Freer elevator, the outer media and adventitia is typically pushed away from the plaque as the “body is dissected from the plaque”. The endarterectomy plane is developed on each side of the artery and advanced posteriorly until circumferential. When dissecting in the appropriate plane, the dissecting instrument meets little resistance. It is very important to stay in the same plane if the endarterectomy is approached from both sides of an artery to meet the same point posteriorly for a clean endarterectomy specimen. Proximally, when a normal part of the wall is reached, either the plaque “feathers out” or it is transected flush with the arterial wall without leaving a significant protruding edge. Completion of the distal endpoint of the endarterectomy can be challenging. Often the plaque clearly

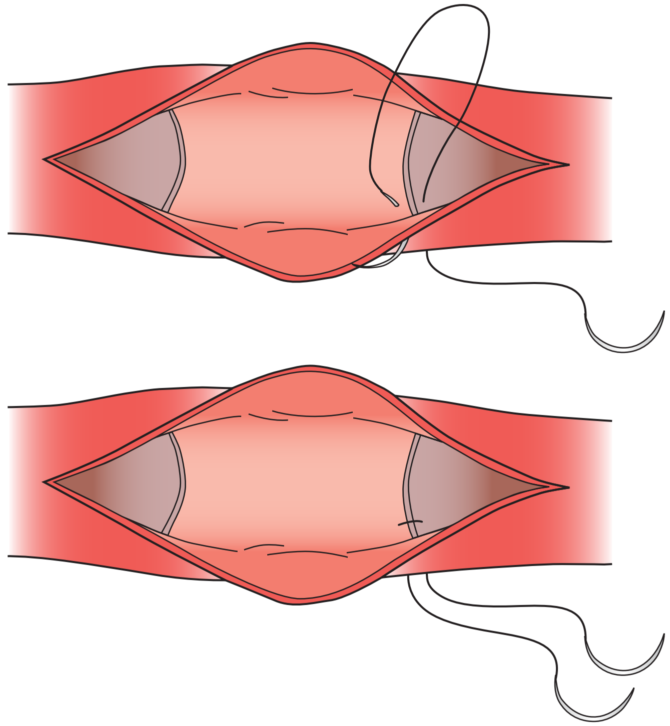


Figure 61.33 Endarterectomy plaque is tacked using multiple interrupted sutures, with one end of the suture placed 1 mm distal to the endpoint and the other end placed at the junction of the endarterectomy and the endarterectomized surface.

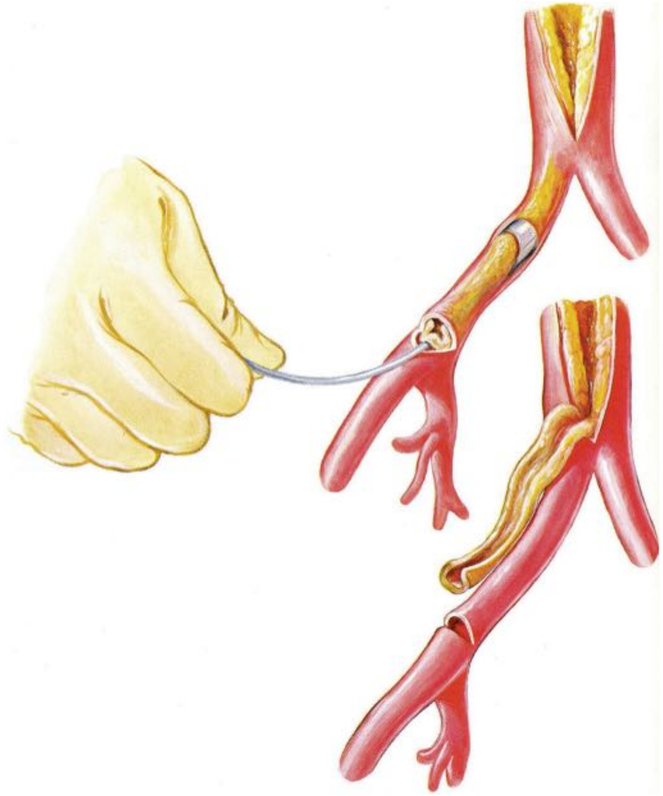


Figure 61.34 Plaque is cored out as a cylinder from the intervening segment, with the help of special ringed intra-arterial strippers.

ends as a tongue into a normal soft artery. In this case, the endarterectomy plane is moved to a more superficial level, allowing the plaque to feather out from the wall. This provides a desirable flat distal endpoint, with a very smooth transition from the endarterectomized to the nonendarterectomized surface. On other occasions, the plaque may extend further distally, with no visible end. In that situation, the plaque can be freed as much as possible with subsequent gentle distal traction in a coaxial plane with the artery to enhance removal with a favorable endpoint. When transection of the plaque is necessary, resulting in a shelf between the endarterectomized and nonendarterectomized surface, suture tacking of the intima and plaque to the adventitia is necessary to avoid plaque lifting, dissection, or thrombosis upon vessel reperfusion. To place a tacking suture, one end of the suture secures the edge of the remaining plaque, and the other end just beyond the junction of the endarterectomized surface (Fig. 61.33). Multiple interrupted sutures may be required to adequately secure the plaque edge to the arterial wall. This may be appropriate for either the proximal or distal end of the endarterectomy, although tacking the proximal end may not be as necessary because the direction of blood flow does not lift or dissect the flap. However, if the proximal plaque is thick and protrudes into the lumen, proximal tacking sutures may be warranted. Diligent inspection of the endarterectomized luminal surface should be performed to remove any residual or loose fibers in the media and other debris that can be peeled away in a circumferential manner. It is essential to create a debris-free surface area at the endarterectomy site before vessel closure and restoration of blood flow.

Semiclosed Endarterectomy

The semiclosed endarterectomy technique was designed to avoid opening the artery longitudinally for the full extent of disease and thus circumvent a long arteriotomy closure. Typically, the artery is opened in a proximal and a distal location. The plaque is first dissected and transected at the proximal level; then it is cored out as a cylinder from the intervening segment with special ringed intra-arterial strippers, transected again at the level of the distal arteriotomy, and removed (Fig. 61.34). With this technique, closure of what would have been a long arteriotomy is replaced by closure of two small arteriotomies, one proximally and one distally. In a modification of the semiclosed technique, only one incision is made in the artery. The plaque is crushed manually or with the help of a clamp at the other end, eliminating the need for the second arterial incision, which is usually used to transect the plaque. Moll ring cutters allow sharp transection of the plaque from the remote site (Fig. 61.35) – hence the term *remote endarterectomy*. The disadvantage of this technique is the unpredictability of the endpoint. To address this concern, angioplasty with stent deployment can be performed to secure the distal endpoint. During this portion of the procedure, intravascular ultrasound is helpful to make certain that guide wires and therapeutic devices are intraluminally positioned. This technique has been successfully used in the external iliac and superficial femoral arteries.

Eversion Endarterectomy

This form of endarterectomy has become increasingly popular as a method of carotid endarterectomy (see Ch. 93, Carotid

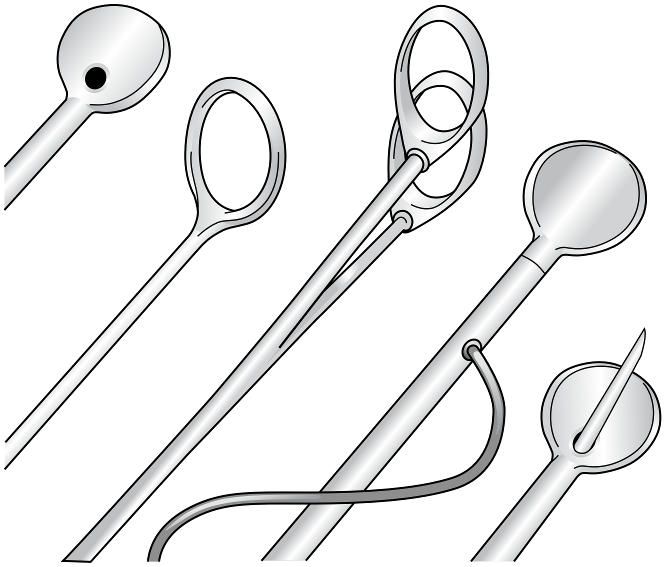


Figure 61.35 Moll ring cutters, spatula, and re-entry needle system.

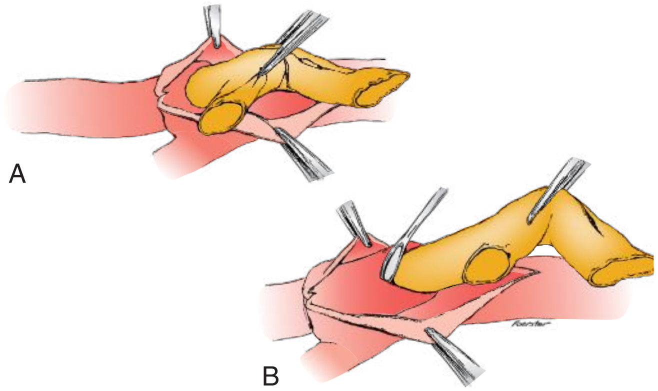


Figure 61.36 (**A,B**) As the plaque is being pulled out of the artery, the adventitia is retracted backward and the artery is pushed forward from within, causing the plaque to protrude and allowing it to be extracted from the artery.

Endarterectomy). In the eversion technique, the artery is transected, and the vessel wall is everted. The outer layer of the blood vessel, which includes the adventitia and part of the media, is held with forceps and gently lifted away from the plaque. The plaque core is developed circumferentially and held firmly with the forceps. As the plaque is being extracted from the artery, the adventitia is retracted backward, and the artery is pushed forward from within, causing the plaque to protrude and be separated from the outer arterial media and adventitia (Fig. 61.36). It is then transected when an appropriate endpoint is reached. This technique requires mobilization of an arterial segment with enough length to allow for eversion and reattachment.

Orificial and Extraction Endarterectomy

Orificial endarterectomy is a modification of the eversion technique used to treat occlusive disease at the orifice of an artery. Typically, the orifice of the artery has been exposed through the lumen of the vessel (Fig. 61.37). The plaque is extruded from the orifice by pushing the artery distal to the plaque toward the orifice in an everting manner. In extraction endarterectomy, a clamp

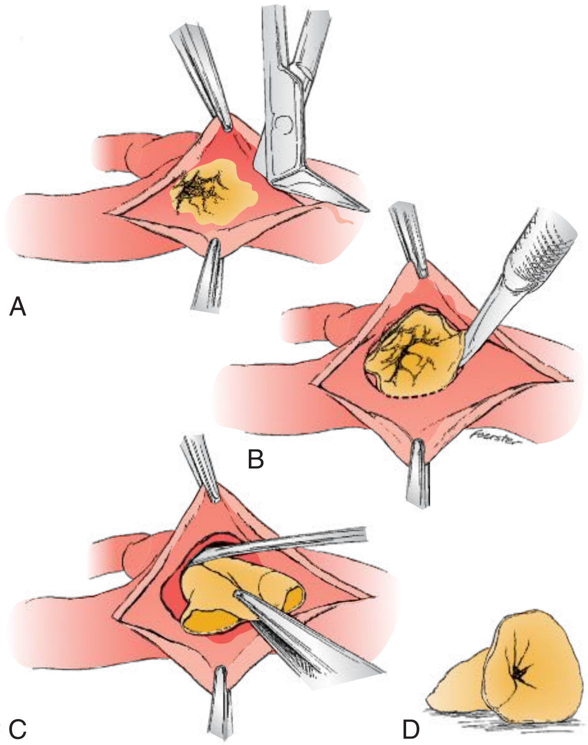


Figure 61.37 (**A–D**) Orificial endarterectomy is a modification of the eversion technique used to treat occlusive disease at the orifice of an artery.

is introduced into the orifice and used to grab the distal plaque or plaque remnant and extract it from the lumen. Generally, this technique is applicable only if the plaque ends a short distance beyond the orifice. Furthermore, because the endpoint is not under direct vision, it must be carefully assessed intraoperatively to ensure that a distal flap is not created after restoring blood flow. This is an especially important technique for establishing perfusion to the profunda femoris artery during femoral thromboendarterectomy. However, if the plaque extends further into the profunda, the endarterectomy needs to be done under direct inspection by extending the incision onto the profunda, and then patching this artery. If the endarterectomy of the common femoral artery needs to be extended to the superficial and profunda femoris arteries, the adjacent walls of both arteries can be sutured together using a running suture to create a common channel, which is then patched. This technique of "syndactylization" can be used in any location where two adjacent branches need to be endarterectomized to avoid patching two arteries separately.

ARTERIOTOMY CLOSURE

An arteriotomy can be closed either primarily or with a patch. The choice of a closure method depends on various factors, including the size of the artery, the direction and shape of the arteriotomy, and the degree of atherosclerotic involvement of the artery.

Primary Closure

Most transverse arteriotomies can be closed primarily even in smaller arteries measuring 2 mm in diameter, such as a radial or

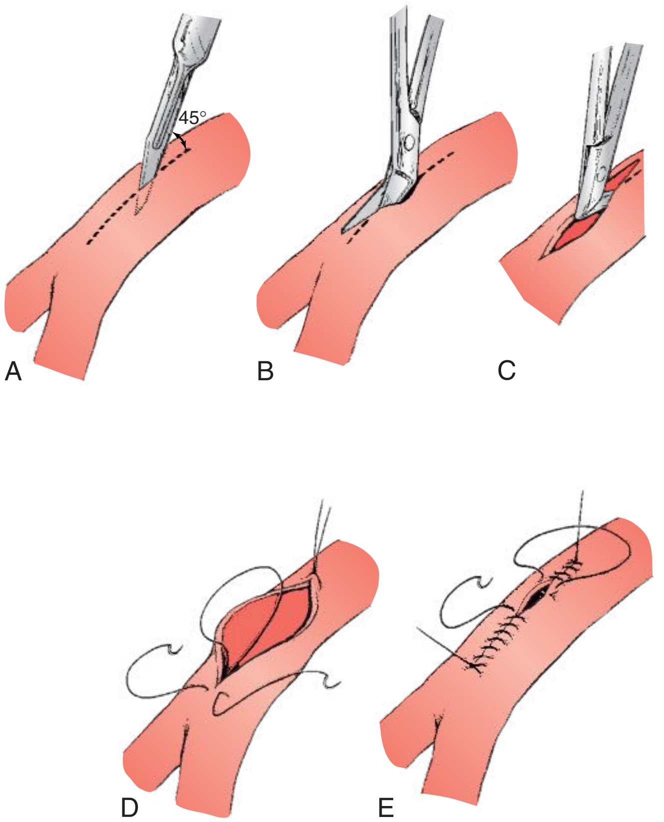


Figure 61.38 (**A–E**) Primary closure is performed most expeditiously using a continuous running suture technique.

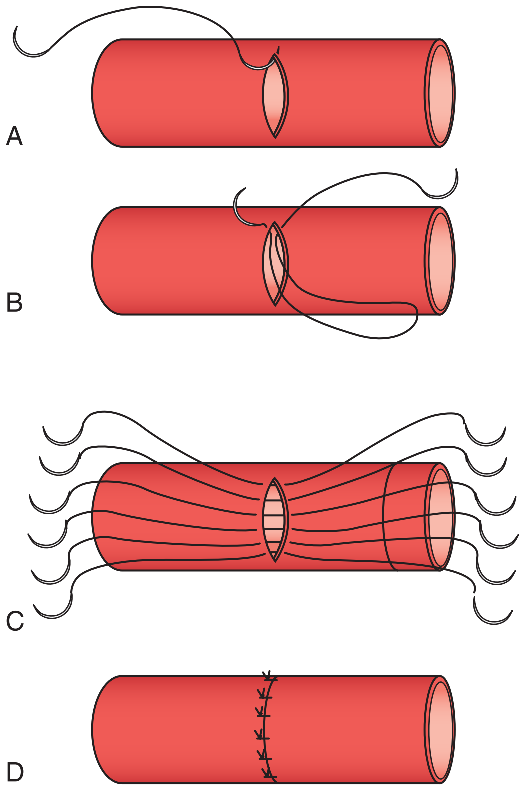


Figure 61.39 (**A–D**) An interrupted suture technique is preferable in the presence of significant plaque.

posterior tibial artery. Similarly, primary closure of longitudinal incisions is performed if the vessel is not diseased and has a diameter that would tolerate the mild narrowing that may occur. A typical example is closure of a longitudinal arteriotomy in the common carotid artery or common femoral artery.

Primary closure is most expeditiously performed using a continuous running suture technique (Fig. 61.38). A basic concept in the placement of arterial sutures during closure is to include all layers of the vessel wall. Adventitial fibers should be trimmed and not allowed to protrude into the lumen because they can be thrombogenic. The needle is preferentially introduced from the intimal side of the vessel toward the adventitial side; "inside to outside." In the presence of atherosclerotic plaque, a needle introduced from the adventitial side can push the plaque away from the arterial wall and create a site for dissection or thrombus formation. In the continuous suture technique, the needle is then introduced from the adventitial surface of one wall to the intimal surface of the opposite wall. Thus, primary closure with a continuous suture is most suitable in disease-free arteries, endarterectomized vessels, prosthetic bypasses, or veins. The sutures should be evenly placed throughout the length of the suture line, and the depth and advancement should be carefully monitored. Sutures placed too deep can result in focal narrowing of the lumen.

In the presence of atherosclerotic plaque at the arteriotomy site, or, with smaller diameter vessels, an interrupted suture technique is considered. When closing transverse arteriotomies, interrupted sutures can be placed individually and then tied after all are placed, to allow better visualization of each suture placement (Fig. 61.39). This allows exact placement of all the sutures, with the needle being introduced from the intimal side and exiting from the adventitial side of the vessel. In addition, the interrupted closure technique can aid in preventing narrowing during the closure of transverse arteriotomies in small diameter arteries.

Patch Closure

When primary closure is expected to cause significant luminal narrowing of an arteriotomy, patch closure should be performed. There are also data to support patch closure to improve the results of carotid endarterectomy. Several technical and nontechnical factors may play a role in the decision to perform patch closure. Technical factors include an artery less than 5 mm in diameter, the presence of significant atherosclerotic plaque at an arteriotomy site, a jagged arteriotomy, or a very tortuous artery. Furthermore, if there is loss of area in the vessel wall or lumen narrowing pathology that cannot be excised, such as neointimal hyperplasia, closure with a patch is indicated. Nontechnical factors include risk factors that predispose to restenosis, such as hyperlipidemia, heavy smoking, female gender, and a history of recurrent stenosis. The advantage of patch closure is that it allows the needle to be introduced constantly from the intimal aspect of the arterial wall. This eliminates the possibility of pushing a plaque fragment into the arterial lumen and precipitating thrombosis

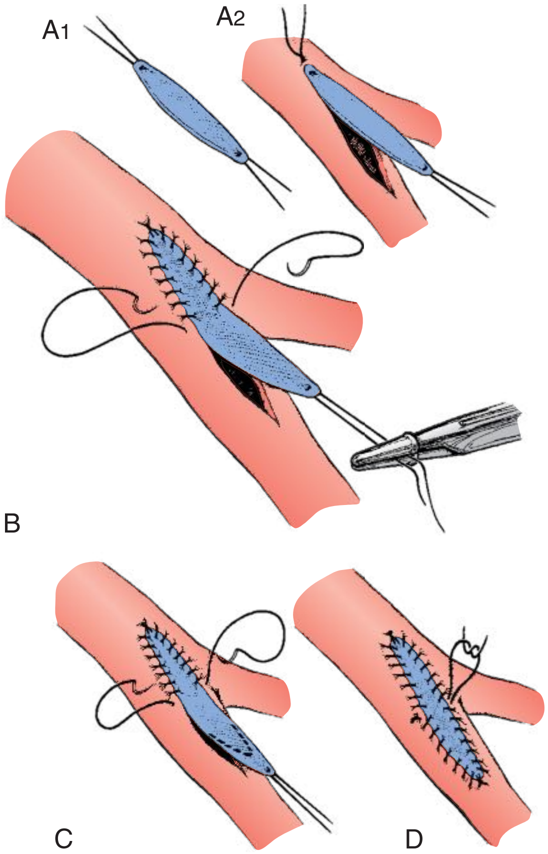


Figure 61.40 (**A–D**) The simplest technique is to place one suture on each apex of the patch and run both sutures on each side of the patch.

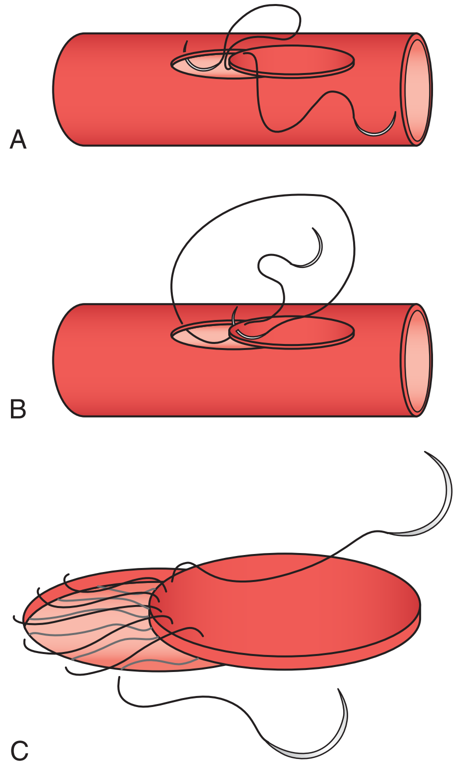


Figure 61.41 (**A–C**) In a parachute closure, the suturing can be started at the apex or a few bites off the apex without tying of the suture.

or dissection. Patch closure also allows adequate arterial purchase in the patch and in the artery without compromising the lumen; taking large bites of the artery has the theoretical advantage of controlling the formation of future pseudoaneurysms. Nevertheless, the bites should be placed carefully, with matching depth and even advancement. Otherwise, undesirable lumen narrowing may occur. When performing patch closure, the width of the patch should be selected to accommodate the vessel size. An overly wide patch can result in excessive redundancy in the arterial patch lumen and act as a nidus for thrombus formation.

Several techniques can be used for closure of a patch. The simplest technique is to place one suture on each apex of the patch and run both sutures on each side of the patch (Fig. 61.40). Alternatively, when suturing in a deep location, the patch can be closed using a parachute technique. In a parachute closure, suturing is started at the apex or a few bites off the apex without tying of the suture (Fig. 61.41). Suturing is continued until approximately three or more bites are placed on both sides of the center of the apex. The patch is then pulled down while intermittent tension is applied to the suture line. When the suture line is pulled, it is helpful to wet the suture with saline solution; be sure that it is clean from dried blood, and wiggle it back and forth from both ends while pulling the patch with a forceps, keeping the suture between the patch and the arterial apex under slight tension.

TRANSECTED OR END-TO-END VESSEL RECONSTRUCTION

The method used to close a transected vessel depends on its size and intraluminal pressure. Small arterial and venous branches are typically controlled by simple ligature with nonabsorbable suture material or the use of metal clips. Vessels with diameters ranging from 3 to 5 mm are usually controlled by suture ligatures, especially if the vessel is short. Larger vessels are typically closed with a running nonabsorbable suture. If the vessel has a low intraluminal pressure, such as in a large transected vein or the distal end of a transected artery, an over-and-over continuous running suture is usually sufficient to secure hemostasis. However, if the vessel is the proximal end of a transected artery, a single row of continuous sutures may not be adequate. This is especially true when closing an aortic stump after the removal of an infected aortic prosthesis. In such situations, two rows of sutures are preferred to secure hemostasis. The first row is usually constructed using horizontal mattress sutures, which can be placed using a continuous or an interrupted technique. The second layer is typically a continuous over-and-over running suture. The proximal row is meant to decrease the pressure and tension on the distal suture line (Fig. 61.42). In the case of a small arterial reconstruction or an end-to-end venous anastomosis, the "four quadrant" technique is advantageous. This involves a suture placed and tied at the toe and heel of a spatulated anastomosis. Each suture is then run to the middle of the anastomosis and tied again to provide four points of fixation and prevent constriction (see below).

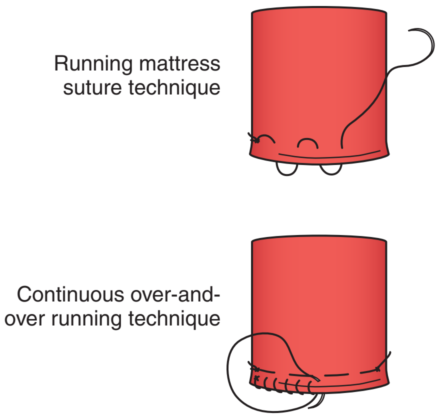


Figure 61.42 The *top panel* shows a running mattress suture technique. The *bottom panel* shows a continuous over-and-over running technique.

REPLACEMENT AND BYPASS PROCEDURES

Vascular replacement or bypass procedures are typically performed to manage occlusive disease or to replace aneurysmal or injured vessels. A variety of anastomotic techniques are employed in these procedures. The technique selected depends on the procedure, the vascular pathology, and the anatomic location of the operative field. Considerations for bypass anatomy include adequate inflow, outflow, and choice of conduit.

Basic Considerations

When creating a bypass to treat lower extremity occlusive disease, the reconstruction should be performed with preservation of the existing circulation. As a result, the proximal and distal anastomoses are typically performed in an end-to-side manner. Such a configuration allows the maintenance of antegrade flow in the native vessel at the level of the proximal anastomosis. Ideally, the distal anastomosis is placed in a disease-free segment of the vessel distal to the occlusive pathology. An end-to-side configuration at the distal anastomosis allows the maintenance of retrograde flow through all patent branches (Fig. 61.43).

Occasionally, disease in the artery requires the creation of an anastomosis with an end-to-end configuration. When treating aneurysmal disease, the aneurysm is typically replaced by interposing a new conduit using end-to-end anastomoses. Aneurysmal pathology is sometimes treated by an end-to-side bypass proximal and distal to the aneurysm and ligation of the aneurysm, as is done for popliteal artery aneurysms.

End-to-Side Anastomosis

An important step in constructing an end-to-side anastomosis is to align the vessels without a twist or kink. Anastomotic failure is more likely to be caused by technical imperfections than by the dimensions of the anastomosis.[6] The anastomosis should be prepared, such that the posterior incision in the conduit is parallel to its long axis; otherwise, a buckle effect may develop at the anastomosis. The ideal arteriotomy length

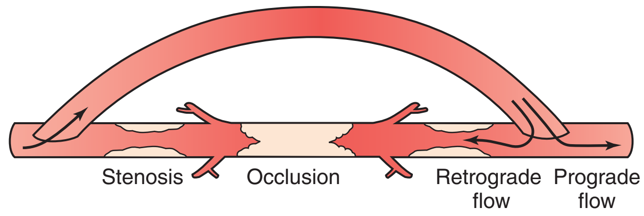


Figure 61.43 End-to-side configuration at the distal anastomosis allows the maintenance of retrograde flow through patent branches.

is poorly defined and is influenced by the bypass diameter. Some recommend that the length be twice the bypass diameter.[3] Others recommend an arteriotomy greater than 2 cm.[7,8] In coronary artery vein bypass, a short arteriotomy (4 to 6 mm) is usually recommended.[9] Most often, an arteriotomy measuring 1.2 to 2 times the graft diameter is created. The end of the conduit is transected, and then a slit matching the arteriotomy length is made in its posterior aspect. This allows spatulation of the conduit end to minimize narrowing at the anastomosis. An arteriotomy shorter than 1.2 times the diameter of the conduit results in the bypass's joining the artery at an unfavorably sharp angle. An arteriotomy that is too long requires more time for construction, with no proven additional benefits. An end-to-side anastomosis can be performed using an anchor or parachute technique.

Anchor Technique

In the anchor technique, the anastomosis is constructed by first placing a suture at the heel of the conduit and the arteriotomy. The suture is tied, thus stabilizing and anchoring the conduit at the heel of the anastomosis. Suturing is continued on one side of the heel to the toe, and then halfway down the other side of the anastomosis. The anastomosis is completed by suturing the other end of the heel suture until it meets the previously placed suture (Fig. 61.44). An alternative is to start another suture at the apex and run it in a continuous manner on both sides of the apex toward the heel to complete the anastomosis, tying the suture on both sides about the middle of the arteriotomy.

There are numerous other variations of the end-to-side anastomosis. The anchoring sutures placed at the apex or the heel can be either simple or mattress sutures. However, in small vessels, mattress sutures at the apex or the heel may cause narrowing of the lumen. Another option is to place interrupted sutures at the apical part of the anastomosis (instead of a continuous suture line). The theoretical advantages of this variation include allowing the anastomosis to stretch and expand with arterial pulsations and not be limited by the length of the continuous suture line. Further, the needle tip in a running suture can become blunted from repetitive piercing, especially of calcified vessels. The anchor technique is ideal for superficial vessels and larger arteries. The anchoring sutures facilitate traction and countertraction during the anastomotic procedure.

Parachute Technique

In the parachute variation of the end-to-side anastomosis, the sutures at the heel and the apex are not initially pulled down or tied. Suturing is started a few millimeters from the center

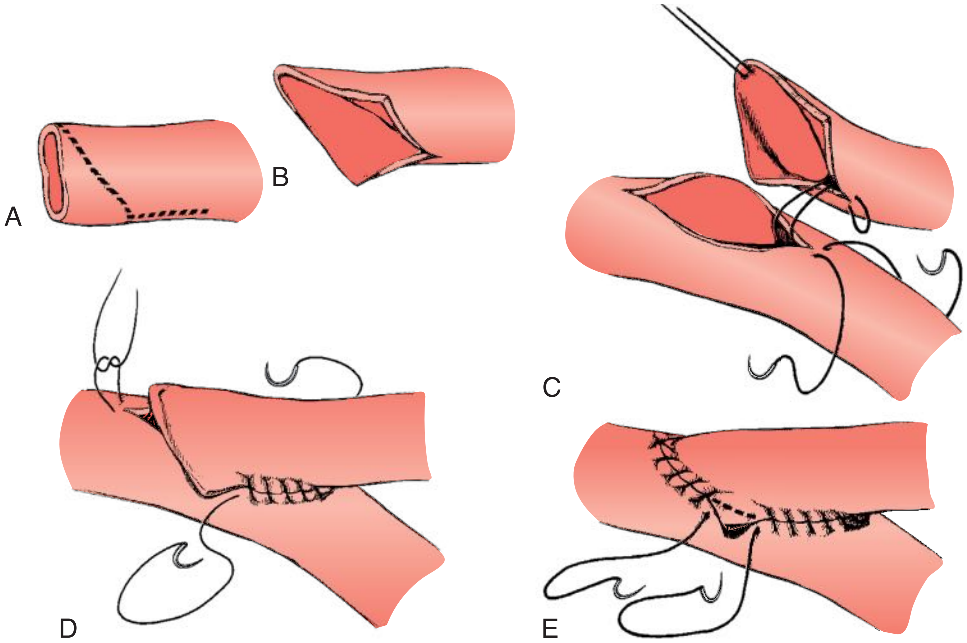


Figure 61.44 (**A–E**) End-to-side anastomosis anchor technique.

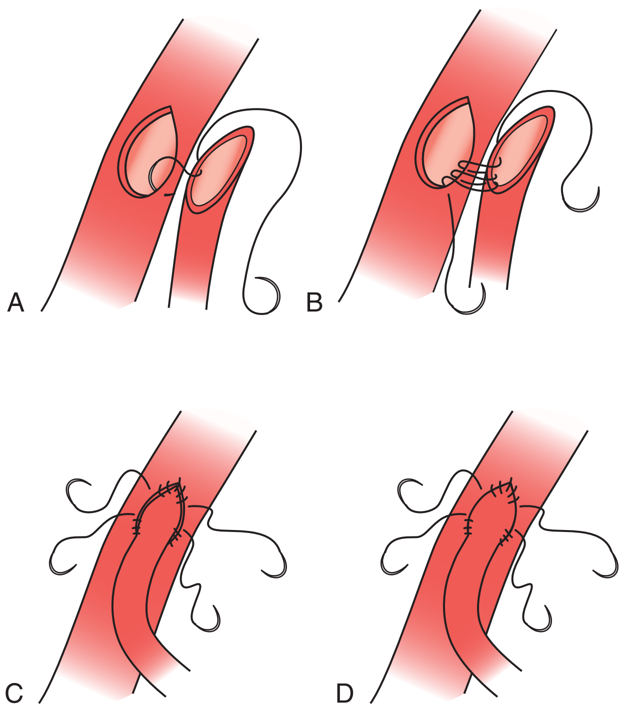


Figure 61.45 (**A–D**) Parachute technique – another variation of the end-to-side anastomosis.

of the heel. The conduit is typically held with forceps a few centimeters from the arteriotomy. This allows the placement of sutures in deep areas without the conduit obscuring or interfering with suture placement. First, several bites are placed in the conduit and the arteriotomy until the challenging part of the anastomosis is completed. This usually requires a total of three sutures on each side of the center of the heel. Tension is then applied on both ends of the suture, and the bypass is slowly pulled toward the anastomosis, achieving a tight suture line (Fig. 61.45). It is important to avoid excessive, continuous pulling on the suture line during this step, because it could result in tearing of the arterial wall. As described previously, when using the parachute technique in patch closure of an arteriotomy, wetting the suture and wiggling its ends back and forth help in tightening the suture without injuring the arterial wall or breaking the suture line.

The parachute technique is especially useful if the vessels are small or in a deep location (i.e., the aorta or below-knee popliteal artery) where visualization of the first few bites at the apex and heel may be suboptimal. Variations in the parachute technique relate to the site where the suture is started: it can be started exactly at the center of the heel or a few bites off-center. The technique of starting a few bites off-center can be challenging to learn. However, with experience, it may become the surgeon's preferred method of performing an end-to-side anastomosis.

End-to-End Anastomosis

An end-to-end anastomosis is typically performed for replacement of an arterial segment, such as an aneurysmal artery or a vessel that has been transected by trauma. An end-to-end anastomosis is also constructed when a composite bypass is needed or when preservation of retrograde or antegrade flow is not essential.

The technique varies, depending on the size of the vessels and their mobility. When constructing an end-to-end anastomosis between two large vessels of comparable diameters, the transection of the vessels and the anastomotic suture line are usually in a plane perpendicular to the long axis of the vessel. If both segments are freely movable, a number of techniques have been developed to simplify suturing in a forward manner, maintaining the most favorable angle for suture placement.

One technique involves placing two diametrically opposed sutures in an anterior and posterior part of the vessel. The

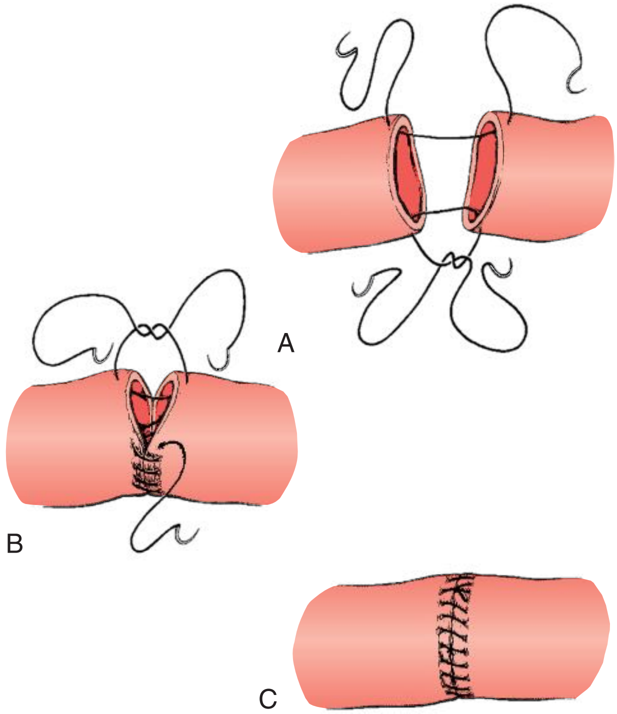


Figure 61.46 (**A–C**) End-to-end anastomosis in large, movable vessels. The vessels are then flipped 180 degrees, placing the posterior wall in an anterior location for completion of the anastomosis.

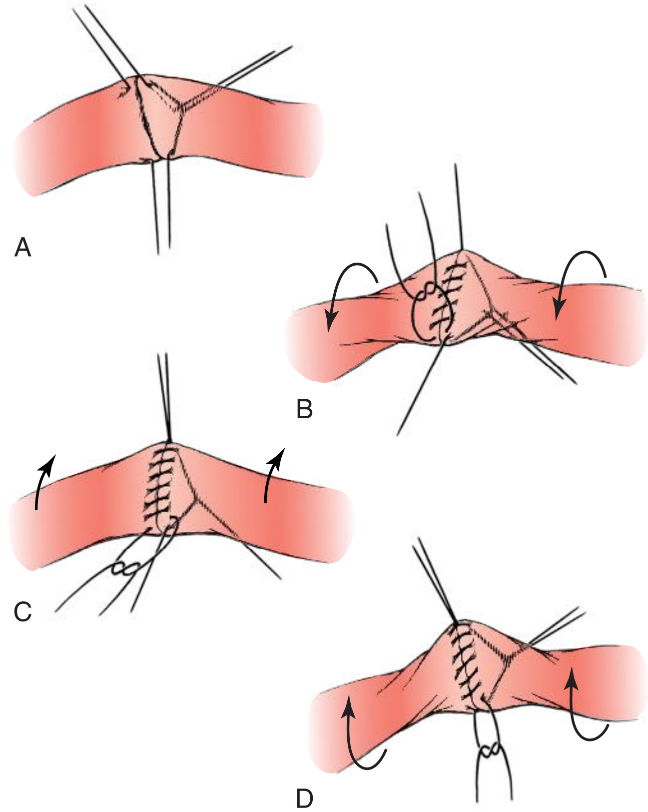


Figure 61.47 (**A–D**) End-to-end anastomosis using the triangulation method.

sutures are tied, and the anterior part of the anastomosis is constructed first. The vessels are then flipped 180 degrees, placing the posterior wall in an anterior location for completion of the anastomosis (Fig. 61.46). This technique is a modification of the triangulation method first described by Carrell. In the triangulation technique, the anastomosis is divided into three parts rather than two parts, anterior and posterior (Fig. 61.47).

When the segments are not freely movable (such as when constructing an anastomosis for aortic aneurysmal disease) the back wall is sutured first, with a continuous suture using a parachute or an anchor technique, based on the depth of the anastomosis and the surgeon's preference (Fig. 61.48). When the back wall is left intact, suturing involves placing a double-layer bite in the posterior wall of the aorta. It is essential to take deep bites; shallow bites may miss the adventitia and do not provide the strength necessary to hold the aortic anastomosis.

When constructing an end-to-end anastomosis between two small vessels, it is essential to spatulate the anastomosis to avoid compromising the lumen. Thus, both segments are transected in an oblique manner, and the incision is extended posteriorly. An anchoring suture is started at the center of the heel and continued on each side of it (Fig. 61.49). The suturing may be continued around the apex. Alternatively, another suture is started at the apex and continued on both sides of the apex toward the heel to complete the anastomosis. The reason why small vessels should be spatulated when they are to be sutured end-to-end is a matter of geometry. If the anastomosis is done in a perpendicular fashion to the length of the vessel, it will be a perfect circle with all the bites located in the same plane, which can be narrowed if some bites are too deep. A spatulated anastomosis will produce

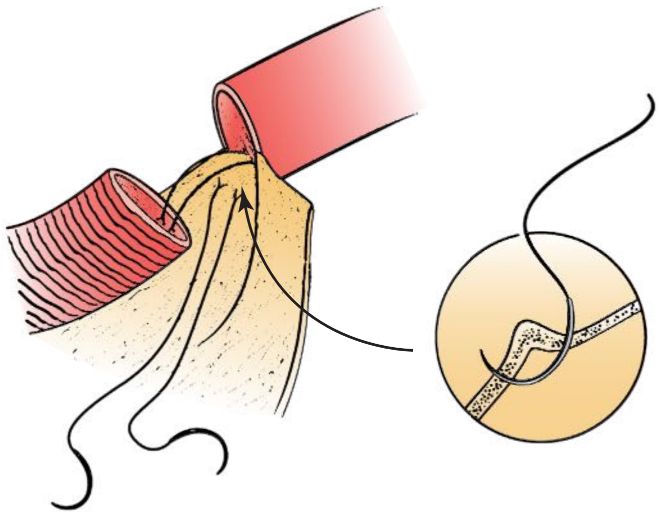


Figure 61.48 When the segments are not freely movable, such as when constructing an anastomosis for aortic aneurysmal disease, the back wall is sutured first with a continuous suture. It is essential to take deep bites because shallow bites may tear.

an oblong shape with the bites in different planes, which makes it more forgiving if some are too deep.

Side-to-Side Anastomosis

A side-to-side anastomosis is rarely performed. It can be used, however, to create a side-to-side radiocephalic arteriovenous fistula for chronic hemodialysis (see Ch. 174, General

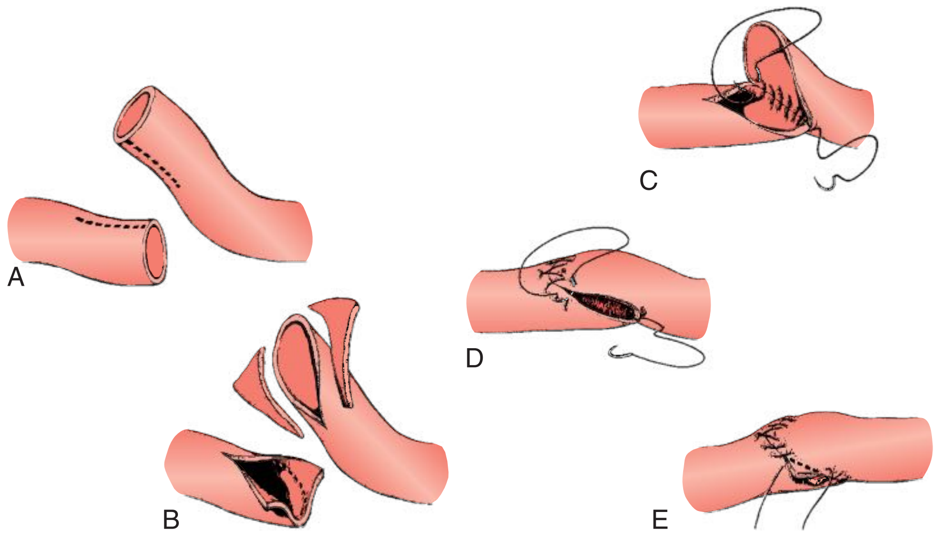


Figure 61.49 (**A–E**) Spatulated end-to-end anastomosis between two small vessels.

Considerations and Strategies to Optimize Access Placement) or a side-to-side arteriovenous fistula distal to an infrainguinal prosthetic bypass as an adjunctive procedure to improve graft patency by decreasing outflow resistance.[10] A side-to-side configuration can also be used in the construction of a second anastomosis in a sequential bypass for limb revascularization. To perform a side-to-side anastomosis, the vessels need to be dissected and mobilized so they lie adjacent to each other with minimal tension. The anastomosis is created by longitudinal arteriotomy or venotomy where the walls come in direct contact. The posterior wall of the anastomosis is typically constructed first. The anastomosis is usually 6 to 10 mm long.

ADJUNCTIVE TECHNIQUES FOR INFRAINGIUNAL BYPASS ANASTOMOSIS

See Ch. 112, Infrainguinal Disease: Surgical Treatment.

T-Junction

A useful technique to facilitate the construction of an anastomosis in infrainguinal vein bypass is the T-junction technique (Fig. 61.50). In this method, a side branch in the vein is identified. The vein is transected 5 to 10 mm from the branch and then slit along the posterior wall in a fashion to incorporate the side branch in the anastomosis. The shape of that segment of vein looks like a "T." This can be used at the proximal or distal anastomosis and is helpful in minimizing sharp angulation of the bypass and narrowing at the heel of the anastomosis.

Saphenofemoral Junction Vein Cuff

When constructing a greater saphenous vein bypass, the vein can be transected at the saphenofemoral junction with a 1-mm rim of femoral vein (Fig. 61.51). This technique provides a large venous hood for construction of the anastomosis, especially if the artery is thickened and the vein is relatively small.

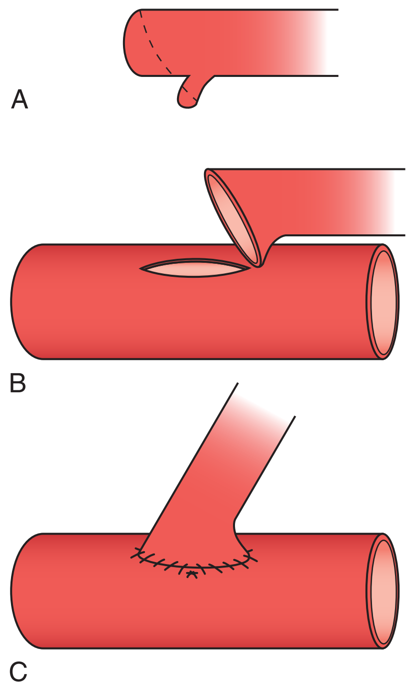


Figure 61.50 (**A–C**) T-junction technique.

Distal Vein Patch Technique

Several different anastomotic configurations have been described in an attempt to improve bypass results by the interposition of venous tissue between the prosthetic graft and the recipient artery, especially to tibial artery targets. Each configuration has certain advantages and disadvantages, both real and potential.

The Miller vein cuff involves the longitudinal opening of a segment of vein and a running suture line to secure the edge of the vein to the arteriotomy. The two cut ends of the vein are then sutured together to construct an oval venous cuff. The prosthetic graft is then sutured directly to the oval vein cuff (Fig. 61.52).[10] However, several potential disadvantages have been recognized in association with the Miller cuff technique.

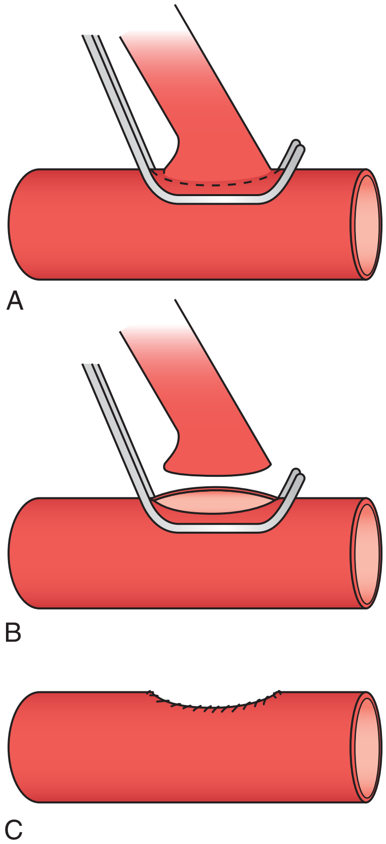


Figure 61.51 (**A–C**) Saphenofemoral junction technique.

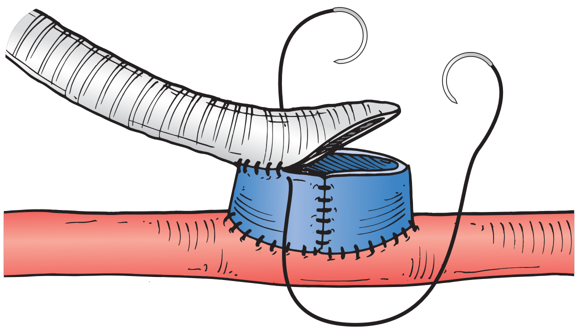


Figure 61.52 Venous cuff at the distal anastomosis of prosthetic grafts.

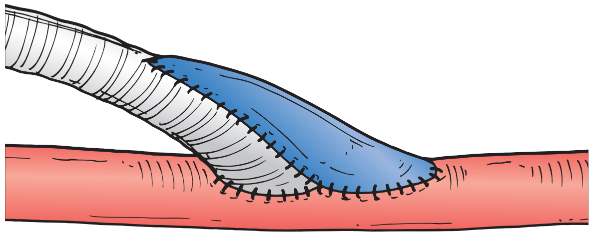


Figure 61.53 Taylor patch.

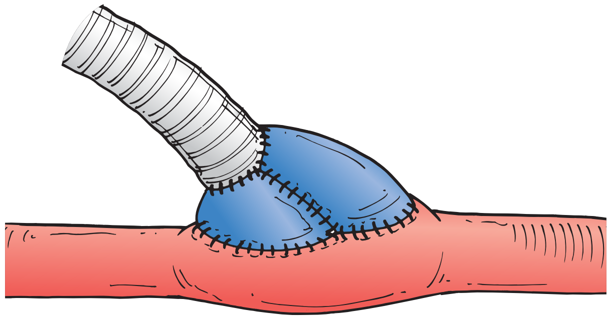


Figure 61.54 Saint Mary's boot

Significant turbulence has been noted due to the deep anastomotic reservoir and the difficulty of achieving a proper angle between the graft and recipient artery. This results in increased turbulence and shear stress at the distal anastomosis. These hemodynamic factors may help to explain the immediate and early graft failures reported in Miller's initial series. In addition, the oval formation of the Miller cuff is difficult to maintain in tight anatomic spaces, such as those involved in very distal bypasses to the dorsalis pedis artery of the forefoot and the plantaris pedis branches of the posterior tibial artery. This feature is especially problematic in the diabetic population where pedal bypass may be required.

The Taylor patch technique requires a long arteriotomy (3 to 4 cm) so that the patch can be constructed longer than the diameter of the prosthetic conduit (Fig. 61.53).[11] A U-shaped slit approximately 1 cm in length is made on the underside of the graft, with minimal angulation to ensure that the graft lays almost parallel to the artery. The heel of the graft is then sutured directly to the proximal portion of the arteriotomy with the suture line continued along each side of the arteriotomy. The anterior surface of the graft is then incised parallel to the arteriotomy to a point 2 cm proximal to the heel of the anastomosis. A vein patch varying from 5 to 6 cm is used to close this elliptical defect. The patch begins distally on the artery with interrupted sutures and is completed proximally onto the PTFE with a running suture. However, there are theoretical and practical disadvantages to the Taylor patch technique. The arterial intima is directly exposed to prosthetic graft material for the proximal portion of the anastomosis, thereby losing the advantage of the venous endothelium for half the anastomosis. There is also a point of possible anastomotic constriction where three suture lines converge between the artery, graft, and vein patch. Finally, a significant length of vein must be available to accomplish the anastomosis using the Taylor patch technique.

The Saint Mary's boot technique utilizes a similar arteriotomy and venous harvest as the Miller cuff; however, the corner of the venous segment is sutured to the apex of the arteriotomy to form the anastomotic toe (Fig. 61.54).[12] The remainder of the venous–arterial anastomosis is formed in a similar fashion to the Miller cuff; however, the redundant vein is excised obliquely and sutured to the longitudinal edge. Next, a segment of the posterior collar is incised to increase the size of the anastomosis between the graft and vein collar. Overall, the Saint Mary's boot maintains a fully compliant venous collar, avoids any direct contact between the artery and graft, and maintains the hemodynamic advantages of the Taylor patch. Its main drawback is the technical difficulty of its construction.

The distal vein patch, also known as Linton patch bypass, requires a shorter arteriotomy, thereby decreasing the amount

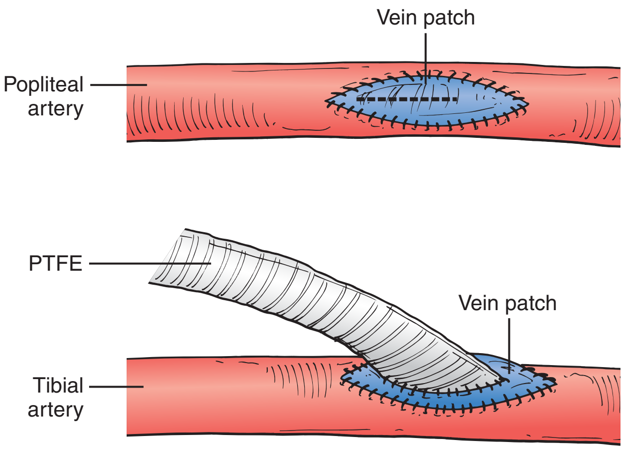


Figure 61.55 Distal vein patch. *PTFE*, polytetrafluoroethylene.

of venous tissue required for the procedure (Fig. 61.55).[13] A 2- to 3-cm segment of tissue for the patch is suitable and can include saphenous vein remnants, arm vein harvested under local anesthesia, superficial femoral vein, or a segment of occluded superficial femoral artery that is opened and endarterectomized. The venous segment is gently dilated with heparinized saline and opened longitudinally, with valve remnants excised. A 2- to 3-cm arteriotomy is then performed in the target artery, and the venous segment is cut to the appropriate length and width in preparation for the patch. In most cases, the width is left unaltered to allow for a generous patch to permit bulging of the patch under arterial flow to have a functional result similar to that of a vein cuff. The patch is sewn to the artery using 7-0 Prolene monofilament suture in a parachute technique. After the patch is sewn in place, a longitudinal venotomy is made in the proximal two-thirds of the patch, and the graft is sutured to the vein patch using 6-0 Prolene suture. The anastomosis is constructed to maintain a rim of venous tissue interposed between the graft and the entire circumference of the arterial wall. Because the venotomy is made in the proximal two-thirds of the patch, only venous tissue is interposed at the toe of the anastomosis.

Distal Anastomotic Arteriovenous Fistula

The addition of an arteriovenous fistula at the distal anastomosis has also been used to improve graft performance, especially when arterial runoff is poor. Dardik et al.[14] used human umbilical vein grafts and added a common ostium distal arteriovenous fistula to decrease the thrombosis rate by reduction of outflow resistance (Fig. 61.56). When there is no venous conduit and poor arterial runoff, an arteriovenous fistula can be added to the distal anastomosis of a distal vein patch bypass.[15] This modification has been performed in patients with no vein available and severely disadvantaged arterial runoff on the preoperative arteriogram. The target tibial artery is opened longitudinally with a venotomy in the corresponding tibial vein. The opposing walls of the artery and vein are sutured together to create a common ostium connection. The vein patch is then sutured to the common ostium created by this fistulous connection. An anastomosis is then constructed between the vein patch and the PTFE as described in the distal vein patch bypass configuration.

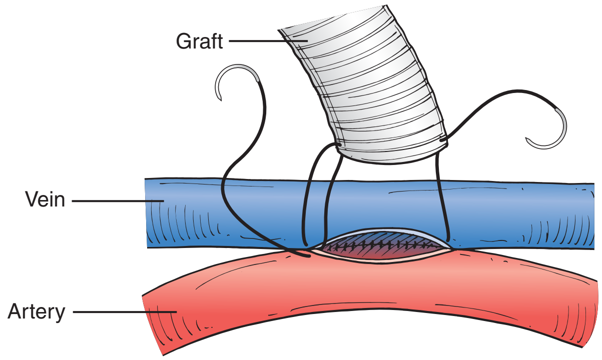


Figure 61.56 Distal arteriovenous fistula.

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This atlas provides a short review of vascular anatomy with simple illustrations of vascular exposures, along with detailed, step-by-step illustrations of vascular reconstructions.

Rutherford RB. *Atlas of Vascular Surgery: Basic Techniques and Exposures*, Philadelphia: WB Saunders; 1993.

This atlas, with sections on basic techniques and vascular exposures, provides clear artistic illustrations of common vascular exposures and basic vascular techniques.

Valentine RJ, Wind GG. *Anatomic Exposures in Vascular Surgery*, 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2003.

This atlas provides a comprehensive, three-dimensional anatomic approach, with clear illustrations of basic and advanced vascular exposures.

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CHAPTER 62

Endovascular Diagnostic Technique

CHRISTOPHER W. McQUINN and KRISTINE C. ORION

Based on a previous edition chapter by Sapan S. Desai and Kim J. Hodgson

INTRODUCTION

Endovascular therapy has become the mainstay of treatment for numerous vascular diseases and has even become preferable over open intervention in a variety of circumstances. In order to fully harness these therapies, vascular surgeons must be facile with a variety of instruments and techniques used for endovascular access, selective vessel catheterization, image acquisition, and post-processing, as well as with techniques to mitigate complications that can occur. The first step to any endovascular diagnostic procedure is to obtain access to a variety of arteries and veins located throughout the body. Safe and effective conduct of these procedures requires proper selection of needles, wires, and catheters. The purpose of this chapter is to familiarize the reader with these tools and techniques for diagnostic purposes.

VASCULAR ACCESS

Choice of Access Vessel

The initial step of most endovascular diagnostic procedures is through percutaneous access of an artery or vein. The common femoral artery (CFA) is the most common site of access especially for aortoiliac or lower extremity diagnostic purposes. Brachial or axillary access is the second most common and can be a useful access point in patients with significant aortoiliac occlusive disease or for approaching the mesenteric or renal vessels due to the favorable angle for cannulation.

When choosing the access vessel, multiple factors must be considered including suitability of the vessel in relation to the procedure being completed, the ability to achieve hemostasis, the ease to readily convert to an open procedure and thoughtfulness of possible effects to tissues downstream of the cannulated vessel.

The suitability of a vessel for a procedure relates most importantly to the size of the vessel; anticipating the size of the catheters or sheaths required for performing the procedures and ensuring the target vessels can be readily reached or intervened on from the access vessel. For example, the aorta, iliac and downstream lower extremity vessels can be easily cannulated and accessed via the femoral vessels. If the iliac arteries are heavily calcified, stenotic, or occluded, an alternate choice might be the left brachial artery.

The terminal step of all angiography procedures is the attainment of hemostasis and is a critical step to ensure safe completion. In fact, the most common complication of angiographic procedures as a whole is related to access site complications (see Ch. 52, Local Endovascular Complications and Their Management). These can include hematoma or pseudoaneurysm which may require further operative intervention. While there are numerous closure devices that can be used to achieve this step, they can be limited by vessel size or the presence of significant calcification which can result in device failure. As such, manual pressure should always be considered as an option for hemostasis. This makes the femoral vessels ideal for access as they can be easily compressed against the femoral head posteriorly. The brachial artery can similarly be compressed against the medial epicondyle of the humerus although the artery's mobility renders compression more challenging. Furthermore, due to the encasement of the brachial sheath, a small hematoma is less forgiving and may result in nerve compression.

In the event of an immediately recognized access complication, such as sheath dislodgement or bleeding, the ability to convert percutaneous access to open to assess and repair any vessel injury is an important consideration. As an example, percutaneous access of the CFA is readily converted to open via a groin cutdown whereas vessels such as the axillary artery would entail much larger, possibly time-consuming surgical exposures for repair.

Selection of an appropriate vessel for access also entails that it is appropriately sized for the anticipated catheter and sheaths being used during the planned procedure. Small vessels may be completely occluded by larger sheaths thus resulting in ischemia in the downstream extremity or tissue being supplied by the access vessel. Although occlusion is less likely during diagnostic procedures since they tend to require smaller caliber catheters and sheaths, this is always an important consideration given that sluggish flow through the vessel can predispose to thrombosis and resultant ischemia. As such, cannulation of smaller vessels or the use of larger sheaths should always prompt consideration for intra-procedure heparinization.

Venous access typically mirrors arterial access with respect to vessel choice with the femoral vein being the most frequently accessed. Following venous cannulations, it is typically easier to achieve hemostasis given the more compliant vessel walls and lower pressures. Therefore, common venous access sites, such as the internal jugular vein (IJV) for vena cava filter retrieval or popliteal vein for venous thrombolysis, may not require direct posterior bony prominence for adequate compression and hemostasis.

Arterial Access Options

Common Femoral Artery

Understanding the anatomy of each vessel is key to avoiding potential complications.

Anatomically, the CFA begins as the external iliac artery emerges from under the inguinal ligament. One can note the origins of the superficial epigastric and circumflex iliac arterial branches at its most proximal aspect as it overlies the medial aspect of the femoral head. It courses for a short distance of 5–8 cm and then bifurcates into the superficial and deep femoral arteries. Within the femoral sheath, the CFA is immediately medial to the femoral nerve, and lateral to the CFV. The inguinal ligament is a useful landmark that can be identified using surface anatomy, but it is critical to recognize that this anatomy can be easily distorted by body habitus or prior surgical procedures. The use of fluoroscopy can assist in identifying the femoral head as well as bony landmarks of the superior iliac spine and pubic tubercle which may be less than easy to palpate. Identification of these bony landmarks are helpful in delineating the superior-most extent of the common femoral artery prior to its transition into the external iliac above the inguinal ligament (Fig. 62.1). Using a skin marker may be useful to define inguinal ligament.

The CFA is an ideal choice for cannulation. It provides direct retrograde access to the aortoiliac system as well as most any arterial bed in the body. Its large caliber permits large devices introduction as well as safe room for most marketed percutaneous closure devices. Probably most importantly, the underlying femoral head allows easy compression and safe hemostasis even in the event of closure device failure. Most commonly, the CFA is accessed in retrograde fashion over the medial aspect of the femoral head. The location of the puncture is critical (see later). If puncture occurs too cephalad, either through or above the inguinal ligament, inadvertent puncture of the external iliac artery occurs, and a life-threatening retroperitoneal hematoma can result. Alternatively, if puncture is too distal, occurring in the superficial femoral artery (SFA), the risk of developing a pseudoaneurysm is quite high. SFA access can also result in an AV fistula from the profunda femoris artery or plaque dissection of the proximal SFA.

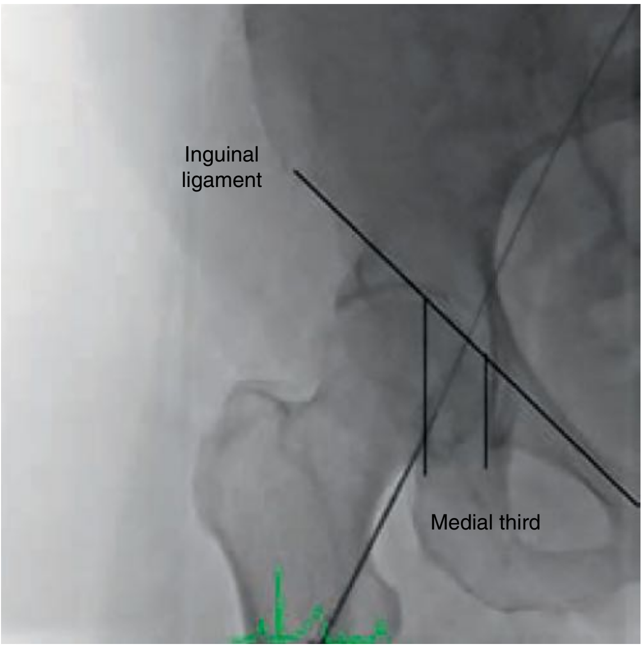

Figure 62.1 Anatomy of the femoral artery with the inguinal ligament and femoral head delineated. The common femoral artery lies over the medial one-third of the femoral head. A wire is located within the femoral artery in this X-ray image.

In certain circumstances, antegrade CFA access may be desired, more often for interventional rather than diagnostic purposes. Antegrade access may be chosen if the patient has a raised bifurcation in the setting of kissing iliac stents, causing difficulty with pushing a sheath over the aortic bifurcation. Antegrade access has the advantage of working in a single plane with excellent push ability for distal extremity procedures. Antegrade access into the CFA, however, can be more challenging than retrograde access. Needle puncture must still enter the CFA, but in antegrade access, the location is generally more on the proximal CFA to allow room to navigate wire and sheath into the SFA rather than the profunda artery. As such, this requires having a steep downward angle. In larger patients, this can be facilitated by retracting the pannus with tape.

Popliteal Artery

Anatomically, the SFA becomes the popliteal artery when it exits Hunter's canal in the distal medial thigh. Fluoroscopically, this is often defined as the point when the femoral artery passes posterior to the medial aspect of the distal femur. The popliteal artery travels behind the knee and bifurcates into the anterior tibial artery and tibioperoneal trunk. The latter subsequently divides into the peroneal artery and posterior tibial artery (together, the so-called trifurcation). The popliteal artery is flanked on each side by the duplicated popliteal vein.

While almost never done for diagnostic purposes, retrograde access of the popliteal artery while in a prone position can be used to attempt to cross and re-enter an occlusion of the SFA. Ultrasound guidance is paramount to distinguish the artery from its accompanying popliteal veins. This method has been largely abandoned as compression in the fatty popliteal space is often ineffective and pedal access has become more attractive.

Infrageniculate Arteries

Pedal access has gained favor in some fields especially for recanalization of severe tibial disease when antegrade attempts fail.[1] Ultrasound guidance and micropuncture needles are universally used. Once arterial access is confirmed, work is often completed without a sheath, using wires and catheters directly.

Anatomically, the anterior tibial artery courses anterolaterally from the below-knee popliteal and traverses deep within the anterior compartment of the leg. It becomes more superficial at the ankle and becomes the dorsalis pedis artery. The dorsalis pedis is the ideal pedal access point for its superficial location and ease of compression for hemostasis. The posterior tibial artery courses posteromedially from the tibioperoneal trunk and is located in the deep posterior compartment of the leg. It becomes palpable near the ankle. This relatively superficial location is also amenable to percutaneous access and can be compressed readily for hemostasis. The peroneal artery is rarely used for percutaneous access. Coursing straight inferiorly from the tibioperoneal trunk, it is difficult to reach in its deep location within the deep posterior compartment of the leg, between the tibia and fibula.

Iliac Artery

Because of inability to manually compress, as well as vital surrounding structures, percutaneous iliac artery access is contraindicated. If these arteries are needed for device deployment, open surgical approach is required. Often these are cases in which a conduit is sewn end-to-side to the iliac artery to allow introduction of large bore sheaths and devices.[2] Alternatively, endo-conduits can be used within the iliac system to allow larger delivery systems of TEVAR and TAVR devices using femoral access (see Ch. 80, Thoracic Aortic Aneurysms: Endovascular Treatment).

Axillary Artery

Percutaneous cannulation of the axillary artery has been historically done in the intramuscular groove between the triceps and coracobrachialis muscle with the upper arm in abduction and flexion. This location has until recently been abandoned due to difficulty with adequate compression against the humerus and risk of median nerve compartment syndrome. Since the caliber change as it becomes the brachial artery, most practitioners favor the latter if upper extremity access is desired.[3] However, percutaneous access of the infraclavicular axillary artery more proximal has recently been described.[4] Theoretically, this allows for larger caliber access similar to the CFA if multiple sheaths are required during complex endovascular interventions. This technique is still under review for two reasons. Compression is impossible in the event of closure device failure and quick surgical exposure (unlike femoral access) carries risk of brachial plexus injury.

Brachial Artery

The axillary artery becomes the brachial artery as it passes under the teres minor. It can be easily palpated over the olecranon process when the arm is supinated. Ultrasound-guided access is often used in conjunction with a micropuncture needle to facilitate safe entry into the vessel.[5] One must take care to access the artery over the medial epicondyle to allow for compression and hemostasis. Furthermore, ultrasound guidance is recommended to ensure a single puncture attempt at the 12 o'clock position. Even a small hematoma can cause nerve compression with the tight brachial sheath. Most practitioners comfortably use 6F or 7F sheaths at this location. Brachial artery access is often used for coronary revascularization procedures, dialysis access, subclavian artery disease and some EVAR or complex EVAR procedures (see Ch. 75, Aortoiliac Aneurysms: Endovascular Treatment). Many favor brachial access for mesenteric vessel cannulation due to the downward angle of their origins.

Radial Artery

The brachial artery bifurcates into the radial artery and ulnar arteries generally at the antecubital fossa. One should note that patients can have a higher bifurcation anywhere along the humerus. The radial artery has become the access of choice for most cardiologists and more recently for peripheral interventions.[6] It is readily palpable in the distal extremity over the distal radius, and thus can be cannulated with ease, with or without using ultrasound guidance. Subsequent hemostasis is relatively straightforward through compression against the radius. Most patients are ulnar-dominant but all patients should undergo Allen's testing or further imaging to ensure an intact palmar arch. If the patient is radial dominant and this is lost during intervention, the hand may become ischemic without collateral flow from the ulnar artery. The radial artery can accommodate sheaths between 4F and 6F, thus facilitating endovascular procedures that are using a 0.014" or 0.018" platform (see later).

Common Carotid Artery

Percutaneous common carotid artery (CCA) access is rarely performed for purely diagnostic purposes due to the risk of cerebral ischemia or embolization. Hemostasis is also a concern due to the inability to manually compress the carotid. Most practitioners will use CFA access with long guiding catheters or sheaths (see later) to achieve cannulation of the carotid artery. A hybrid technique is relied on for transcarotid artery revascularization (TCAR) when a small surgical incision is made to expose the CCA and direct puncture is then performed for antegrade sheath placement.[7]

Venous Access Options

Venous access differs from arterial access in several important ways. While the pressure is significantly less, making hemostasis easier, it can also make access more difficult. There is less radial force keeping the vessel open, and one may find the wall collapsing with each attempt of needle puncture. Using a through and through technique in this case may be appropriate in some veins. While veins are capacitance vessels and can be quite large, they cannot stretch as much as arteries. When compared to arteries, veins are more prone to tearing if too large a sheath or device is used. The final important consideration is that while a simple access needle can be used to access arteries and confirm vessel entry, a syringe is helpful for venous cannulation. This serves two purposes: first, the plunger can be pulled back to generate a vacuum and confirm proper entry into the vein, and second, inadvertent entry of air into the venous system (air embolism) is avoided. This is particularly important when accessing a vein located above the heart, such as the IJV with the patient's head up, where a negative venous pressure may exist and facilitate the entry of air into the system with potentially fatal consequences.

Common Femoral Vein

The CFV is commonly used for access when completing diagnostic procedures in the vena cava or its branches, such as the ovarian and internal iliac veins for pelvic congestion syndrome. The CFV is located medial to the CFA and can be compressed over the femoral head. Ultrasound guidance is often used for access to avoid injury to the CFA. This access readily allows catheterization of the contralateral extremity venous system, though navigating against the valves can require patience.

Popliteal Vein

To access the popliteal vein, the patient is generally positioned prone. Popliteal veins are paired, flanking the popliteal artery on each side, and either vein can be used for access. Ultrasound is used for guidance, which is particularly important when cannulating this vessel to diagnose and treat deep vein thrombosis of the extremity veins, as the access location itself may be thrombosed, rendering blood return via the needle meager or nonexistent. Ultrasound visualization of the puncture and guide wire passage can be extremely helpful in this situation. Accessing a thrombosed popliteal vein can require practice as the halting advancement of the guide wire can fool the practitioner into believing they are not intraluminal.

Saphenous Veins

The great and small saphenous veins are often cannulated for diagnostic and therapeutic purposes when treating patients for extremity deep vein thrombosis or for chronic venous insufficiency. Ultrasound guidance is typically necessary for access given their small size and distensibility. Most saphenous veins, both great and small, will typically accommodate at least a 6F sheath. The proximal small saphenous can be accessed to provide direct access to the popliteal vein to facilitate thrombolysis of femoral deep vein thrombosis (see Ch. 149, Acute Lower Extremity Deep Venous Thrombosis: Surgical and Interventional Treatment).

Arm Veins

An arm vein is commonly used for evaluation and treatment of central venous stenosis, dialysis access, or venous thoracic outlet syndrome (see Ch. 126, Thoracic Outlet Syndrome: Venous). For the latter, the superficial basilic vein is ideal as it enters the deep system within the arm, unlike the cephalic which enters more cephalic therefore causing potential of missing a DVT at the distal subclavian or axillary veins. The basilic vein is also a lone vessel, negating the chance of arterial injury or nerve compression from small hematoma, as is the case for the brachial veins. Cannulating arm veins for vein mapping has largely been replaced by duplex ultrasound.

Internal Jugular Vein

The internal jugular is easily accessed between the sternal and clavicular heads of the sternocleidomastoid. It is positioned lateral to the carotid artery within the carotid sheath. Ultrasound guidance is not necessary but is preferred to avoid inadvertent carotid artery injury. The IJV can accommodate large sheaths and is most often accessed for the purpose of insertion of central lines or hemodialysis catheters. It is also a common site for access when retrieving IVC filters.

Subclavian Vein

The subclavian vein is most commonly accessed at its lateral aspect for the placement of central lines and pacemakers and is rarely used for purely diagnostic purposes. The development of newer ultrasound probes such as microconvex pediatric probes have allowed for cannulation of the subclavian vein under real-time ultrasonography thereby reducing the risk of trauma to the subclavian artery and brachial plexus.

Adjuncts to Obtain Access

Manual Palpation

Manual palpation is traditionally the most common method for percutaneous puncture and access of vessels. Certain qualities of the artery can be understood with simple palpation. If calcium is present or the artery wall is thickened, the artery will roll back and forth. A healthier artery will simply feel like a pulse rather than a structure. This method typically involves identifying the artery manually and placing two fingers on the pulse – one proximal and one distal and spread out by a few centimeters. Ideally, the vessel will travel in a straight line between the two fingers and the access needle inserted directly between the two fingers into the artery. In thin patients, with straightforward anatomy and without significant vascular disease, this can be easily accomplished. However, in obese patients or those with significant aortoiliac disease, access with manual palpation may be more difficult and other adjuncts to access should be utilized.

Fluoroscopy

The use of fluoroscopy in the initial attempt to gain access can be useful to identify relevant bony anatomy and its relation to needle placement.[8] Although ultrasound guidance is now most commonly used to identify vessel anatomy and verify appropriate vessel puncture, fluoroscopy is still useful, especially in the femoral region, to verify an appropriate access point in relation to the femoral head thereby avoiding suprainguinal puncture and its associated complications.

Ultrasound

Ultrasound guidance allows direct visualization of the vascular structures along with the surrounding anatomy and can be particularly helpful in patients with large body habitus, severe occlusive disease and in a hostile access due to previous surgical incisions or scarring from multiple previous percutaneous procedures. In fact, there have been multiple studies showing that ultrasound-guided arterial access not only facilitated the proportion of successful percutaneous cannulations but also decreased access site complications.[9,10] Adjunctive ultrasound access typically entails the use of B-mode whereby real-time grayscale images can be obtained to identify the vessels and their relationship to other structures. For instance, when accessing the CFA, ultrasound can be helpful in identifying the femoral bifurcation, its relationship to the femoral nerve and vein, the depth of the vessel and identifying heavily plaque-burdened areas of the artery which may complicate access and the use of closure devices. Insonation while advancing the access needle will allow the operator to visualize the needle as it compresses and passes through various tissues, and eventually indenting the artery as it pushes against the wall providing instantaneous visual feedback of vessel cannulation.

Access Needles

Single-wall puncture needles are almost universally used for percutaneous access. The larger 18-gauge needle permits passage of a 0.035-inch guide wire, while the smaller 21-gauge needle permits passage of an 0.018-inch guide wire.

Historically, double-wall needles were used, particularly in the femoral location, where they were inserted through and through the femoral artery. The inner stylet would then be removed and the hollow end brought into the lumen of the artery. These cause unnecessary trauma to the posterior wall and are no longer used. There is some utility in understanding the use of these needles as a similar needle is often used for translumbar aortic cannulation of endoleaks, withdrawing the stylet once the aneurysm sack has been penetrated so that further needle advancement cannot puncture the endograft.

Micropuncture Needle Technique

The micropuncture technique is the most commonly used technique for vascular access. The vessel is identified, typically with a combination of ultrasound and fluoroscopic guidance, and a 21-gauge needle is then inserted at a 30- to 45-degree angle such that it pierces the artery wall at the site of visualization. Once the needle enters the vessel wall, blood return should be evident. The nature of the blood return can indicate whether an artery or vein has been accessed.

After the vessel has been accessed with the needle, a 0.018" floppy tip guide wire is inserted into the vessel. Fluoroscopy should be used to confirm appropriate tracking of the wire and to evaluate for dissection of the vessel wall by the wire. The 21-gauge needle is then removed over the wire in exchange for a 4F introducer sheath. The passage should be without tension as the 0.018" wire is prone to bending from excess torque, leading to loss of access. If difficulty is encountered, a small rotating motion on the introducer sheath can be used to facilitate passage through scar tissue or a thick arterial wall. As an alternative the tract and vessel can be pre-dilated with the dilator of the sheath, sharp and stiff 4F introducer sheaths are also now available that can be used to cut through dense tissue.

With the 4F sheath in the vessel, the inner cannula and wire are removed and exchanged for a 0.035" guide wire. This is commonly a J-tip wire for atraumatic passage. Again, fluoroscopy should be used to confirm proper passage of the wire to ensure that inadvertent cannulation of a side branch or a dissection plane has not occurred. The 4F sheath is then exchanged over the wire for a short 5F or 6F sheath while holding pressure above and below access site. It is important to maintain strict control over the wire during all sheath exchanges so as not to lose access or the wire within the vascular system. The side port of the sheath is then aspirated and flushed with heparinized saline to remove any air in the system and to prevent thrombosis.

Standard Needle Technique

Another option for access in patients with easily palpable femoral pulses and otherwise uncomplicated anatomy is the standard needle technique. An 18-gauge needle is used for access and an 0.035" J-tip wire is passed up into the vessel. The technique eliminates the need for an exchange of the 4F introducer sheath used in the micropuncture technique to the larger 5F or 6F sheath, saving a little time and expense. Because of the large needle, and stiffer wire and sheath, this technique can be advantageous in scarred groins, deep vessels, or when accessing Dacron grafts.

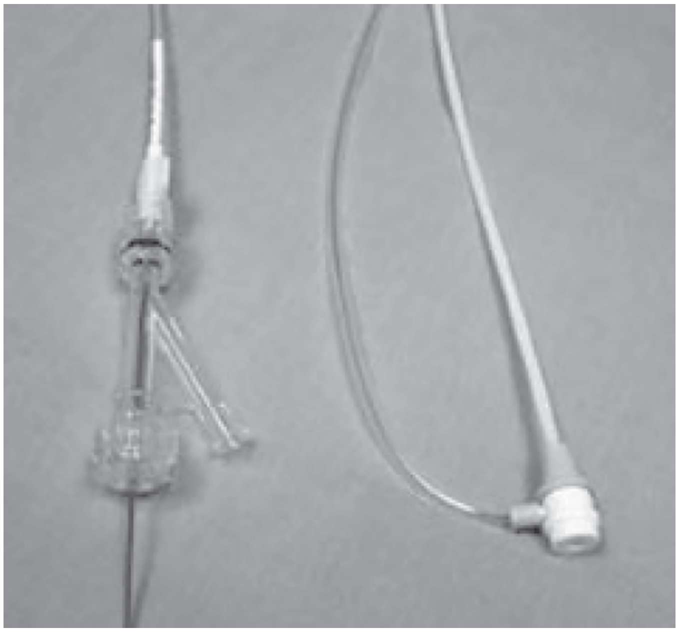

Figure 62.2 Y adapter on a guiding catheter *(left)* and hemostatic valve of a sheath *(right)*.

TECHNIQUE FOR CATHETERIZATION

Guide Wires

There are a multitude of guide wires that can be utilized to assist in catheter placement for diagnostic imaging. The important variables to consider when choosing a guide wire include the tip of the wire, the stiffness and the diameter and length. Most guide wires have a soft, floppy tip that will reduce the risk of vessel trauma. The standard entry guide wire is a J-tipped moveable core steel guide wire designed for atraumatic passage up the iliac system. J-tip wires are ideal for rapidly cannulating vessels and doing sheath exchanges, as the rounded bend will reduce the risk of creating a dissection plane or inadvertently cannulating a side branch. Although floppy tip wires allow for safe passage through the vascular tree, they often are unable to negotiate tortuous vessels and are certainly ineffective for cannulating side branches. In order to mitigate this, some wires have a stiffer construction at the tip with a slightly angled bend, such as a stiff angled glidewire. These wires can permit navigation of tortuous vessels and cannulation of side branches by manipulating the wire and rotating it along its longitudinal axis. Fluoroscopic observation should always be performed while the guide wire is advanced to ensure safe passage and also to glean clues about the underlying pathology. Of note, it is critical that hydrophilic-coated guide wires not be used as the initial entry guide wire as the hydrophilic coating is known to shear off and embolize when moved in and out of an entry needle.

For the purposes relevant to vascular surgeons and diagnostic imaging, guide wires come in two size categories – the larger 0.035″/0.038″ wires and the smaller 0.014″/0.018″ wires. Multiple wire lengths are available typically in the range of 120 to 360 cm. Longer length wires are often used to introduce a long catheter to a site distant from the site of access and are referred to as "exchange length" wires. A drawback of these longer wires is that they can be difficult to handle and careful attention must be paid to ensure that they do not get contaminated by falling off the working table or hitting other objects. Wires can be variably stiff depending on the application, this is determined by the construction of the outer spring coil and core wire. Steel core wires tend to be stiffer in contrast to the very flexible nitinol wires. To facilitate the ease of passage within vessels some wires have Teflon or hydrophilic coatings thereby reducing friction.

Sheaths

Sheaths are used for maintaining vascular access and serve as a portal through which any variety of wires, catheters, or devices are passed. Sheaths have a one-way valve, a side port that permits aspiration or administration of fluids, and come in a variety of lengths and calibers (Fig. 62.2). The inside caliber of a sheath is measured by French size, where 1F = 0.013″ = 0.33 mm (Box 62.1). Thus, a 5F sheath will accommodate catheters and devices up to 0.065″ (5F). Sheaths typically vary in size from 4F to 11F, but much larger sheaths are available to accommodate devices such as endografts (Fig. 62.3). Sheaths have hemostatic valves on the end that maintain hemostasis during wire and catheter exchanges and prevent the passage of air into the vascular system. When cannulating a vessel through dense tissue or making sharp turns, braided sheaths can be useful to prevent kinking and provide a stiff, stable platform. Radiopaque markers may be present to facilitate making measurements as well as fluoroscopic identification of the sheath tip.

BOX 62.1 Conversion Between Gauge, French, Imperial, and Metric Units

18 gauge = 0.040 inches = 1.024 mm
21 gauge = 0.028 inches = 0.723 mm
1 millimeter = 3 French = 0.039 inches
3 millimeters = 9 French = 0.118 inches

Figure 62.3 Color-coded Sheath Caliber Identification.

The length of the sheath used will depend on the desired application and distance from the access site. Sheath lengths range from 5 to 100 cm but for diagnostic purposes the most commonly used is the standard 10-cm sheath, given that distant contrast administration is generally through a longer catheter if required. Short sheaths are helpful when the working distance is very small, such as for dialysis access. Longer sheaths are useful when a stiff platform is required for interventions distant from the site of access, such as the contralateral lower extremity vessels or the aortic arch when accessed from the femoral artery. A 45-cm sheath is generally sufficient for interventions on the contralateral iliac system or beyond. When intervention is planned on the arch vessels via femoral access or the mesenteric vessels via brachial access a 90-cm sheath is typically required. A general rule of thumb is that the sheath should be no longer than necessary to allow adequate imaging during the intended intervention.

Diagnostic Catheters

Diagnostic catheters are the primary vehicle for delivering contrast for angiographic procedures and come in a range of sizes, lengths, and tip configurations (Table 62.1). They have various features that enhance their ease of use including radiopaque markers, hydrophilic coatings, and braided configurations. The caliber of diagnostic catheters is measured by their outer diameter; thus a 5F catheter has an outer diameter of 0.065″ and will fit inside a 5F sheath (which is measured by its inner diameter; Table 62.2). Most diagnostic catheters used by vascular surgeons are between 2F and 6F in size; the 2F and 3F catheters, referred to as microcatheters, are used primarily to deliver embolization coils to small distant targets. Diagnostic catheters can be grouped into nonselective, selective and crossing catheters (Table 62.3).

Nonselective Catheters

Nonselective catheters such as the omni flush or pigtail are used to inject a high volume of contrast into large blood vessels such as the aorta or vena cava, typically by power injection. These catheters have multiple side holes along the terminal 15 mm (Fig. 62.4) allowing for complete opacification of the vessels by dispersing the contrast evenly and reducing the "jet effect" of power injection through a simple end hole. The form of these catheters is typically curved to facilitate contrast dispersion; guide wire removal allows the catheter to form in the vessel. Their shape is also conducive to selection of the contralateral iliac system thereby allowing sequential aortography and selection of the contralateral system without catheter exchange.

TABLE 62.1 Commonly Used Diagnostic Catheters

Vessel	Catheter Shape	Catheter Name
Contralateral iliac	Self-forming Manual-forming	Cobra 2, pigtail, Omni flush Simmons 1 or 2
Renal, mesenteric	Self-forming Manual-forming	Renal double curve, Cobra 2, SOS Omni Simmons 1 or 2
Axillary, brachial	Self-forming	Kumpe, Cobra 2
Subclavian, carotid	Self-forming Manual-forming	Headhunter H1, Vitek Simmons 1 or 2

TABLE 62.2 Endovascular Device Size Conventions

Device	Measurement Standard	Unit
Entry needle	Outer diameter	Gauge
Guide wire	Outer diameter	Inch
Sheath	Inner diameter	French
Diagnostic catheter	Outer diameter	French
Guide catheter	Outer diameter	French

TABLE 62.3 Names of Catheter by Type

Catheter Type	Name
Flush catheter	Pigtail, tennis racket, Omni flush, Contra 2
Single curve	Kumpe, vertebral, angled glide, Bernstein, multipurpose A and B
Double curve	Cobra (C1, C2, C3), Headhunter, renal double curve, rim
Reverse curve	SOS, visceral selective (VS1, VS2, VS3), Simmons, Sidewinder (1, 2, 3, 4), Vitek
Crossing catheter	Quick-cross, TrailBlazer, WildCat, CX1, CrossCath, Minnie, Seeker

Selective Catheters

Selective catheters are shaped for the purpose of cannulating branch vessels to facilitate either imaging or intervention. Selective catheters have an end hole only, with no side holes,

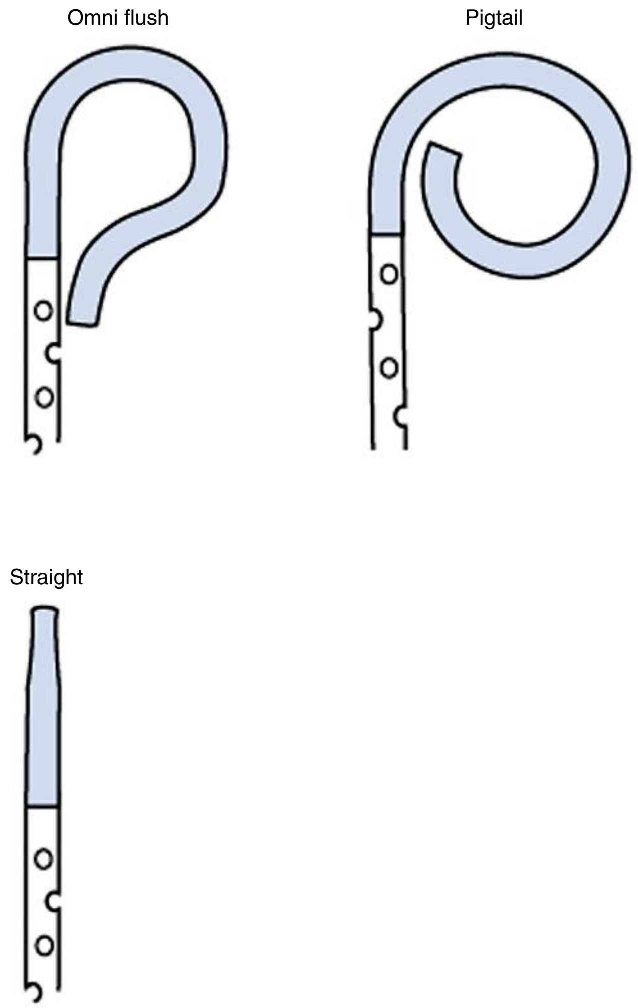

Figure 62.4 **Nonselective Diagnostic Catheters with Multiple Side Holes.** (Courtesy AngioDynamics, Queensbury, NY.)

and thus are typically unsuitable for power injection as the concentrated jet of contrast could be traumatic to the vessel wall. Selective catheters come in a variety of shapes and curves that facilitate selective cannulation of particular vessels and side branches. Generally, selective catheters are divided into single-curved, double-curved, and reverse-curved configurations (Fig. 62.5).

For vessels that come off the aorta at less than a 45-degree angle, a single curve catheter can facilitate cannulation. An example of a single-curved catheter is the Kumpe catheter, which is ideal for cannulating a side branch such as the contralateral iliac artery via brachial access. An example of a double curve catheter is the renal double-curve (RDC) catheter, which has an angle of 90 degrees and is useful for cannulating side branches that come off more acutely from the aorta. Finally, reverse-curve catheters typically have a 180-degree curve in the catheter with the tip flaring off at an angle. Reverse curve catheters are typically used to facilitate cannulation of vessels that come off the aorta at steep angle such as the aortic arch vessels. Some examples are the Simmons 1 and 2, which are designed for arch vessel cannulation via femoral access. Forming reverse curve catheter can be difficult when the lumen of the aorta is small or

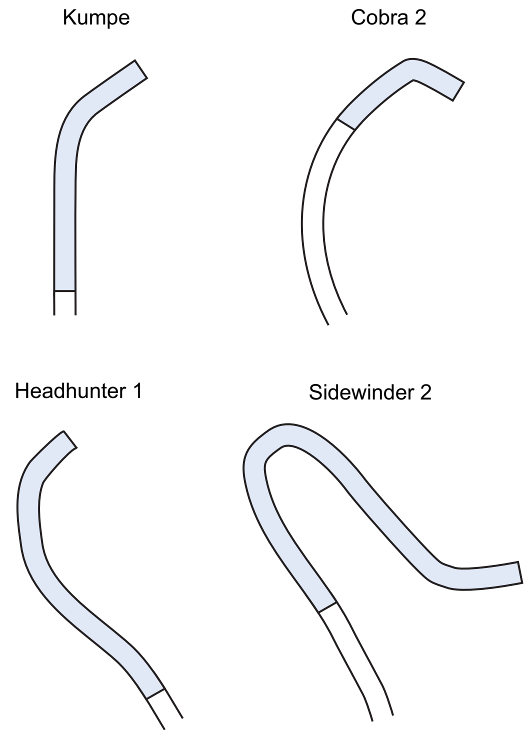

Figure 62.5 **Selective Diagnostic Catheters.** (Courtesy AngioDynamics, Queensbury, NY.)

has significant atherosclerotic plaque burden. To facilitate cannulation, reverse curve catheters have varying side arm lengths although longer side arms are usually more difficult to form.

Crossing Catheters

Crossing catheters are low profile, relatively stiff catheters with tapered tips that facilitate their passage through a tight stenosis or occlusion. They are typically used during interventional procedures but can be useful when the diagnostic site of interest is difficult to access. They are available in a variety of diameters and lengths and have multiple tip conformations.

Guiding Catheters

Guiding catheters are essentially sheaths that come in a variety of tip shapes, lengths and shapes and are useful for selective cannulation of vessels. Although similar to diagnostic catheters they are distinguished by a constant diameter throughout the length of the catheter. The constant diameter allows the insertion of a variety of smaller catheters (such as microcatheters), wires, and devices, thus their use is primarily interventional in nature.

Closure Devices

Closure devices can be an effective method to decrease overall procedure time length given the amount of compression time associated with manual hemostasis. Although compression can be performed in a recovery area, freeing up the operating room or angiosuite, most patients have 4–6 hours of mandated bedrest, which must be included in overall procedural costs.

There are a variety of devices that range from an extravascular plug to suture-based techniques for closure. The Angio-Seal device (St. Jude Medical, St. Paul, MN) works by placing an intra-arterial absorbable anchor against an externally placed collagen sponge; these are sandwiched together. This device works well on arteries that are at least 5 mm in size and free of significant calcification, and can be used to close puncture sites up to 8F.[11] The Mynx device (AccessClosure, Santa Clara, CA) uses a polyethylene glycol polymer to close the tissue track over the puncture site, thereby providing hemostasis for puncture sizes up to 6F.[12] The ProGlide device (Abbott Vascular, Santa Clara, CA) uses a single polypropylene stitch to suture close arteriotomy sites up to 6F.[13] Some practitioners have used this device off-label to close much larger puncture sites by placing two ProGlide devices through a single puncture site, thus allowing a totally percutaneous method for doing a TEVAR or EVAR procedure.[14] A variety of other closure devices are available. Closure devices increase the risk of groin infection and leg ischemia but decrease the time needed to achieve hemostasis.[13,15]

APPLICATIONS

Although there are many techniques of angiographic evaluation of the different vascular territories, variables such as vessel size, flow rates, cannulation pathway, and downstream organ sensitivity will invariably influence the choice of catheter and infusion technique to be used.

Abdominal Aortography

A standard diagnostic abdominal aortogram typically involves femoral access and positioning of a multi-side-hole flush catheter at L2 to adequately visualize the renal arteries. Imaging is obtained in AP orientation with the patient elevated off the X-ray emitter to include as much of the abdominal aorta and iliac vessels as possible. The catheter is then pulled back to the aortic bifurcation to include the distal external iliac arteries and femoral vessels. Improved visualization of individual iliac systems can be obtained by oblique orientations of the image intensifier, LAO for right and RAO for the left iliac system. A standard aortogram usually uses 15 mL of 50% contrast per second for a total of 30 mL of contrast ("15 for 30") at a pressure of 800 psi (pounds per square inch). Longer catheters can be used if doing imaging of the thoracic aorta, and a catheter with regular 1-cm markings (i.e., "marker pig") can be used for distance calibration and making measurements, particularly relevant for aortic endografting.

Extremity Angiography

The first step of lower extremity angiography is an abdominal aortogram. After this has been obtained there are two primary methods for obtaining lower extremity images. One option is to perform bolus chase angiography. The multi-side-hole flush catheter is positioned at the aortic bifurcation and continuous bilateral DSA of the lower extremities is performed with the contrast being tracked distally via table movements relative to the image intensifier. A typical contrast load is 8 mL per second for a total of 80 mL of contrast. Although expeditious, the quality of the imaging via this method can be compromised by differential limb perfusion, less flexible radiographic projections, and contrast dilution. Furthermore, inadequate opacification or delineation of pathology can be problematic, since repeating a bolus chase run involves a substantial increase in contrast administered as well as radiation.

The second method for lower extremity angiography is through selective catheterization of the vessels within the extremity of interest with multiple DSA runs. This is accomplished by getting "up and over" the aortic bifurcation. This is accomplished by positioning the pigtail or omni flush catheter with the tip of the catheter pointed towards the contralateral iliac artery. A wire can then be passed down contralateral iliac and the catheter pushed over this into position in the external iliac or common femoral artery (Fig. 62.6). A variety of alternative selective diagnostic catheters are available to facilitate crossing over the aortic bifurcation and selecting other vessels (Fig. 62.7). Anterior oblique positioning, in the direction of the extremity being imaged, can be used to splay out the femoral vessels. Ipsilateral oblique positioning is also useful for better visualization of the tibial trifurcation. Imaging can then be performed through multiple hand injection runs at various levels of the extremity via the previously positioned catheter. Extremity angiography on the side of arterial access is typically performed via simple sheath injection of contrast into the ipsilateral iliac system.

An alternative to multiple hand injection angiographic runs is power injection, though care must be taken to reduce injection rates and pressures commensurate to the vessel size and circumstances. An advantage of power injection is the ability for the operator and team to be sheltered from radiation, controlling contrast injection remotely during the angiographic runs. The primary disadvantage is the inability to vary the contrast concentration throughout the course of the evaluation, as can easily be done with hand injection.

Renal/Mesenteric Angiography

For diagnostic purposes, adequate visualization of the renal arteries can be obtained with standard AP abdominal aortography given that renal artery stenosis typically occurs at the origins of the vessels on the aorta. In situations where more detailed imaging is desired or if further intervention is planned, it may be necessary to selective cannulate the renal vessels individually. Selective renal angiography is typically performed by placing a RDC catheter (see Fig. 62.7) at the renal orifice followed by multiple hand injections at various angles to facilitate adequate visualization.

As with the renal arteries, the mesenteric vessels can usually be imaged with aortography, though adequate visualization will often require a lateral projection. Due to acute angle of the celiac and SMA relative to the aorta, selective cannulation can be challenging from the femoral arteries. Curved catheters and sheaths are helpful in this respect. In the event a concurrent

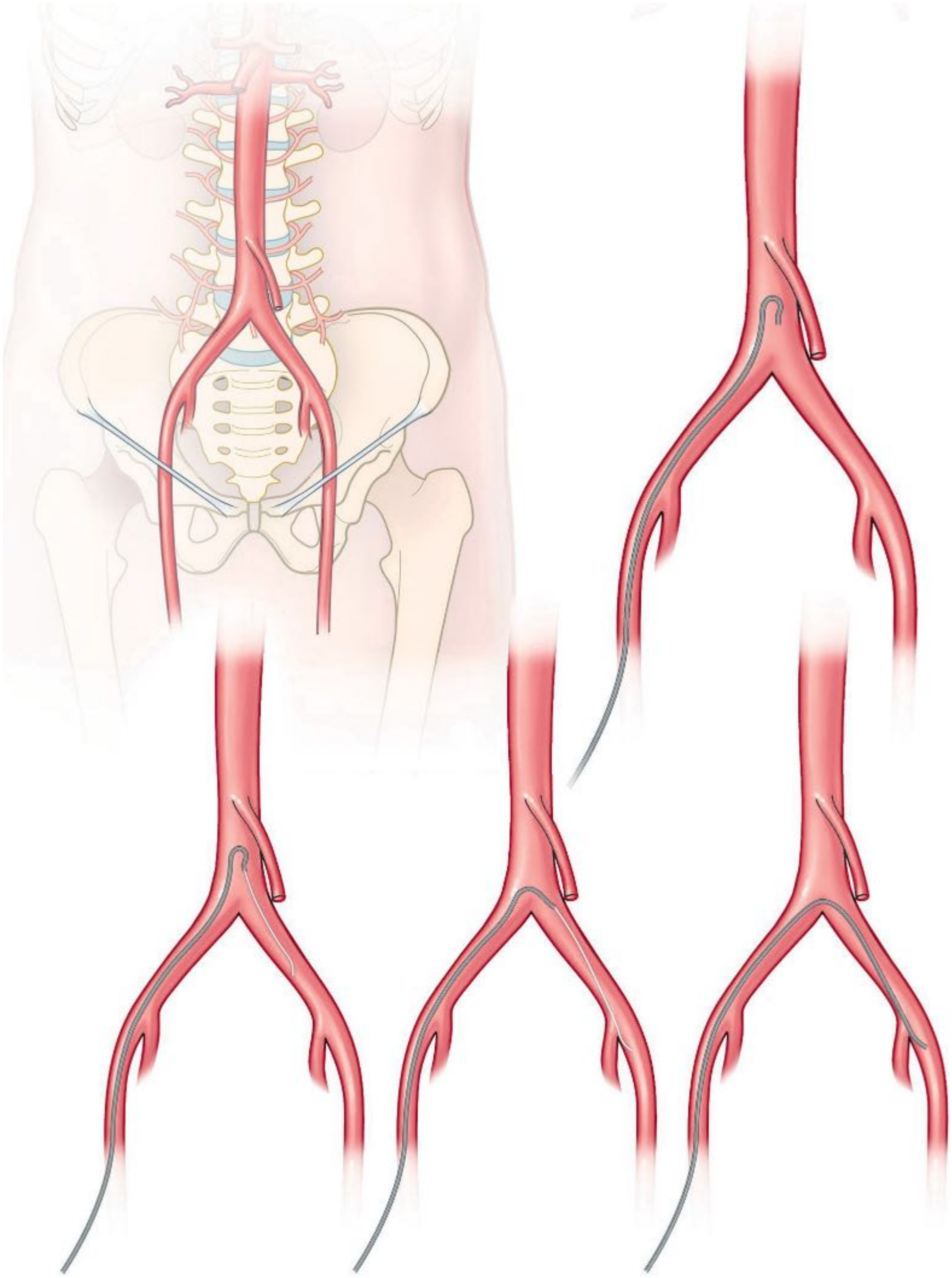

Figure 62.6 Crossing the aortic bifurcation to enter the contralateral iliac artery using an Omni flush catheter and soft angled wire.

intervention is likely, brachial access can facilitate easier cannulation of the vessels, eliminating the U-turn necessary to do so via femoral access.

Carotid Angiography

The initial step of endovascular imaging of the carotid arteries is nonselective angiography of the aortic arch. This is typically accomplished via femoral access and placement of a multi-side-hole catheter in the ascending aorta followed by power injection usually administering 15 mL of contrast per second for a total of 30 mL (15 for 30). Left anterior oblique positioning of the image intensifier is useful to separate the arch vessels for better visualization. Often arch angiography by itself will not provide enough information and selective angiography of one or more of the branch vessels will be required. Importantly, arch arteriography prior to cannulation of the arch vessels will not only provide a useful roadmap but also allow for assessment of the safety of selective cannulation in relation to orificial disease and the risk for distal embolization. The anatomy of the arch and the positions of the arch vessels typically require reverse-curved catheter for cannulation. A reverse curve catheter, such as a

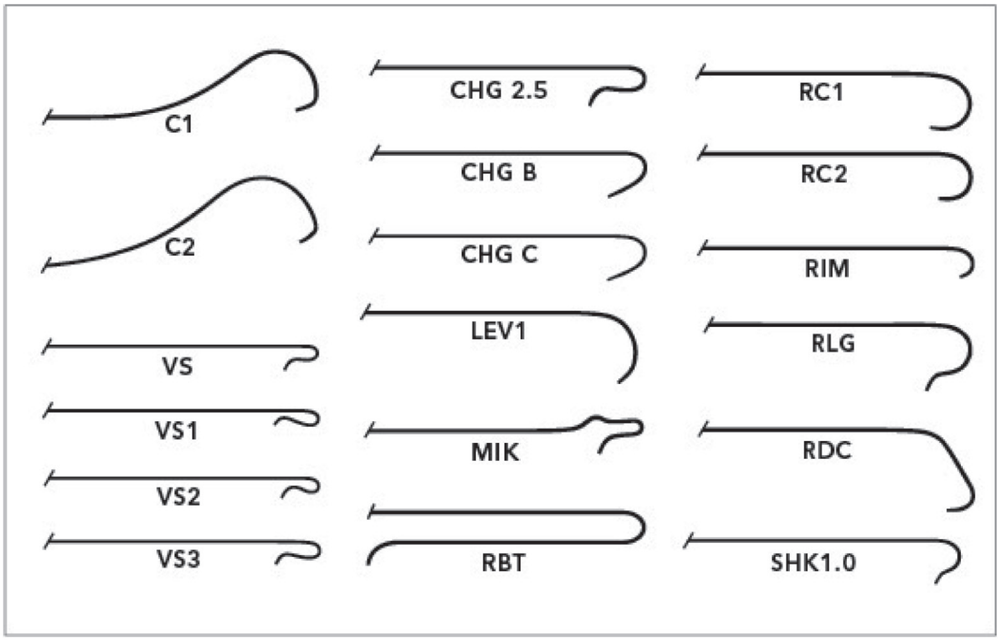

Figure 62.7 **Common Multipurpose Catheters.** (Courtesy Cook Medical, Bloomington, IN.)

Simmons 1 or 2, is advanced into the proximal aortic arch over a wire (see Fig. 62.8). The tip is reformed either at the aortic root or by hooking the left subclavian artery or brachiocephalic trunk (Fig. 62.8). The catheter can now be slowly pulled back to selectively cannulate either the brachiocephalic trunk or left common carotid artery. The Simmons 1 catheter has a shorter side arm that allows for easier manipulation and reforming in the arch while the Simmons 2, with its longer side arm, may be required for selecting the right carotid or subclavian arteries. There are self-forming reverse curve catheters, such as the VTK (see Fig. 62.8), that negate the need to be manipulated into shape, but they are limited by a short side arm length.

Once the common carotid artery is cannulated, filming can be performed with either hand injection of contrast or, if the catheter position is stable, with power injection. Power injection rates for the carotid arteries are typically 4 mL of contrast per second for a total 8 mL. The complexity of carotid angiography increases in type II and type III arches, in which the aortic arch branches come off earlier on the curve of the arch, and a more steeply curved catheter may be necessary. It must be emphasized that the meticulous, careful manipulation of the wires and catheters in this region is required to prevent embolization from the aortic wall or from the orifices of the branch vessels.

Fistulography

Fistulography is most commonly performed in the setting of a failing hemodialysis access or fistulas that fail to mature (see Ch. 177, Hemodialysis Access: Failing and Thrombosed). Access is obtained by direct access of the fistula or graft in a location that allows for intended intervention. Preoperative duplex lends clues to the likely etiology, and therefore, one can direct sheath access in the appropriate direction. Although these fistulas or grafts are normally easily accessed through manual palpation during dialysis runs, ultrasound guidance can be helpful particularly in un-matured fistulas or failing access sites. A small sheath, such as the 4 Fr microsheath, is all that is typically required for diagnostic purposes. This can be quickly scaled up to larger sheaths if intervention is warranted. Imaging of the outflow tract is straightforward due to the brisk proximal flow through the access vessel. Imaging of the inflow can be assisted by compression of the fistula or graft, either manually or by tourniquet, during contrast administration.

Pelvic Congestion Syndrome Venography

Venography generally mirrors arteriography in respect to technique and imaging, though pelvic congestion syndrome presents several unique facets that bear discussion. Cannulation of the CFV is obtained and a diagnostic venogram performed in order to visualize the renal vein orifices. These can be seen as areas of lower opacification, or contrast washout from contrast-free blood entering from the kidney. A combination of an appropriately shaped catheter in conjunction with a guide wire is then used to cannulate the proximal ovarian vein. Filming is generally performed with hand injection of contrast under low pressure, so as not to traumatize the veins. If necessary, a more distal catheter position can be pursued to enhance opacification of the pelvic venous network.

COMPLICATIONS

Access Site

Issues arising due to vessel access and hemostasis account for the majority of complications related to angiographic procedures including clinically significant hematoma (3%), thrombosis

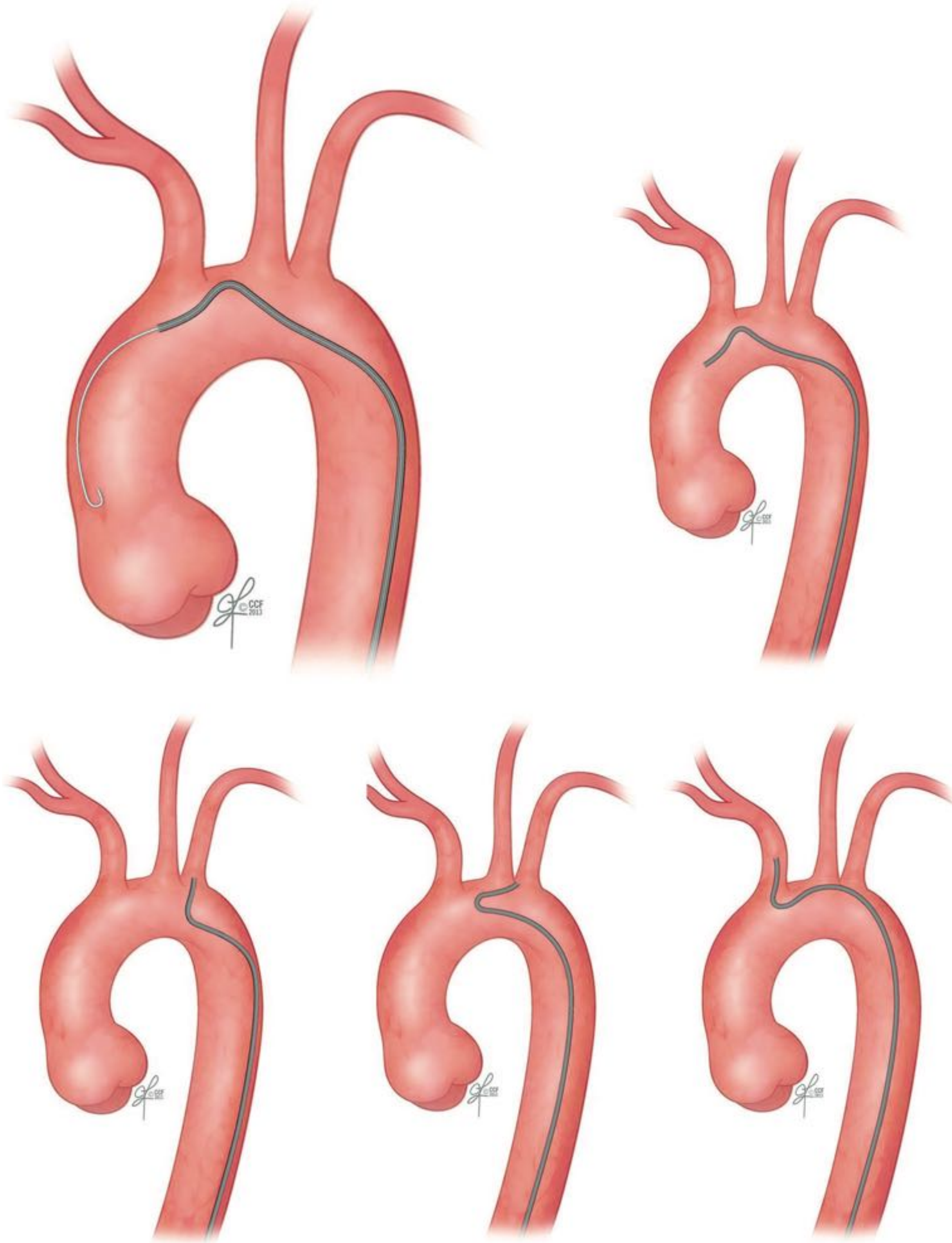

Figure 62.8 Technique for forming a Simmons 2 catheter with the aortic arch and selective cannulization of an arch branch.

(2%), bleeding (1%), traumatic arteriovenous fistula (0.9%), and pseudoaneurysm (0.6%).[16]

The use of adjuncts including fluoroscopy and especially ultrasound have been shown to reduce the risk of these complications and improve the rate of successful vessel access.[8–10] Patients who are obese, have significant atherosclerotic occlusive disease, or who are on systemic anticoagulation are at increased risk for access site complications.[8–10]

The most common access site complication is a hematoma, with or without associated pseudoaneurysm in the groin. Small hematomas with intact uncompromised overlying skin can be safely managed conservatively. PSAs with appropriate anatomy can be treated with ultrasound-guided thrombin injection or compression.[17,18] When persistent, enlarging, or symptomatic, most access site false aneurysms are treated by simple ultrasound-guided thrombin injection. Pseudoaneurysms >3 cm should not be observed and if thrombin injection is unsuccessful, open repair is curative.

The most dangerous complication related to arterial access in the groin is retroperitoneal hemorrhage from supra-inguinal puncture of the external iliac artery. Manual pressure is ineffective and closure devices are contraindicated at this location. Unfortunately, patients can become hemodynamically unstable quickly and may require operative exploration and repair. If noted early, endovascular intervention from the contralateral side is an option either with stenting across the puncture site or as an adjunct to obtain control with placement of a balloon proximal to the puncture site.

Arteriovenous fistula is a rarer complication that tends to occur with more distal punctures. Commonly it involves the superficial femoral or profunda femoris arteries with adjacent or crossing veins. The majority are likely unrecognized as many are asymptomatic and will close spontaneously. If persistent and symptomatic, AV fistulae should undergo repair, most commonly through open surgery. There are some case series describing the use of covered stents to close the fistula although this is currently not the standard of care.

Catheter- or Guide Wire-Related

Catheter- or guide wire-related complications are secondary to damage to the vessel wall from their passage or manipulation, such as the creation of a perforation or dissection, with or without embolization. Observation of wire and catheter advancement under fluoroscopy helps avoid these complications. Similarly, appropriate selection of wires and catheters can also minimize the risk of dissection, perforation, and embolization. Perhaps most important is that the catheter, in its natural shape, is not excessively larger than the diameter of the vessel that it is in, lest the tip inflict trauma on the vessel wall. Perforation of a vessel can be minimized by rigorous control over wires and catheters, particularly relevant when dealing with terminal vascular territories like the renal artery or mesenteric circulation, where excessively deep guide wire penetration can easily lead to perforation. The super-stiff variety of guide wires have a rather abrupt transition from the floppy to the stiff areas and, consequently, do not lead out well. These are rarely used for diagnostic purposes, but when used are best positioned initially through a catheter to minimize vessel wall trauma. Dissections, if clinically relevant, can be treated with angioplasty or stenting, while perforations and AV fistulae are best treated with endografting, if significant. Catheter guide wire-induced embolization, often secondary to dissection, is typically microembolic and therefore not amendable to angiographic detection or aspiration. Larger emboli, especially those that occur during thrombolysis, may be extracted or lysed through standard endovascular techniques. Finally, leading catheters without an intraluminal wire may result in tying a knot with the catheter. If discovered and a wire cannot be passed, this may require cutdown for safe retrieval of the catheter.

Systemic

Systemic complications associated with endovascular diagnostic procedures are related to the use of iodinated contrast, anticoagulation, and radiation. Contrast-related complications relate to either contrast-induced nephropathy (CIN) or allergic reactions to iodinated contrast. Patients with chronically reduced glomerular filtration rates are at increased risk for CIN (see Ch. 46, Systemic Complications: Renal). The safest practice is to judiciously use contrast to minimize the total amount given and ensure patients are well hydrated prior to and immediately postoperatively. Another option for patients with chronic kidney disease is the use of CO_2, which can be effective for visualization of larger vessels, although it is limited in its ability to opacify smaller infrageniculate vessels. Patients with allergies to iodinated contrast can be pre-treated with a combination of antihistamines and steroids prior to the procedure. Following the principles of ALARA (as low as reasonably achievable) for radiation exposure will help prevent tissue damage from excessive X-rays (see Ch. 26, Radiation Safety).

CONCLUSION

Multiple principles must be considered if one is to perform successful endovascular diagnostic angiograms. Selection of an adequate access vessel is the first step. Adjuncts such as ultrasound guidance and proper wire and catheter selection can decrease the incidence of complications. Hemostasis must be achieved, often with closure devices but also definitively with manual compression. Developing a strategy for each angiography as well as mastery of the variety of wires, catheters, and sheaths are paramount to the safe and effective practice of vascular surgery.

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63 CHAPTER

Endovascular Therapeutic Technique

TAKESHI BABA and TAKAO OHKI

INTRODUCTION

Endovascular intervention has replaced open surgery as the primary treatment option for many vascular diseases. This chapter reviews the basic principles, devices, and techniques of endovascular therapy, including indications, limitations, pitfalls, and complications.

BALLOON ANGIOPLASTY

The first percutaneous treatment for peripheral artery disease (PAD) was performed in 1964 by Dotter and Judkins, who described a transluminal technique using progressively larger dilators in the lower extremities.[1] The balloon catheter, well-known today, was developed by Gruntzig and Kumpe to dilate stenotic arterial lesions with flexible polyvinylchloride (PVC) balloons.[2] Balloon dilation for stenotic lesions creates a blunt dehiscence effect leading to fracture and separation of the arterial media from the intima, with stretching of the media and adventitia. The disadvantages of percutaneous transluminal angioplasty (PTA) depend upon the lesion type. The treatment of severely stenotic lesions and those with dense calcification may result in elastic recoil or flow-limiting dissection after PTA, and stents are often used to prevent such complications. New technologies such as drug-coated balloons (DCBs) are also expected to provide equivalent performance to stents without the disadvantage of leaving foreign bodies prone to fracture. However, if the lesion can be treated with PTA alone, it is most cost-effective. Furthermore, the concept of vessel preparation before stenting is also important, and it is expected that high quality PTA treatment will contribute to stent patency. It is essential to choose the appropriate balloon for a given lesion to maximize the clinical outcomes of PTA; therefore, an understanding of the characteristics, behavior, and techniques of balloon angioplasty is essential.

Balloon Catheter Types

There are two types of balloon catheters for PAD: the over-the-wire (OTW) system and the rapid exchange (RX) system (Fig. 63.1). The length of the shaft for OTW balloons ranges from 80 to 150 cm. If a long shaft, such as 130 or 150 cm, is selected, a 260-cm wire, or longer, will be needed to treat the lesion.

The RX system, often referred to as "monorail," has the wire enter from the distal tip of the catheter and exit from a side hole 20–25 cm proximal to the balloon. The RX balloons, which are generally used in coronary interventions, are supported by a 0.014 or 0.018-inch guide-wire system. In PAD, these balloons are used for below-the-knee lesions where vessel diameters are much smaller than above-knee vessels. Since an RX catheter shaft does not have a wire through the lumen, RX balloons can be inserted, delivered, or exchanged by a single operator who can hold the wire close to the insertion point. Thus, an exchange length wire is not necessary for RX systems, which can use a wire of any length, shortening the procedure time. The RX system generally has a lower profile than the OTW system, at the expense of less "pushability" and "trackability." The wire cannot be exchanged without a transfer catheter or the use of a long sheath or guiding catheter.

Balloon Characteristics

Balloon Compliance

Balloon compliance is the expansive ability of the balloon, which is determined by the function of pressure and diameter. Currently available balloons for PAD are usually made of a plastic polymer with varying degrees of compliance. Compliance is expressed as a range from nominal pressure to rated burst pressure. Nominal pressure is defined as the pressure at which the balloon expands to its designed diameter and length, and generally lies somewhere between 4 to 10 atmospheres (atm). Rated burst

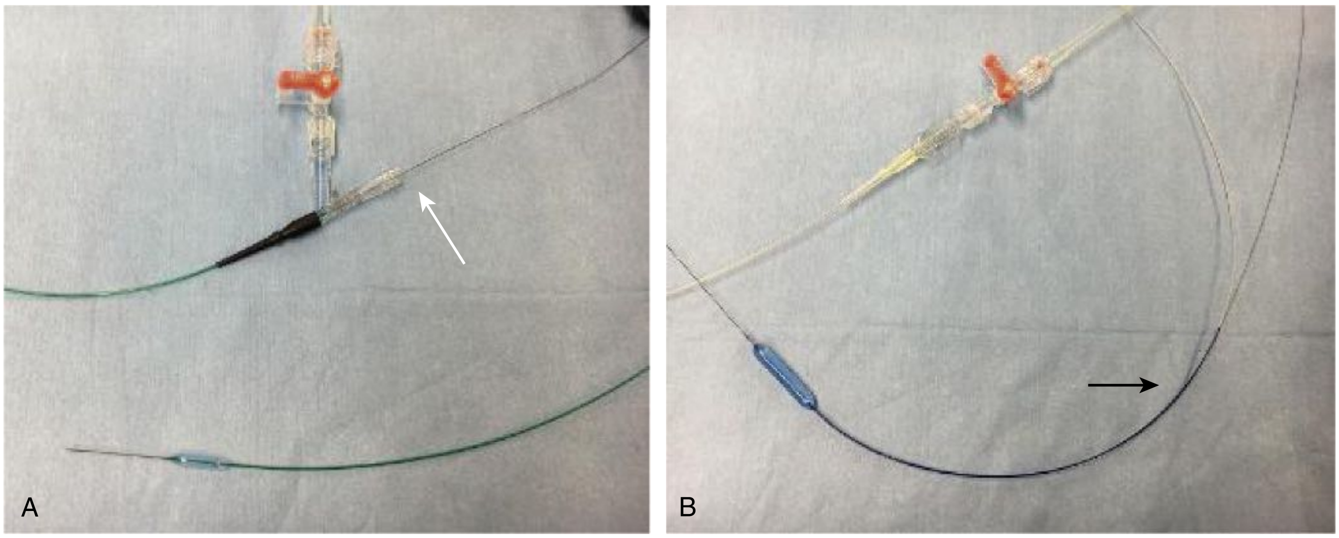

Figure 63.1 (**A**) The balloon of an OTW system: a wire is exiting the hole at the end of the balloon (*white arrow*). (**B**) The balloon of an SOE system: a wire is exiting the proximal side port of the balloon (*black arrow*).

pressure (RBP) is the pressure at which less than 1% of tested balloons will burst and beyond which the probability of rupture increases. RBP typically ranges from 6 to 20 atm.

Compliant balloons are usually made of polyolefin copolymer and polyethylene. These balloons, including semi-compliant balloons, are superior in trackability and are suitable for lesions in a curved portion of a vessel. Although they produce less vascular damage because of their gentle dilation, high-pressure inflation can result in a "doggie bone" effect that may damage the normal vessel proximal and distal to the lesion. Thus, a compliant balloon is not suitable for severe calcific lesions. However, an advantage of a compliant balloon is that a single balloon may be used for various vessel diameters.

Non-compliant balloons are referred to as high-pressure balloons or low compliance balloons. Most non-compliant balloons are made of polyethylene terephthalate or nylon-reinforced polyurethane. These materials improve the radial force of the balloon and allow high-pressure expansion. Non-compliant balloons are constructed to maintain their designed shape and size under high pressure and have a higher RBP compared with compliant balloons. Non-compliant balloons, preferred by most interventional specialists, exert more recoil force when used for severe calcific lesions or following insufficient expansion during post-dilatation following stent deployment.

Profile and Balloon Ability

A balloon's profile is usually expressed in French (Fr) size and is determined by the cross-sectional area and diameter of the balloon and shaft. A smaller profile is better than a larger profile for delivering to the lesion crossing severe stenotic lesions. Most peripheral balloons are deliverable via a 4- to 6-Fr compatible sheath. Balloons of 0.014 or 0.018-inch wire systems have a smaller profile compared to the 0.035-inch systems.

Specialty Balloons

Specialty balloons have been developed for specific purposes to improve PTA outcomes and to reduce recoil, dissection, and restenosis.

Cutting Balloons

The cutting balloon is a specialized device made of 3 or 4 microsurgical blades (atherotomes) mounted longitudinally along the surface of a standard PTA balloon (Fig. 63.2).[3] Peripheral cutting balloons (PCBs) require a 0.014- or 0.018-inch guide-wire system with a 6-Fr sheath. More specifically, small diameter (2–4 mm) PCBs are supported by a 0.014-inch guide wire and either an OTW or RX system. Large diameter (5–6 mm) PCBs are only used with a 0.018-inch guide wire with an OTW system. PCB length is typically 1.5–2.0 cm, and the nominal pressure of PCBs is 6 atm. Peripheral lesions that are suitable for treatment with a PCB are mainly short lesions. These include venous graft stenosis following bypass, bifurcation stenosis, highly calcified lesions, a no-stenting zone (such as common femoral or popliteal artery), and in-stent restenosis (ISR), as opposed to areas that require primary treatment of occlusive disease.

The midterm results of a retrospective study of PCBs versus conventional PTA (non-compliant balloons) for the treatment of short lesions of femoropopliteal artery stenosis were reported by Controneo et al.[4] The results revealed better primary patency rates at 6, 12, and 24 months for the PCB vs. PTA group, with no recoil, dissection, or arterial tears requiring stents observed in the PCB group. In another study of 128 patients undergoing treatment of infrainguinal lesions, the primary patency rate following treatment with PCB was 82.1% at 1 and 2 years. In patients with critical limb ischemia (CLI),

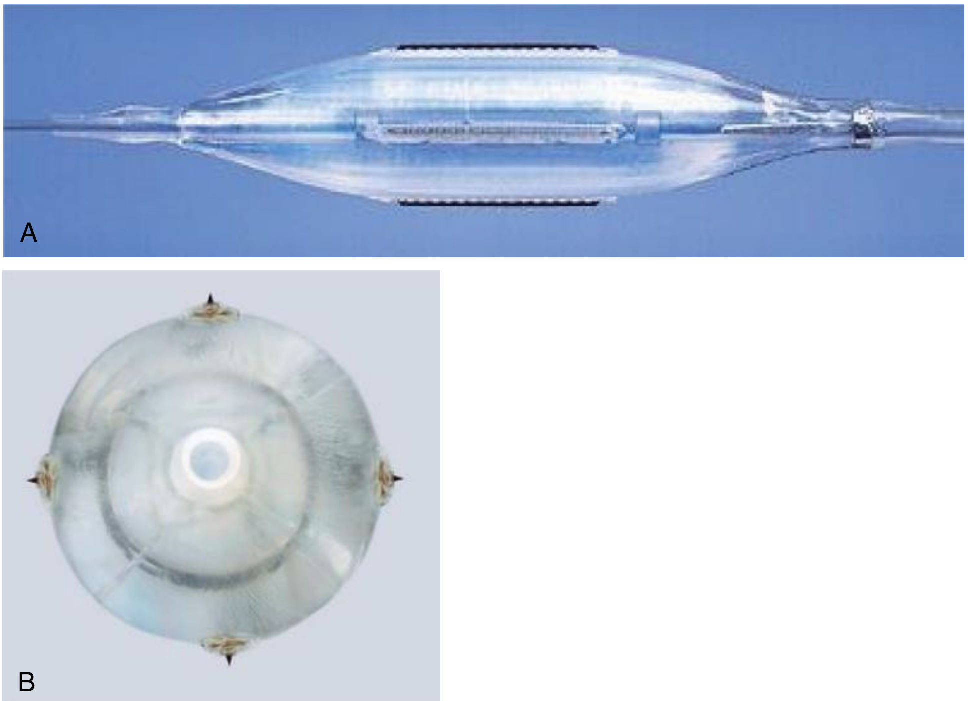

Figure 63.2 Peripheral cutting balloon (Boston scientific, Natick, MA) seen from the side (**A**) and from the top of the balloon (**B**).

the primary patency rates at 1 and 2 years were 64.4% and 51.9%, respectively.[5] In the treatment of short infrapopliteal bifurcation disease in 23 patients, the primary and secondary patency rates were estimated as 89.3% and 93.5% at 6 months and 77.7% and 88.8% at 12 months, respectively; the 1-year primary and secondary patency rates of the treated bifurcation were 74.2% and 87.0%.[6] PCBs have also been utilized for hyperplastic stenosis in hemodialysis arteriovenous fistulae. In a review of several randomized trials, the patency of the target lesion at 6 months was significantly higher in the PCB group compared to the conventional balloon group implying greater freedom from restenosis without a significant increase in the complication rate.[7,8] Furthermore, in severely calcified lesions, calcium fracture was more often associated with rotational atherectomy followed by cutting balloon compared with rotational atherectomy followed by conventional balloon predilation before stenting.[9] A strategy of rotational atherectomy followed by cutting balloon before stenting can increase the lumen diameter and acute lumen gain.

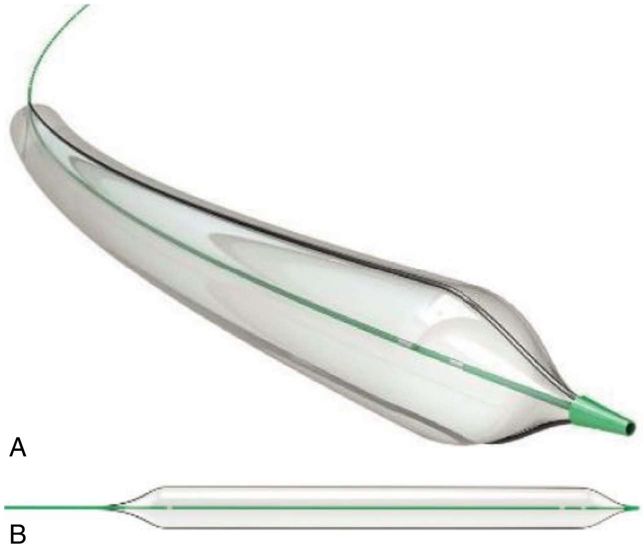

Figure 63.3 Peripheral scoring balloon (Bard Peripheral Vascular, Tempe, AZ) seen from the top of the balloon (**A**) and from the side (**B**).

Scoring Balloons

The AngioSculpt balloons (AngioScore, Fremont, CA) and VascuTrak 2 (Bard Peripheral Vascular, Tempe, AZ) are designed to exert focal pressure on the lesions. The AngioSculpt balloon is composed of nitinol wires placed as spiral struts along the surface of a standard semi-compliant balloon. The 1-year outcomes of treatment for femoropopliteal lesions with the AngioSculpt balloon were reported by Lugenbiel et al.,[10] who treated 124 calcified femoropopliteal lesions in 101 consecutive patients. Overall, the primary patency rate after 12 months was 81.2%. Preparation with the AngioSculpt scoring balloon may offer a safe and valuable treatment option for calcified femoropopliteal lesions. The VascuTrak balloon catheter has two wires located along the longitudinal axis of the balloon to provide focal pressure, which is estimated to be approximately 50 to 400 times greater than a conventional balloon (Fig. 63.3). Although there is no solid evidence supporting the VascuTrak, it is reported that its use in vessel preparation, and subsequent DCB angioplasty, was safe and effective in patients with femoropopliteal lesions.[11]

Cryoplasty

Cryoplasty is a type of balloon angioplasty that combines the dilation force of balloon angioplasty with the delivery of cold thermal energy to the vessel wall. This system was expected to have the theoretical advantage of reduced myointimal hyperplasia in long-term patency and therefore avoid the need for stenting and reduce restenosis. When the balloon reaches the target lesion, liquid nitrous oxide inflates the balloon and exposes approximately 500 μm of the lesion to a cooling temperature of 14 degrees F (–10°C). Seven randomized controlled trials (RCTs) involving 478 patients with iliac, infrainguinal, femoropopliteal, and popliteal lesions treated by cryoplasty or conventional angioplasty were reviewed. There was no statistical difference between the treatment groups in target lesion patency and restenosis rates calculated at various periods in two primary cryoplasty trials. Adjunctive cryoplasty, which was performed for ISR of superficial femoral artery (SFA) lesions, was associated with improvements of patency only at 6-month (OR 5.37, 95% CI: 1.09–26.49). The authors concluded that the efficacy of cryoplasty over conventional angioplasty could not be proven.[12] Since the effectiveness of cryoplasty is not supported, and there are additional costs ($1700) compared to conventional PTA, the value and role of cryoplasty for PAD is limited.

Drug-Coated Balloons

A drug-eluting balloon (DCB) is a non-stent technology for the effective homogenous delivery of antiproliferative drugs to the vessel wall through an inflated balloon. The balloon technology relies on targeted drug delivery, which helps in the rapid healing of the vessel wall and prevents the proliferation of smooth muscle cells. The drug-eluting stent (DES) was developed in 1999 to achieve local administration of an agent capable of inhibiting intimal hyperplasia without systemic side effects. The Cypher stent (Cordis Corporation, Fremont, CA), which was developed for the treatment of coronary artery disease, releases sirolimus. This is a macrolide antibiotic with a potent immunosuppressive effect that controls intimal hyperplasia. Subsequently, the TAXUS stent (Boston Scientific, Natick, MA), which is coated with paclitaxel, was developed as a second-generation DES. These stents could provide greater durability and reduce restenosis; however, they did not prolong life expectancy or decrease cardiac events compared to coronary bypass according to the SYNTAX trial.[13] Moreover, dual antiplatelet drug therapy was required for 3 to 6 months after stent placement because of an increased risk of subacute thrombosis.

The DCB adopted the DES technology for the treatment of femoropopliteal or below-the-knee (BTK) lesions to treat *de novo* or restenotic lesions. The DCB consists of an OTW dual-lumen catheter with a distally mounted semi-compliant inflatable balloon and an atraumatic tapered tip. A minimum inflation time of 60 seconds is recommended in the instructions for use.

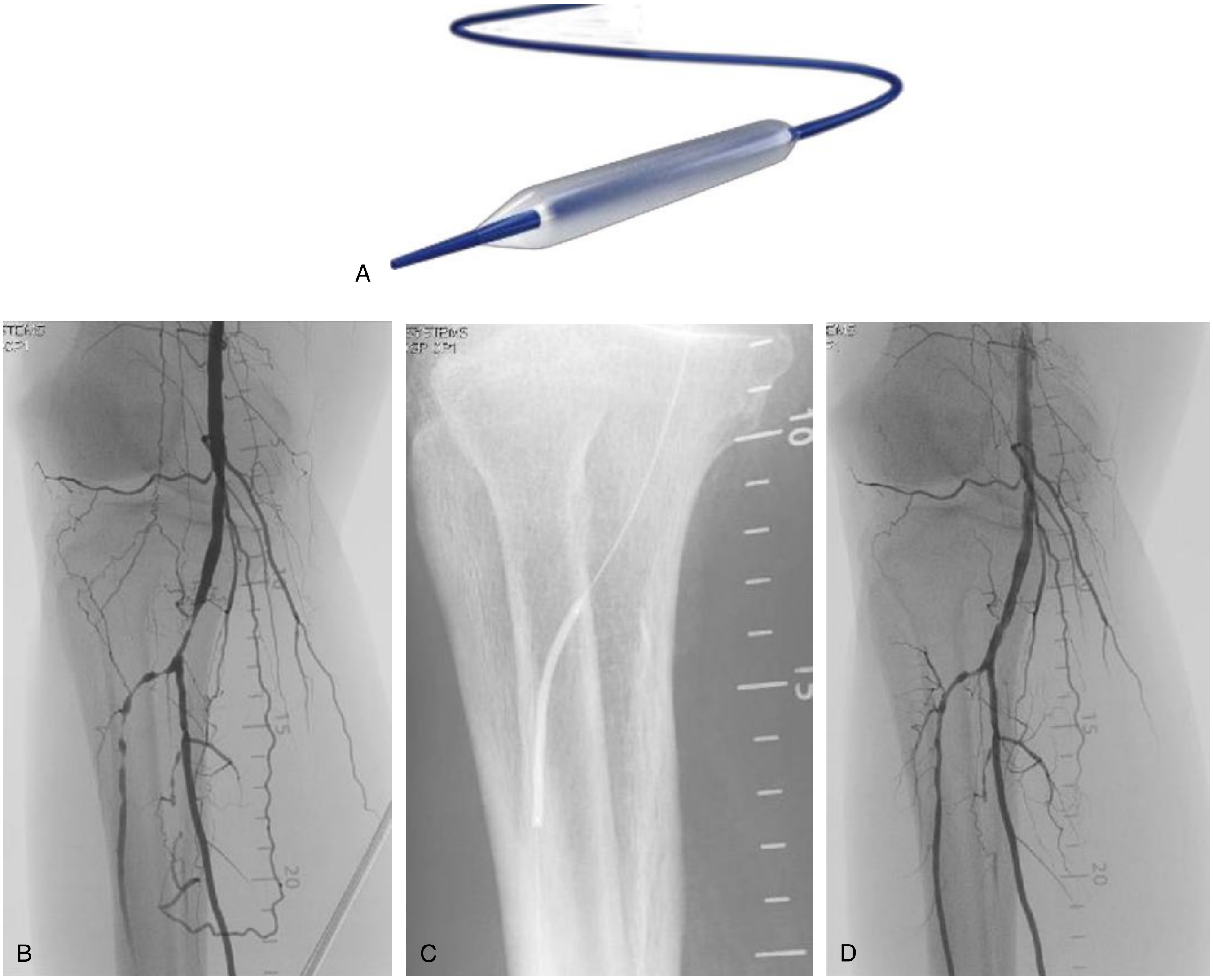

Figure 63.4 (**A**) The Lutonix drug-coated balloon (DCB) (Bard Peripheral Vascular, Tempe, AZ). (**B**) Pre-intervention angiography showing a popliteal artery and anterior tibial artery stenosis. (**C**) The stenotic lesion was treated with the Lutonix DCB. (**D**) The angiography 1 year after PTA.

The LEVANT 1 trial was a European single-blind study that compared DCB and non-coated balloons. It evaluated the safety and efficacy of the Lutonix DCB (Bard Peripheral Vascular, Tempe, AZ) (Fig. 63.4) for the treatment of femoropopliteal lesions.[14] The Lutonix DCB is coated with a low dose of paclitaxel (2 µg/mm^2) as an antiproliferative drug. The primary outcome of 6-month angiographic late lumen loss was significantly lower in the DCB group than in the uncoated group by intention-to-treat analysis (0.46 ± 1.13 mm vs. 1.09 ± 1.07 mm, $P = 0.016$). The primary patency rates were 72% in the DCB group versus 49% in the non-coated group at 6 months, and 67% in the DCB group versus 55% in the non-coated group at 12 months, respectively.

Consequently, LEVANT 2, a global, prospective, single-blind randomized trial, was conducted comparing Lutonix DCB with standard PTA.[15] In this trial, 476 patients with symptomatic intermittent claudication or rest pain were randomly assigned in a 2:1 ratio to undergo angioplasty using DCB or a standard balloon for the treatment of femoropopliteal arterial disease. The primary patency rate (primary endpoint) of the DCB group was superior to the standard PTA group (65.2% versus 52.6%, $P = 0.02$). Additionally, the proportion of patients free from death or limb-related death at 12 months, amputation, or reintervention was 83.9% in the DCB group versus 79.0% in the standard PTA group, with no statistical difference.

The RANGER SFA study, the IN.PACT SFA study, and the ILLUMENATE study demonstrated the greater efficacy of paclitaxel-coated balloons over PTA in the SFA.[16–18] Recently, the data of 3 years after DCB treatments became available revealing a durable and superior treatment effect among patients treated with DCB versus standard PTA, with significantly higher primary patency and lower clinically driven target lesion revascularization.[19]

The LEVANT 2, the RANGER SFA, and the ILLUMENATE balloons are coated with paclitaxel at a dose density of 2 µg/mm^2, whereas the IN.PACT balloon coating has a dose density of 3.5 µg/mm^2. A recent systematic review and meta-analysis of summary-level data from 28 RCTs suggested an increased risk of death after femoropopliteal artery DCB treatment, beginning 2 years after the DCB procedure.[19] The systematic review and meta-analysis of Katsanos et al. found an almost 2-fold increase in the relative risk for all-cause mortality after treatment with paclitaxel-containing devices compared with uncoated PTA for femoropopliteal PAD.[20] However, this analysis has been criticized for its lack of long-term, homogeneous, patient-level data that might have identified confounding factors to better explain the observations. In the patient-level meta-analysis of the ILLUMENATE study at 3 years, there was no significant difference in all-cause mortality between the two cohorts through a full follow-up of the 589 patients for 3 years.[21] Schneider et al. published the outcomes of a patient-level meta-analysis comprising 2 RCTs and 2 single-arm trials of 1980 patients: 1837 patients treated with a higher-dose paclitaxel-coated balloon from a single manufacturer and 143 patients treated with PTA with an uncoated balloon. Overall, there was no statistically significant difference in all-cause mortality between patients treated with DCB versus PTA through 5-year follow-up (15.1% vs. 11.2%, $P = 0.09$).[22]

Initially, favorable outcomes have been presented for several DCB trials, but their long-term patency and safety remain unclear. Therefore, further long-term follow-up will be required to decide whether DCB therapy is appropriate for the treatment of complex stenotic lesions or occlusive lesions in infrainguinal PAD.

STENTS

The term "stent" originated from Charles R. Stent, a British dentist, who developed an apparatus to make dental molds. After that, a mold embedded inner lumen came to be known as a stent. Stenting for vascular lesions is a widely used method to reduce the incidence of restenosis or address balloon PTA failure due to elastic recoil or dissection. In 1964, Charles Dotter, who performed the first PTA, initially reported laboratory experience with the long-term patency of coil spring endoarterial tube grafts in canine popliteal arteries.[23] This was the first report of transluminal metallic stent placement. The nitinol stent, which accounts for the majority of the currently available stents, consists of an alloy of nickel and titanium and was not used until 1983.[24,25] In 1985, Palmaz et al.[26] introduced the first balloon-expandable stent (BES) which was approved for peripheral vascular use by the US Food and Drug Administration (FDA). The improved patency of the Palmaz–Schatz stent compared to PTA was demonstrated in several trials.[27,28] Currently, many stents have been developed (Table 63.1), are available, and have been evaluated in clinical studies.

Stent Types

Stents are classified as balloon-expandable stents (BES), self-expanding stents (SES), and also either as bare metal or covered stents. Most bare metal stents are composed of stainless steel, nitinol, cobalt chrome, or various metal alloys. Covered stents (stent grafts or endografts) have added woven, expanded polytetrafluoroethylene (PTFE), polyurethane, or silicon. Stent characteristics, including flexibility, radial strength, kink resistance, and biocompatibility, vary depending on their material and design and may affect the ultimate patency of the stent.

Balloon-Expandable Stents

The first commercially available balloon-expandable bare metal stent is the Palmaz stent. The efficacy of this stent has been validated in clinical trials.[29–31] BESs are slotted metal tubes that are mounted, or "crimped," onto a balloon suited to the diameter of the target vessel. The balloon is inflated to deploy the stent and secure it to the vessel wall. At first, the proximal and distal ends of the stent are expanded into a "doggie bone" shape, and subsequently, the middle portion of the stent is expanded. These stents are typically rigid to provide resistance against elastic recoil, but they may become irreversibly deformed when subjected to an external compression force. Thus, these stents are suitable for vessels that are not prone to external compression. Other advantages of BESs are the ability to place them precisely, and that they tend to be more radiopaque than SESs. Therefore, BESs are better suited to treat calcific ostial lesions involving the renal, mesenteric, iliac, subclavian, or brachiocephalic arteries. They are contraindicated for vessels prone to external compression, including the internal carotid artery and SFA. BESs may foreshorten if they are over-distended beyond their intended diameter. Furthermore, most stents made of a stainless alloy cause artifacts (signal loss) with magnetic resonance imaging (MRI). Although most BESs are made from stainless steel, newer BESs are composed of cobalt-chromium, which is stronger and provides a greater radial force with a lower crossing profile and enhanced flexibility.

Self-Expanding Stents

SESs are typically composed of nitinol, a nickel–titanium alloy, which provides flexibility and shape-memory. Due to the elastic properties of nitinol, stents with a diameter greater than the target reference vessel are selected so that they exert an outward force, resulting in appropriate vessel wall apposition. The eventual diameter of a lesion treated with an SES is a balance between the recoil of the lesion and the radial expansion force of the stent. SESs are more flexible than BESs, which provides greater trackability, allows for the navigation of tortuous vessels, and resistance to fracture. As a result of their elastic property, the diameter sizing of the stent is more forgiving than BESs, and an SES generally apposes well to the vessel with less chance of vessel perforation. In addition, because nitinol is a nonferromagnetic metal, it is less likely to create artifacts on MRI. The radial strength, flexibility, and most importantly, the maneuvers for deployment differ by manufacturer. Most SESs are stored in the delivery sheath, and they are deployed from the distal to the proximal end of the stent by unsheathing. Once deployed, most SESs cannot be restored or repositioned, with the exception of the Wallstent (Boston Scientific, Natick, MA), which can be repeatedly sheathed and repositioned. With the exception of the Misago stent (Terumo, Somerset, NJ), SES platforms are OTW systems. Various modifications

TABLE 63.1 Variation of Available Stents

	Company	Introducer sheath (Fr)	Diameter (mm)	Length (mm)	Endohole (inch)
Iliac					
Self-Expandable					
Absolute Pro	Abbott	6	6–10	20–100	0.035
E-Luminexx	Bard	6	7–10	20–100	0.035
LifeStar	Bard	6	7–10	20–100	0.035
Wallstent	Boston Scientific	6	6–10	18–69	0.035
Zilver	COOK	6	6–10	20–80	0.035
EverFlex	Medtronic	6	6–8	20–120	0.035
SMART	Cordis	6	6–10	20–100	0.035
Epic	Boston Scientific	6	6–12	20–120	0.035
Balloon-Expandable					
Omnilink Elite	Abbot	6, 7	6–10	12–59	0.035
Express LD	Boston Scientific	6, 7	6–10	17–57	0.035
Palmaz	Cordis	6, 7	4–8	10–29	0.035
Assurant	Medtronic	6	6–10	20–60	0.035
Stent Graft					
i-CAST	Atrium Medical	6, 7	5–10	16–59	0.035
Viabahn VBX	Gore & Associates	7, 8	8–16	29–79	0.035
BeGraft	Bentley	7, 8	5–10	27–57	0.035
LifeStream	Bard	7, 8	5–11	15–79	0.035
SFA					
Self-Expandable					
LifeStent	Bard	5, 6	5–7	20–170	0.014-0.035
Misago Rx	Terumo	6	6–8	40–150	0.035
SMART	Cordis	6	6–8	20–100	0.035
Innova	Boston Scientifics	6	5–8	20–200	0.035
BioMimics	Veryan Medical	6	5–7	60–150	0.035
EverFlex	Medtronic	6	6–8	20–200	0.035
Supera	Abbott	6	4.0–6.5	20–150	0.018
Drug-Eluting					
Zilver PTX	COOK	6	5–8	40–120	0.035
Eluvia	Boston Scientifics	6	6–7	40–140	0.035
Stent Graft					
Viabahn	Gore & Associates	6–12	5–13	25–250	0.014/0.018
Flair	Bard	9	6–9	30–70	0.035
Fluency	Bard	8–10	6–13.5	40–120	0.035

have been developed aiming at improving performance in calcified lesions or areas subject to significant external stresses such as the adductor canal or the knee joint. In the Supera (Abbott Cardiovascular, Plymouth, MN) peripheral stent, a woven self-expanding stent constructed from nitinol, six pairs of closed-ended interwoven nitinol wires are arranged in a helical pattern designed to provide increased flexibility and resistance to fracture.

SESs are classified as open-cell or closed-cell design. An open-cell stent is a cylindrical structure of stacked serrated metal. The current stents, such as SMART (Cordis Corporation, Fremont, CA), Misago (Terumo, Somerset, NJ), EPIC (Boston Scientific Corporation, Natick, MA), Lifestent (Bard Peripheral Vascular, Tempe, AZ), and E-Luminexx (Bard Peripheral Vascular, Tempe, AZ) are composed of an open-cell configuration for the body of the stent and a closed-cell

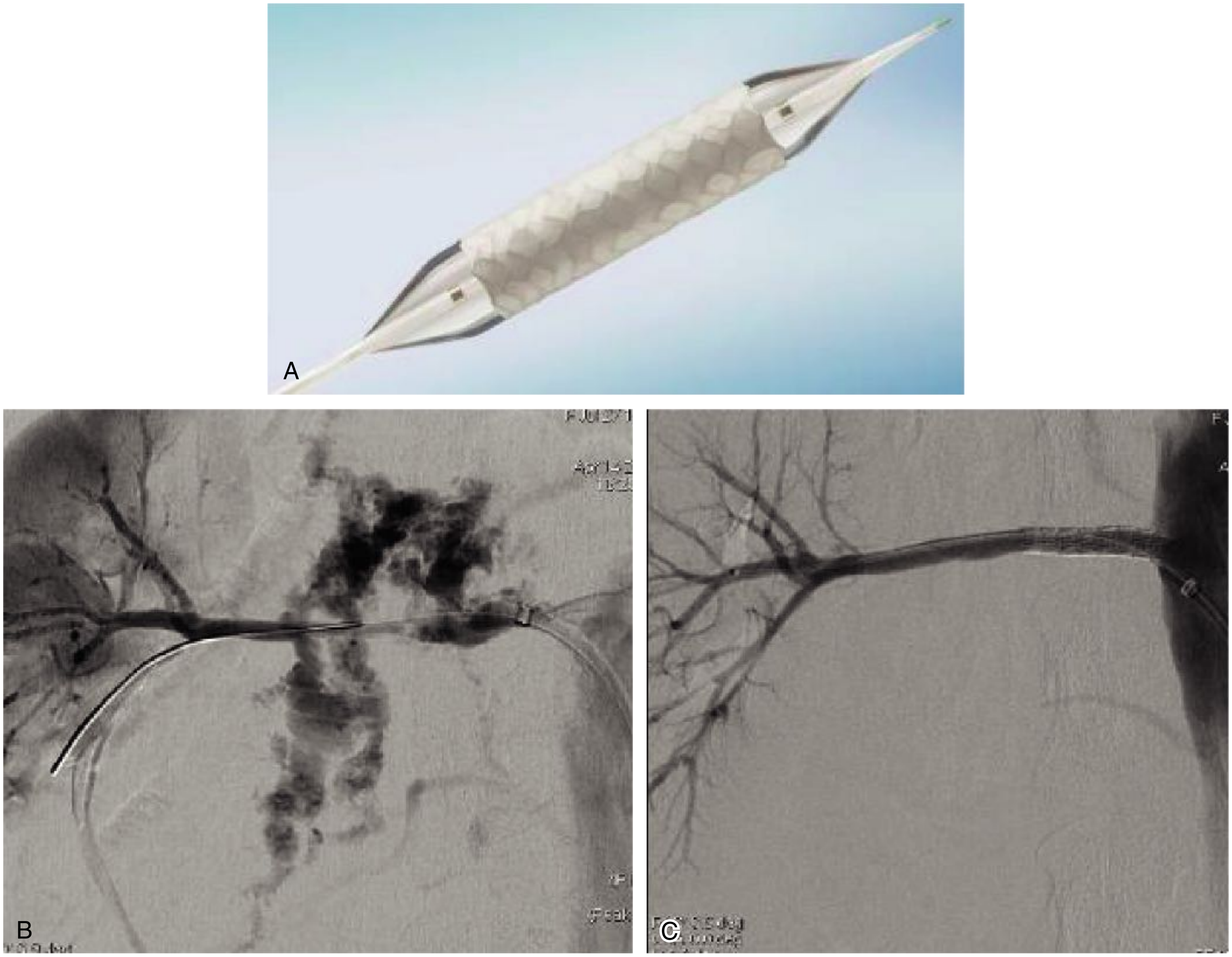

Figure 63.5 (**A**) The i-Cast balloon-expanding covered stent (Atrium Medical Corporation, Hudson, NH). (**B**, **C**) A perforation of the renal artery treated by a covered stent (i-Cast).

configuration for the stent edge. Although the open-cell structure has high flexibility, it is more susceptible to deformation, bending (strut), and could exert a non-uniform radial force on the target vessel. In addition, due to the large cell size, it is prone to plaque protrusion through the strut. However, the open-cell design allows for better tracking through tortuous vessels. In contrast, with a closed-cell design, all edges and vertices of the stent cells constituting the mesh are shared with an adjacent cell. Thus, it is advantageous for lesions at risk of embolization because the stent mesh is very fine. The disadvantages of closed-cell stents include less flexibility, which makes them less deliverable, and they also conform less well to tortuous vessels compared to open-cell stents.

Stent Grafts

Balloon-Expandable Covered Stents

There are several balloon-expandable covered stents available for use: the i-Cast (Atrium Medical Corporation, Hudson, NH) (Fig. 63.5), Viabahn VBX (W.L. Gore & Associates, Flagstaff, AZ) (Fig. 63.6), LifeStream (Bard Peripheral Vascular, Tempe, AZ), JOSTENT (Abbott Vascular Inc., Redwood, CA), and BeGraft (Bentley InnoMed, Hechingen, Germany). The i-Cast (Advanta V12) is made of 316L stainless-steel stent struts encased in PTFE fabric. This stent graft can be expanded beyond the stated stent diameter, although at the cost of foreshortening. All i-Cast stent grafts of <10 mm require 0.035-inch guide wire and 6- to 7-Fr sheaths depending on the diameter. This stent graft is approved by the FDA for the treatment of tracheobronchial strictures but not for PAD. However, it has been used off-label for various vessels such as the iliac or renal artery for occlusive lesions and perforation after PTA or stenting, and ISR. It has also been used for in-branch reconstruction for fenestrated endovascular treatment of thoracoabdominal aortic aneurysms. An advantage of the i-Cast is that it has the lowest profile. However, as with the balloon-expandable bare metal stent, due to its rigidity, the device is not suitable for tortuous vessels or lesions that are subject to structural changes. Although the improvement in patency using an i-Cast for the treatment of occlusive lesions has been demonstrated, data are limited.[32] Long-term data are only available for the i-Cast device, which has a primary patency rate of 74.7% at 5 years.[33]

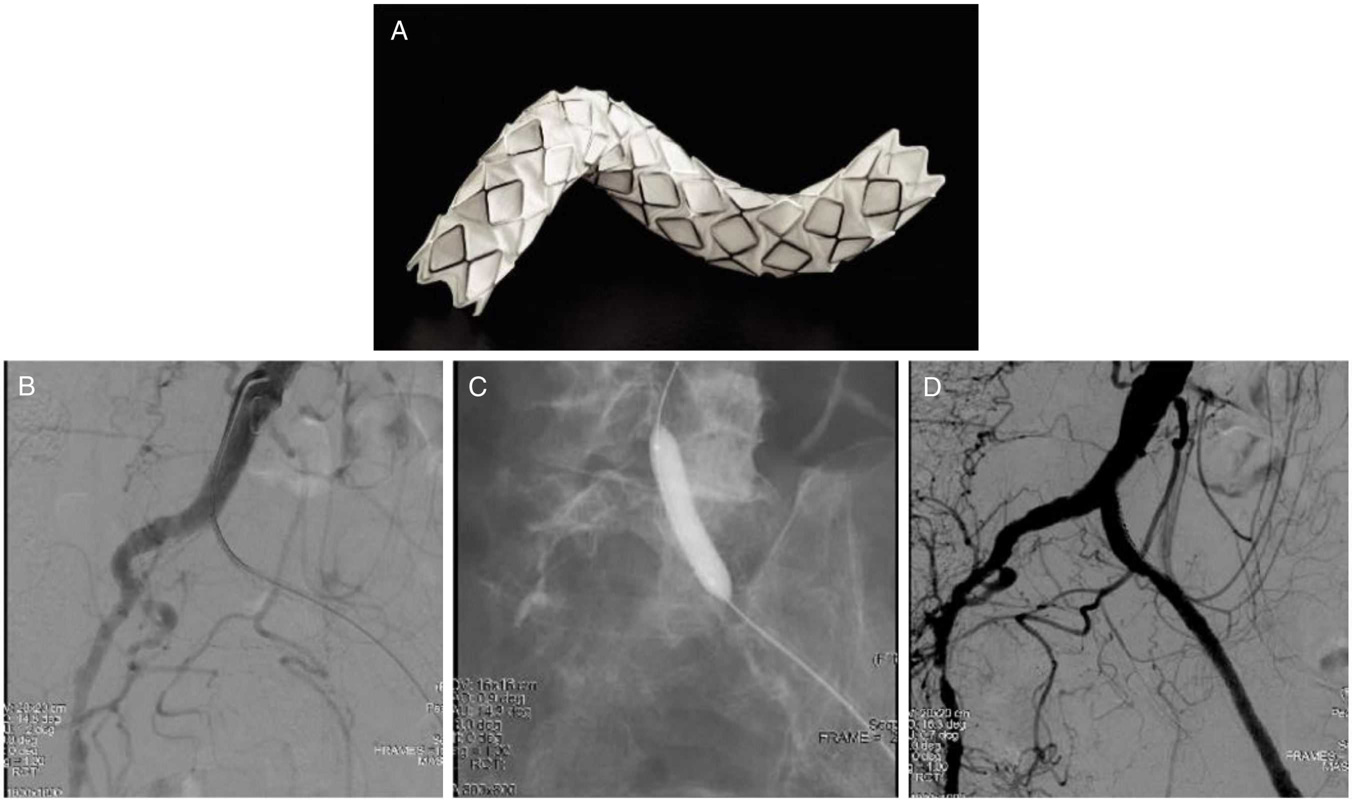

Figure 63.6 (**A**) Viabahn VBX Balloon Expandable Endoprosthesis (W.L. Gore & Associates, Flagstaff, AZ). (**B**) Pre-intervention angiography showing a long obstructive lesion of the iliac artery. (**C**) The VBX is deployed. (**D**) Completion angiography shows an improvement of the iliac artery blood flow.

Self-Expandable Covered Stents

There are three main devices: the Viabahn (W.L. Gore & Associates, Flagstaff, AZ), Fluency (Bard Peripheral Vascular, Tempe, AZ), and Flair (Bard Peripheral Vascular, Tempe, AZ). The Viabahn endoprosthesis consists of heparin-bonded PTFE attached to a nitinol stent. It is composed of a single-wire nitinol stent frame, without longitudinal connections, that is attached to the PTFE graft material with a thin film. These two proprietary design features confer its flexibility.

The VIPER trial, a prospective, single-arm, non-RCT, was conducted to evaluate primary patency at 12 months or performance of the device for the treatment of long SFA occlusive disease.[34] The overall primary patency was 73%, and notably, patency was not significantly different for the lesion length over 20 cm or under 20 cm (70% vs. 75%). Subsequently, the VIASTAR trial, a randomized, prospective, single-blind, multicenter study, compared the Viabahn endoprosthesis with a conventional bare metal stent in 141 patients with symptomatic SFA lesions (Rutherford stage 2–5).[35,36] At 24 months, the overall primary patency rates of the Viabahn and the bare metal stent were 63.1% vs. 40.0%, respectively ($P = 0.004$). The patency rate of the Viabahn device at 24 months for lesions ≥20 cm was higher than that of the bare metal stent (65.2% vs. 26.7%; $P = 0.004$). Freedom from bypass surgery and TLR and secondary patency were comparable between the two groups. Restenotic lesions after deployment of the Viabahn are usually focal and limited to both edges of the graft (Fig. 63.7). Restenosis occurring after the bare metal stent, however, usually develops diffusely throughout the stent. The Viabahn endoprosthesis requires 0.018-inch wires and 6- to 7-Fr sheaths, depending on the diameter of the device, and the available length ranges from 2.5 cm to 25 cm. The Viabahn is deployed by withdrawing a ripcord and is similar to that of the Excluder stent graft (W.L. Gore & Associates, Flagstaff, AZ).

The Flair endograft, like the Viabahn, is composed of a nitinol stent and PTFE fabric. This graft is used in hemodialysis patients for the treatment of arteriovenous graft anastomotic stenosis. The tip of the graft has either a straight or flared shape. This graft has demonstrated improved patency compared with the standard PTA. The required delivery sheath is 9 Fr and it is supported by a 0.035-inch wire. The Fluency stent is approved by the FDA only for biliary application, and its vascular use is off-label. This stent graft is made of a nitinol stent based on the design of the Luminex stent and encapsulated with PTFE along its length, except for 2 mm at either end where the stent is flared. Its crossing profile is 9 Fr sheath compatible. The Fluency is supported by 0.035-inch wires, and the deployment method is like other self-expanding bare metal stents in which the stent is deployed by withdrawing the covering sheath.

Drug-Eluting Stents

Stents have shown improved patency in the treatment of PAD compared to conventional balloon angioplasty. However, the incidence of ISR and stent thrombosis due to intimal proliferation became apparent when treating long lesions with multiple

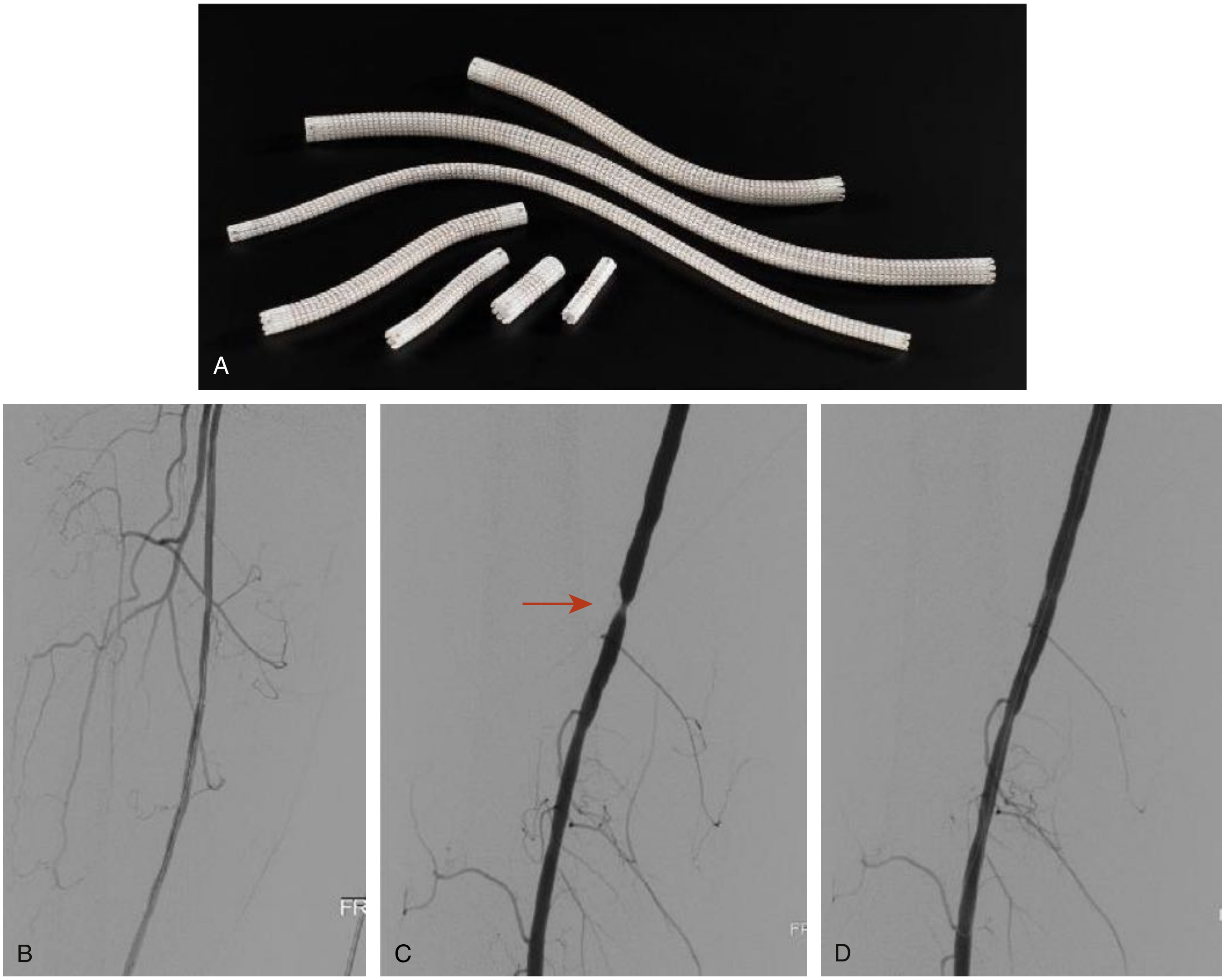

Figure 63.7 (**A**) Viabahn endoprosthesis (W.L. Gore & Associates, Flagstaff, AZ). (**B**) Angiography of the first operation using Viabahn. (**C**) Angiography 7 months after Viabahn deployment. A re-stenosis is exiting at the end of the Viabahn (*red arrow*). (**D**) Re-intervention (PTA) for edge re-stenosis.

stents. The DES was developed to overcome this, initially for coronary arteries. DESs are loaded with agents such as Paclitaxel and sirolimus, usually using polymers, and have been shown to dramatically improve the patency and ISR rates in coronary stenosis.[37,38] Subsequently, the coronary DES technology was applied to the femoropopliteal segment. The sirolimus-eluting stent, based on the SMART stent (Cordis Corporation, Fremont, CA), was the first peripheral DES. It was compared to a bare metal SMART stent in the prospective randomized SIROCCO I and II trials.[39,40] However, the restenosis rates at 24 months were not reduced (22.9% in sirolimus-eluting SMART stent versus 21.1% in bare metal SMART stent), and the program was terminated. The Dynalink stent (Abbott Vascular Inc., Redwood, CA), which is an everolimus-eluting stent, also failed to show superiority at 12 months (unpublished) compared with the historical controls of the STRIDES trial.[41] Neither study was able to show a statistically significant difference between the "limus"-eluting stents and their respective bare metal counterparts.

The Zilver PTX stent (COOK Medical, Bloomington, IN) is a unique DES since it does not utilize a polymer to load the paclitaxel; the drug is simply applied to the stent. It has a 3 μg/mm^2 dose of paclitaxel, which upon implantation is released during the first few days and remains in the vessel wall for up to 56 days. The sustained patency and freedom from TLR of the Zilver PTX stent were proven in a landmark multinational RCT with 479 patients, comparing primary Zilver stents with PTA with or without standard stents for the treatment of femoropopliteal (above-the-knee) lesions.[42] In this trial, patients with symptomatic PAD underwent primary DES or standard PTA. When PTA patients suffered from flow-limiting dissection and required placement of a stent, secondary randomization was performed between bare metal stent and Zilver PTX. The primary patency rates at 12 months for the Zilver DES and PTA were 83.1% and 32.8%, respectively ($P < 0.001$). In addition, the secondary randomization showed that the primary patency rate of the DES was superior to the patency rate of the bare metal stent group at

12 months (89.9% vs. 73.0%; $P = 0.01$), and the sustained superiority of the Zilver PTX stent has been demonstrated up to 5 years.[43]

The Eluvia drug-eluting stent has drug-eluting technology designed to deliver controlled, localized, low-dose amorphous paclitaxel to the target lesion. Eluvia is built on the Innova stent platform, and the polymer allows the 0.167 μg/mm^2 paclitaxel dose drug delivery to sustain beyond 1 year.

The IMPERIAL randomized cohort is a prospective, single-blind multicenter RCT comparing the Eluvia stent ($n = 309$) to the Zilver PTX ($n = 156$).[44] The primary patency was 86.8% in the Eluvia group and 81.5% in the Zilver PTX group ($P < 0.0001$). In all, 94.9% of patients in the Eluvia group and 91.0% of patients in the Zilver PTX group had not had a major adverse event at 12 months ($P < 0.0001$), and no deaths were reported in either group. The Eluvia stent was noninferior to the Zilver PTX stent in terms of primary patency and major adverse events at 12 months after the treatment of patients for femoropopliteal PAD.

Multilayer Stents

The Multilayer Flow Modulator (MFM) stent is designed to exclude peripheral or visceral aneurysms while maintaining branch vessel flow. The MFM is an uncovered SES with high radial force and flexibility, constructed of braided fatigue and corrosion-resistant cobalt-alloy wire. The 3-dimensional wire layering of the MFM, which permits porosity in the range of 65%, alters blood flow and supports the formation of an organized, stable-layered thrombus inside the aneurysm sac. The Cardiatis MFM (Cardiatis, Isnes, Belgium) was approved in Europe in 2009. The first case report detailing implantation in a human was for a patient with a renal artery aneurysm, involving a branch of the renal artery.[45] The efficacy of the Cardiatis MFM for the treatment of peripheral and visceral aneurysms was evaluated in an Italian multicenter trial.[46] The primary patency at 1 year was 86.9%, and the cumulative side branch patency was 96.1%. Complete thromboses of aneurysms were achieved in 93.3%, and no aneurysmal rupture occurred. The MFM is currently being investigated for the management of complex aortic dissection or as a supplement to endovascular aortic repair.[47]

Bioabsorbable Stents

The concept of bioresorbable vascular scaffolds (BVSs) with additional antiproliferative drug delivery has recently attracted great interest. These devices unify the advantages of metallic stents and DCBs by offering acute vessel support and limiting neointimal hyperplasia and late lumen loss. They ultimately disappear and allow the return of physiologic vasomotion. Full BVS resorption over 2–3 years could facilitate future endovascular procedures, and the previously stented segment could even serve as a suitable landing zone for bypass surgery. Bioabsorbable stents that were initially developed for coronary interventions are being applied to the peripheral arterial fields. The first coronary absorbable stent implanted in a human was the Igaki–Tamai stent (Igaki Medical Planning Company, Kyoto, Japan), which is made of poly-L-lactic acid and consists of a helical coil with a straight bridge configuration. In the peripheral fields, long, complex femoropopliteal lesions with a high degree of calcification were not suitable for the currently available technologies. The Igaki–Tamai stent was the first BVS to be evaluated for femoropopliteal interventions. The GAIA study, the most informative series testing this device, evaluated 30 femoropopliteal lesions with a mean length of 5.9 cm.[48] Although immediate technical success was 96.7%, the binary restenosis rate for the 6 and 12 months follow-up was 39.3% and 67.9%, respectively. Histopathologic analysis of restenosis from eight specimens showed a mixed picture with hyperplastic tissue and remnants of stent struts (37.5%), inflammatory cells (50%), and thrombus (50%). A prospective, multicenter, observational registry from Belgium composed of 99 patients who received the Igaki–Tamai BVS reported lower patency rates (58% at 12 months), compared with contemporary studies using modern nitinol stents in the SFA.[49] Considering these results, it is unclear if and when the technology will advance enough to replace modern metallic permanent implants for PAD.

ATHERECTOMY DEVICES

Atherectomy devices are used to remove a heavy plaque burden from atherosclerotic lesions to prepare the lesion area for balloon angioplasty, with or without stenting. They are especially useful for lesions where a stent should be avoided, such as those in the common femoral artery or popliteal artery behind the knee joint. Currently, there are four types of atherectomy devices, including directional (excisional), rotational, orbital, and laser atherectomy.

Directional Atherectomy

The SilverHawk and TurboHawk Plaque Excision Systems (eV3 Inc., Plymouth, MN) were approved by the FDA as directional atherectomy devices. They consist of a carbide cutting blade with variable height and a plunger used to pack the atheroma into the nose cone (Fig. 63.8). The cutting blade rotates at a speed of up to 8000 revolutions per minute (rpm) and shaves atherosclerotic material from the luminal portion of the arterial wall. The cutting blade of the TurboHawk is designed for treating severe calcification. The devices are composed of a monorail catheter with a 0.014-inch compatible wire system, and the recommended sheath size is 6 to 8 Fr. They can be used in many cases without balloons or stents. The DEFINITIVE Ca^{++} study[50] demonstrated that the SilverHawk and TurboHawk atherectomy devices coupled with distal embolic protection (Spider FX;eV3 Inc, Plymouth, MN) were safe and effective for the treatment of moderate to severe calcified lesions in the femoropopliteal arteries. The primary endpoint (≤50% residual diameter stenosis) was achieved in 92.0%, and the 30-day freedom from major adverse event rate was 93.1%. Further, the DEFINITIVE LE trial,[51] a prospective multicenter trial and DEFINITIVE Ca^{++}, enrolled 800 subjects suffering from claudication, or CLI, with an infrainguinal lesion up to 20 cm in length. The primary patency at 12 months was 78%, and the rate of freedom from major unplanned amputations in CLI subjects was 95%.

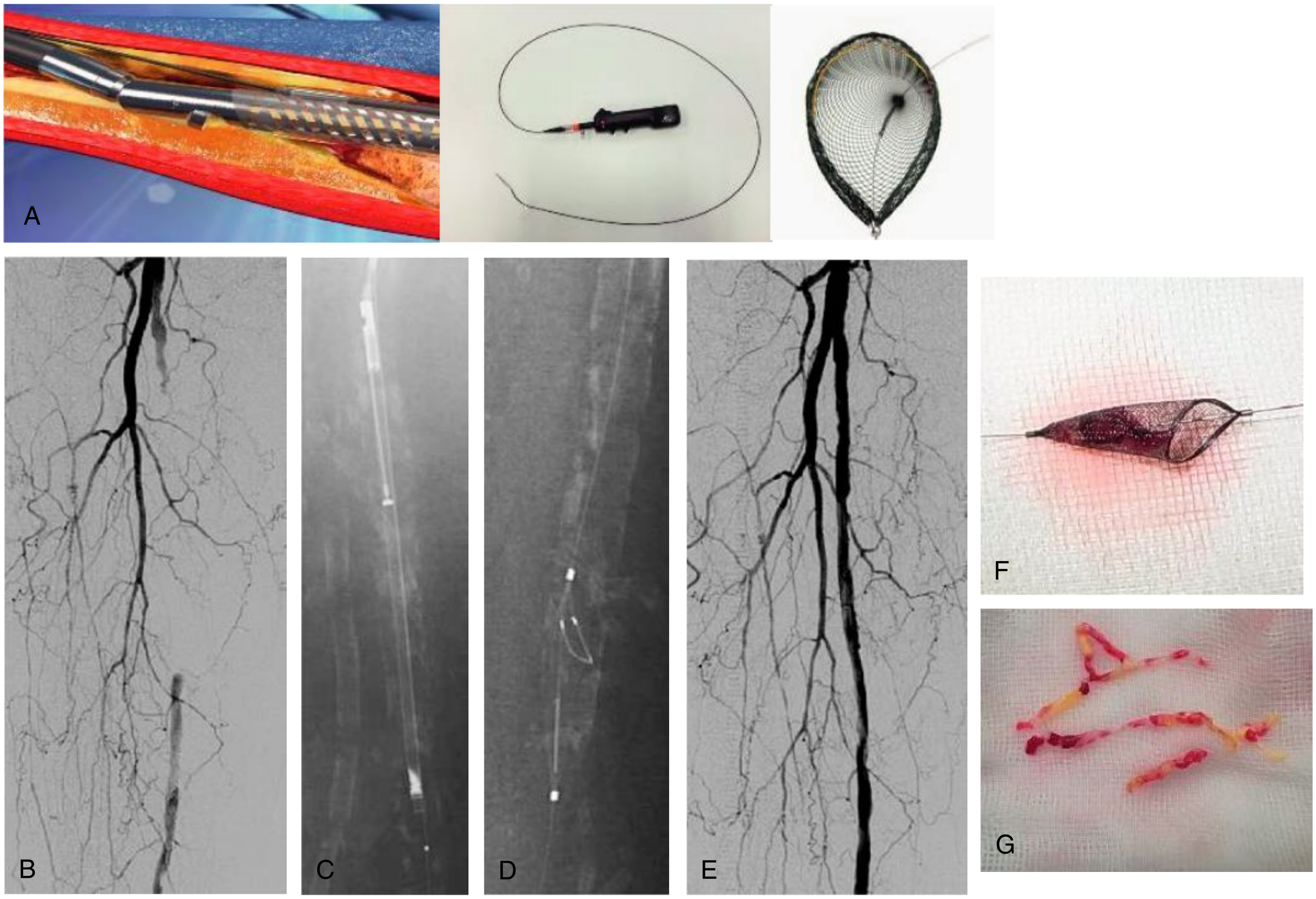

Figure 63.8 (**A**) TurboHawk atherectomy system (eV3 Inc., Plymouth, MN). (**B**) Pre-intervention angiography showing a superficial artery occlusion. (**C**, **D**) The plaque is shaved off by the TurboHawk device with a Spider FX located distally to prevent embolization. (**E**) Completion angiography showing an improvement in vessel flow without distal embolization. (**F**, **G**) The shaved plaque captured by the nose cone of the TurboHawk and the filter of Spider FX.

Rotational Atherectomy

Rotational atherectomy involves inserting a small drill into the artery to fracture a plaque and create a smooth lumen (Fig. 63.9). A high-speed rotating metallic burr abrades the calcified plaque into millions of microscopic particles, of which 95% are less than 5 microns in size, which is smaller than red blood cells. Rotational atherectomy uses an elliptical brass burr coated with sharp diamond microchips that rotates up to speeds of 150,000 to 200,000 rpm to separate healthy elastic vessel wall from inelastic plaque.

Several studies have sought to investigate the effects of rotational atherectomy in the SFA. The first of these trials was the Pathway PVD Study for percutaneous peripheral vascular interventions in 2009.[52] In this multicenter trial that included 172 patients, the device success rate was 99%, and major adverse events occurred in 1%. The TLR rate was 26% at 12 months. The device was also evaluated in a prospective cohort study of 29 patients with femoropopliteal ISR lesions.[53] The acute success (≤30% residual narrowing with no serious adverse events) rate was achieved in 91%, and TLR at 6 months and 12 months occurred in 14% and 41%, respectively. These studies were followed by the release of the 2018 postmarketing JET Registry studying the Jetstream (Boston Scientific, Marlborough, MA) atherectomy device.[54] Recently, a hybrid treatment method combining rotational atherectomy with DCB angioplasty in patients with total in-stent occlusion in the iliac or infrainguinal arteries was reported, the restenosis rate assessed by duplex ultrasound at 12 months was 20.5%.[55]

Orbital Atherectomy

The Diamondback 360° Orbital Atherectomy System (Cardiovascular Systems Inc, St. Paul, MN) consists of an orbiting diamond-coated crown mounted on the end of a drive shaft. The device can be delivered through a 4-Fr sheath along an 0.014-inch guide wire. Like rotational atherectomy devices, the orbital atherectomy devices create plaque debris small enough to minimize distal embolization. The CONFIRM series,[56] a prospective multicenter registry, was created to evaluate the performance of orbital atherectomy for PAD of the lower extremities. Plaque removal was most effective in severely calcified lesions and least for soft plaque. The overall

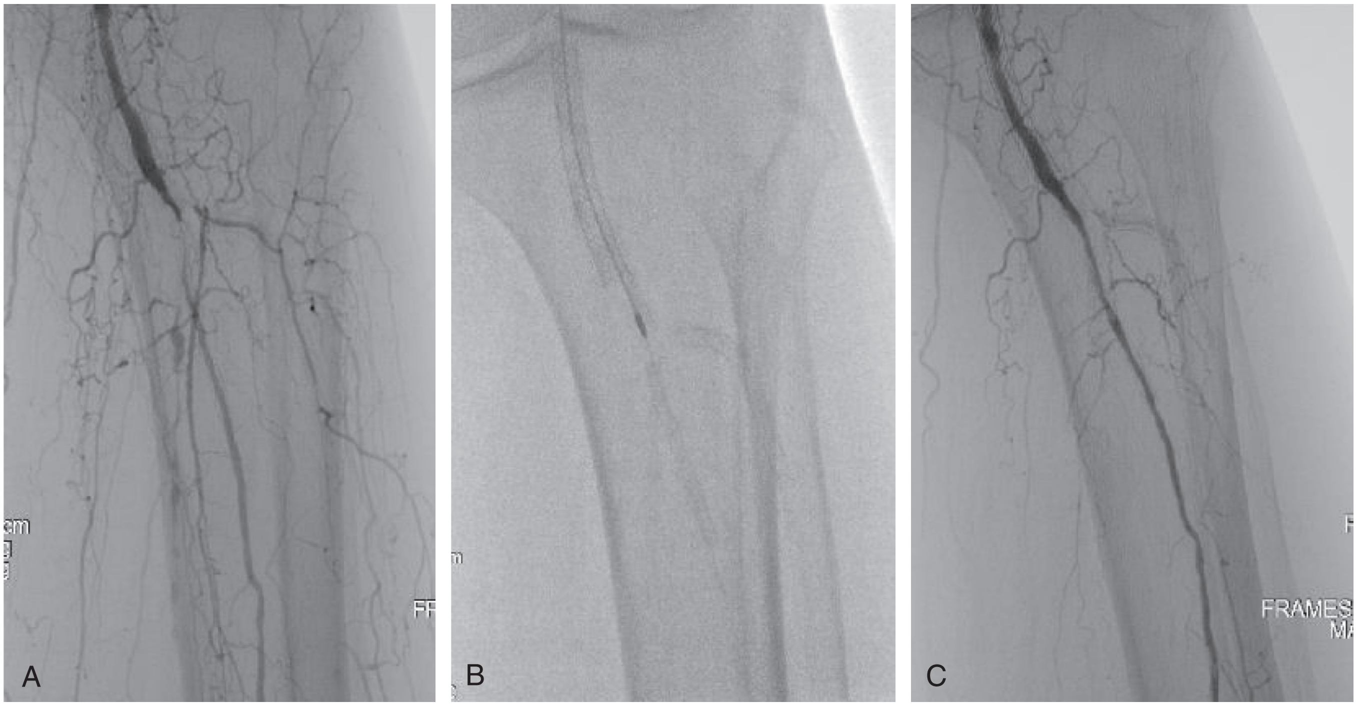

Figure 63.9 **Rotational Atherectomy.** (**A**) Pre-intervention angiography showing a short obstructive lesion of the tibial–peroneal trunk. (**B**) The occlusive lesion was treated with rotational atherectomy. (**C**) Completion angiography showing a satisfactory result.

plaque burden was reduced by more than 50% on follow-up angiogram. In another study,[57] atherectomy for 352 patients with lower extremity ischemia in an office endovascular center achieved a primary patency of the 571 treated vessels of 90% at 12 months, and 84% at 29 months.

Laser Atherectomy

Advances in laser catheter design and recanalization techniques have resulted in improved outcomes for the treatment of complex PAD. The excimer laser, using a 308-nm wavelength, ablates the plaque and thrombus. The plaque is ablated on direct contact alone, minimizing surrounding thermal injury. In a prospective study of 35 patients, the CVX-300 Excimer Laser system (Spectranetics, Colorado Springs, CO) was evaluated as a first-line endovascular treatment for CLI. Clinical success, defined as restored direct arterial flow to the foot, was achieved in 88.2%.[58] The estimated patency rates were 96.6% at 12 months and 82.7% at 24 months, respectively, and limb salvage at 24 months was 94%. Recently, an RCT[59] was conducted across 40 US centers to assess the excimer laser plus PTA versus PTA alone for patients with ISR. The freedom from TLR of the laser plus PTA and PTA alone at 6-month was 73.5% and 51.8%, respectively, and 30-day major adverse event rates for the laser plus PTA were also significantly lower than for PTA alone (5.8% vs. 20.5%). In a systematic review of 4 RCTs,[60] it was reported that adjuvant excimer laser atherectomy achieves better outcomes than standard balloon angioplasty. Ongoing clinical trials may elucidate uncertainties in the optimal management of ISR.

THROMBOEMBOLECTOMY

Over the years, the Fogarty catheter and other products have been developed to remove thrombosis in the arterial or venous circulation.[61] Innovations have made it possible to perform totally percutaneous thromboembolectomy in coronary and peripheral arteries, deep vein thromboses (DVT), pulmonary thromboses, and cerebral vessels. Despite its efficacy, catheter-directed thrombolysis (CDT) has potential risks such as cerebrovascular hemorrhage, major bleeding, embolization, and recurrence of thrombosis.[62–64] Several thrombectomy devices have been developed to reduce these risks. These include rheolytic or rotational thrombectomy devices, including aspiration and ultrasound-enhanced platform.

Aspiration Thrombectomy

The simplest procedure for thrombectomy is to aspirate the thrombus with a large catheter or sheath (Fig. 63.10). Currently, available aspiration devices are the PriorityOne AC (Terumo Interventional Systems), the Aspire (Control Medical Technology), Xpress-Way (Getinge), Export (Medtronic), ASAP aspiration catheter (Merit Medical Systems), Pronto (Teleflex), and QuickCat (Spectranetics).

The Export catheter has a separate lumen for the wire and the aspiration port to maximize aspiration capability while the PriorityOne catheter has guide wire-style stylet technology. With such devices, the risk of distal embolization due to the crushing of the clot remains. Thrombolytic drugs may, therefore, be used with aspiration devices. These catheters seem to

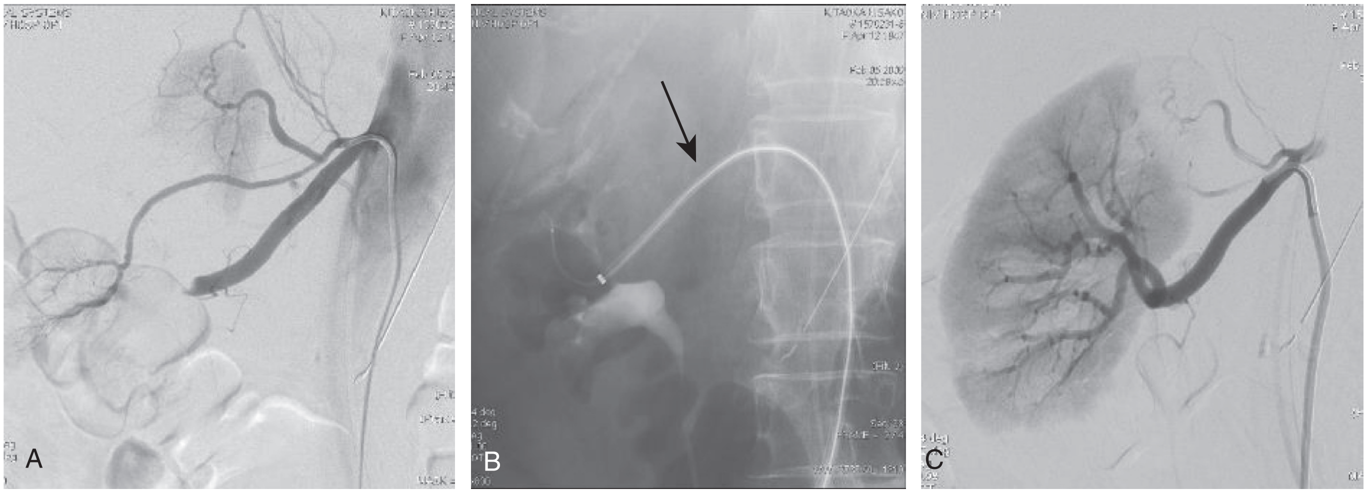

Figure 63.10 (**A**) Angiography of renal artery occlusion due to embolism. (**B**) Aspirating the thrombus with a 7-Fr guiding sheath. (**C**) Completion angiography shows a disappearance of thrombus.

be well suited for small vessel diameters (<6 mm) and are less effective for a large thrombus burden. Schleder et al.[65] reported in 2015 on 47 patients treated with aspiration thrombectomy following infrainguinal angioplasty. Aspiration thrombectomy alone had a technical success rate of 64% (achieving a residual narrowing of less than 50%), but secondary technical success after balloon angioplasty and stenting was 96% with excellent clinical outcomes.

Rheolytic Thrombectomy

In rheolytic thrombectomy, a jet of saline is ejected from the tip of a catheter and used to dissolve the thrombus by creating a “Venturi” effect. The Angiojet catheter (Possis Medical, Minneapolis, MN) is the most used mechanical thrombectomy catheter with a hydrodynamic device. It provides a high-speed saline jet that travels backward to create a low-pressure zone causing a vacuum. The vacuum removes thrombus material, which is then aspirated into the exhaust lumen of the catheter. In the PEARL registry, a total of 238 patients with acute limb ischemia (ALI) undergoing Angiojet catheterization were enrolled.[66] Procedural success was achieved in 83%. The amputation-free rate and freedom-from-mortality rate at 12 months were estimated to be 81% and 91%, respectively. The device can also be used for DVT and potentially reduce the need for additional CDT. Furthermore, from the prospective Bern Venous Stent Registry, early clinical outcomes of patients with acute iliofemoral DVT treated with the Angiojet Zelant-eDVT® system (Boston Scientific, Maple Grove, MN) were investigated, and the primary treatment success rate of rheolytic thrombectomy was 95%.[67]

Rotational Thrombectomy

Rotational thrombectomy devices remove the thrombus by rotating the tip of the catheter. The Rotarex (Straub Medical, Wangs, Switzerland) consists of three individual components that can be assembled in a few minutes. The Rotarex catheter is a 6-Fr or 8-Fr polyurethane catheter, which contains a steel spiral powered by an electric motor, which rotates at a speed of 40,000 rpm. The catheter tip is connected to the spiral. This device was evaluated in the treatment of peripheral arterial thromboembolic occlusions.[68] A total of 40 patients were enrolled, and the technical success rate was 95%. Six-month post-intervention follow-up is available for 34 patients. Patency was preserved in 65% of patients, and amputation had to be performed in 12% of them.

The Trellis infusion catheter (Bacchus Vascular, Santa Clara, CA), is a hybrid device that combines the delivery of thrombolytic drugs with a thrombus aspiration system. It is composed of a proximal and distal balloon, and the drug and the debris are trapped between the two balloons. Gupta and Hennebry[69] evaluated the Trellis in 24 patients with ALI. More than 90% of vessels had a complete or substantial response. There was one in-hospital death due to severe limb ischemia with extensive occlusion of an axillofemoral graft, but the amputation rate at 30 days was 0%.

In the treatment of lower extremity DVT with a rotational thrombectomy device, the CLEANER Rotational Thrombectomy System (Argon Medical) has also been evaluated.[70] The technical success rate of the procedure was 91.3%. The venous patency rates in patients at the 1-, 3-, 6-, and 12-month follow-up visits were 95%, 92.5%, 89.7%, and 79.5%, respectively.

Other Devices

The Solitaire stent retriever (Medtronic, Minneapolis, MN) is a new device for mechanical thrombectomy combining the ability to restore blood flow, administer medical therapy, and retrieve the clot. This device is used for cerebrovascular lesions in the treatment of acute ischemic cerebral infarction. Its safety and efficacy have been demonstrated in several RCTs.[71,72] Although it is not indicated for peripheral lesions,

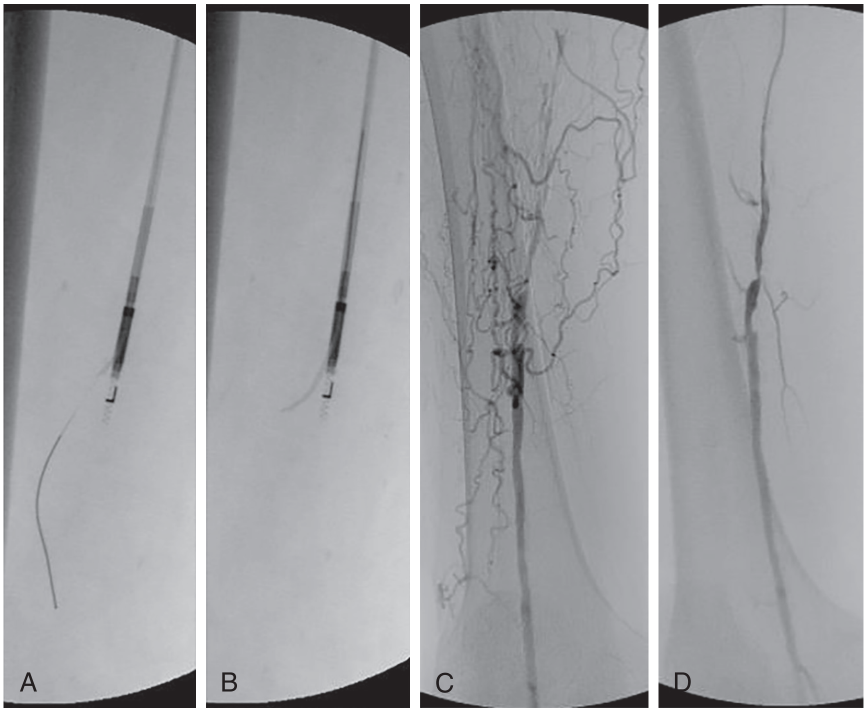

Figure 63.11 (**A**) Angiography of superficial femoral artery occlusion. (**B**) The Outback LTD (Cordis Corporation, Fremont, CA) was advanced in the most distal subintimal location and the image demonstrates the Outback in the L position with the distal L marker pointing toward the true lumen. (**C**) After the cannula is deployed, the guide wire is advanced into the true lumen. (**D**) A distal injection after crossing back into the true lumen to confirm catheter position and distal anatomy.

in a case report of off-label use, the Solitaire enabled the removal of a BTK thrombus after aspiration thrombectomy had failed.[71,72]

Trevo XP (Stryker Neurovascular, Fremont, CA) is also a stent retriever device and is the first fully visible device that allows the operator to view placement or strut behavior. In an open-label trial comparing the Trevo with Merci retrievers for revascularization,[73] the stroke score significantly improved in the patients in the Trevo group.

Indigo System (Penumbra Inc, Alameda, CA), which became commercially available in 2014, is expected to be a useful device for managing thromboembolic disease in the peripheral circulation, including visceral and upper extremity lesions. Treatments with this device have been reported in cases of visceral artery embolism.[74] Further case accumulation and evidence are expected.

DEVICES FOR CROSSING CHRONIC TOTAL OCCLUSIONS

Devices for crossing chronic total occlusions include those designed to achieve recanalization via the true lumen (Crosser and Frontrunner XP) or via an intimal flap with reentry into the true lumen (Outback LTD, Pioneer, Enteer, OFFRoad) (Fig. 63.11). Success at recanalization of CTOs have been reported in the range of 83%–88% with the Crosser and Frontrunner catheters with no major complications.[75,76] Similar success rates and low complications have been reported with the reentry devices.[77–79] The risk of an extension of the dissection 5 cm beyond the distal end of the CTO has been noted with the Outback LTD reentry system.[77]

VASCULAR CLOSURE DEVICES

Vascular access site complications are one of the important and frequent causes of morbidity following endovascular therapy. Manual compression (MC) has remained the gold standard for obtaining hemostasis at the access site. However, MC is time-consuming and can fail. In addition, with the introduction of newer and larger interventional devices, a better method to obtain hemostasis is needed. The ideal vascular closure device (VCD) can achieve secure hemostasis without complications (see Ch. 52, Local Endovascular Complications and their Management). In the RCT trial (ISAR-CLOSURE trial),[80] 4524 patients undergoing coronary angiography with a 6-Fr sheath via the common femoral artery were enrolled. Patients were randomized in a 1:1:1 ratio between two VCDs and MC. The primary outcome was the incidence of vascular site complications, including major bleeding, infection, leg ischemia, and the need for surgical repair or endovascular treatment. Access site-related complications were identified in 6.9% of patients in the VCD groups and 7.9% in the MC group, confirming that VCDs were equally effective. Additionally, according to multiple small RCTs, meta-analyses, and a Cochrane review,[81] complication rates and outcomes remain comparable between VCD and MC (12% for VCDs vs. 13% for MC). It is important to balance the goals of the comfort of the patient and the resources of the staff.

Extravascular Plug

Angio-Seal

The Angio-seal (Terumo Interventional Systems, Somerset, NJ) device exerts a hemostatic effect by sandwiching the arteriotomy with a bioabsorbable anchor connected with sutures and a collagen sponge. It dissolves within 60 to 90 days. The device is compatible with 5- to 8-Fr sheaths (5, 6 Fr are applied to the 0.035-inch wire, while 7, 8 Fr are used for 0.038-inch wires). The device sheath is exchanged with the procedural sheath, confirming the proper location by withdrawing and reinserting the device until blood flow resumes. The inner core (locator) and wire are removed, leaving the outer sheath in place. The body of the Angio-seal is then inserted into the outer sheath. The anchor is released into the vessel by fully connecting the body and the outer sheath. The body and sheath are pulled back until the colored compaction marker is revealed as a guide.[82,83]

Exoseal

Exoseal (Cordis Corporation, Fremont, CA) is a percutaneous closure device, which uses a bioabsorbable polyglycolic acid plug to achieve hemostasis. The device is compatible with 5- to 7-Fr sheaths. A small plug is stored in the distal end of the device and is fully absorbable within 60 to 90 days. For deployment, the appropriate Exoseal is inserted in the procedural sheath, advancing to the level of the black marker band. The combination of the procedural sheath and the Exoseal is then pulled out until backflow from the bleed-black indicator is encountered. Then the sheath and the Exoseal are retracted further until the blood flow slows. When the flow from the bleed-back indicator is interrupted, and when the indicator window changes to "all black", the plug is deployed adjacent to the vessel wall.[84,85]

Manta

The MANTA (Teleflex, Wayne, PA) device is the first commercially available biomechanical VCD designed specifically for large bore femoral arterial access-site closure. It effectively closes femoral arterial access sites following the use of sheaths ranging from 12 Fr to 25 Fr OD. This is achieved by having a resorbable collagen and anchor sandwich the vessel entry site. Recent insights from the first 100 consecutive cardiovascular procedures with MANTA closure have been published, with a hemostasis achieved immediately in 70 patients, and within 5 min in 87. There were 7 patients (5.7%) with major and 4 patients (3.3%) with minor MANTA-associated vascular complications.[86]

Femoral Introducer Sheath and Hemostasis

FISH (Morris Innovative, Bloomington, IN) utilizes a bioabsorbable extracellular matrix of porcine small intestinal submucosa. The plug is remodeled into native arterial wall tissue, which is absorbed in 30 days. The effectiveness of this device has been recently reported.[87]

Mynx

The Mynx (Cordis Corporation, Fremont, CA) deploys a polyethylene glycol sealant outside the artery, while a small balloon is inflated at the arteriotomy site to create temporary hemostasis within the artery. The device is compatible with 5- to 7-Fr sheaths, and the sealant is absorbed in 30 days. Among 766 patients undergoing a cerebral angiogram or intervention using the Mynx device,[88] procedural success was achieved in 92%, and device-related complications occurred in 2.5% of the patients.

Suture-Based Devices

ProGlide

The ProGlide (Abbott Vascular Inc, Redwood, CA) is a suture-based device that deploys a suture on either side of the arterial wall at the arteriotomy site, mimicking open surgical closure. The polypropylene sutures are pulled together outside the body, resulting in closure of the arteriotomy site. Since it is a mechanical closure, there are theoretically no limitations to re-access or the administration of antiplatelet or anticoagulant drugs. The ProGlide can track over a standard 0.038-inch (or smaller) wire and accommodate 5- to 21-Fr arteriotomies. With larger than 8-Fr sheaths, at least two devices are required to close the arteriotomy. Therefore, the device facilitates EVAR as well as TAVR through percutaneous femoral access. In such cases, the ProGlide is deployed before the insertion of large bore devices and it is often referred to as the Perclose technique.

Prostar XL

The Prostar XL (Abbott Vascular Inc., Redwood, CA) is designed for large bore device closures. It also utilizes a polyester suture to close the arteriotomy site. The device has two polyester sutures and four nitinol needles and is deliverable over an 0.038-inch (or smaller) guide wire. It is indicated for 8.5 to 10 Fr closure. Similar to the ProGlide device, vascular access can also be maintained throughout deployment, and the device can be used for EVAR or TAVR. The BRAVO-3 trial randomized 802 patients undergoing transfemoral TAVR,[89] a total of 746 (93%) patients were treated with either Prostar XL (PS) (n = 352, 47%) or ProGlide (PG) (n = 394, 53%). PG was associated with a significantly lower incidence of major or minor vascular complications compared to PS (adjusted OR: 0.54; 95% CI: 0.37–0.80; $P < 0.01$).

ENDOVASCULAR THERAPEUTIC TECHNIQUES

Percutaneous Transluminal Balloon Angioplasty

Puncture and Approach to the Lesion

Puncture is the most basic and important procedure for the percutaneous treatment of PAD in terms of reducing postoperative complications, such as bleeding or pseudoaneurysm formation. The selection of the most appropriate puncture site should include consideration of the location and extent of the target lesions. The common femoral artery (CFA) is the most common puncture site in endovascular treatment. However, the location of the CFA bifurcation differs between patients. If the CFA bifurcation is located cranially, there may be a risk of a high puncture, resulting in difficulty in compressing the access site after the procedure, which may lead to retroperitoneal hemorrhage. If there is severe calcification of the CFA, the puncture may cause dissection or arterial occlusion. In such cases, one should consider utilizing the contralateral CFA, brachial artery, radial artery, or SFA. Before puncturing the artery with the needle, sufficient local anesthesia should be administered subcutaneously and around the femoral sheath. As most endovascular interventionists are right-hand dominant, generally, the needle is held and advanced to the puncture site with the right hand, while the left hand palpates the pulse of the target artery. Ultrasound or fluoroscopic guidance is helpful in difficult cases (Fig. 63.12) or antegrade punctures. By using either anatomical landmarks (palpation and fluoroscopy) or ultrasound, safe CFA access for retrograde and antegrade procedures can be achieved. When treating BTK lesions, an ipsilateral antegrade CFA approach may be chosen due to the limited length of the catheters and balloons and for better pushability. Bidirectional approaches (see below) via the popliteal or tibial artery are often effective for the treatment of SFA or BTK CTO lesions. A retrograde brachial or radial artery approach is often preferred for the treatment of celiac or superior mesenteric artery disease because the angle between the aorta and visceral branches is sharp.

When arterial access is achieved, a sheath is inserted into the vessel over the guide wire using the Seldinger technique. The guide wire should be advanced under fluoroscopic guidance to avoid accidental cannulation of the side branches. Most of the currently available endovascular devices, including guide wires, catheters, balloons, or stents, allow for delivery through a 5- to 7-Fr sheath. It is important to choose an adequate sheath to avoid sheath-related complications. The image intensifier or

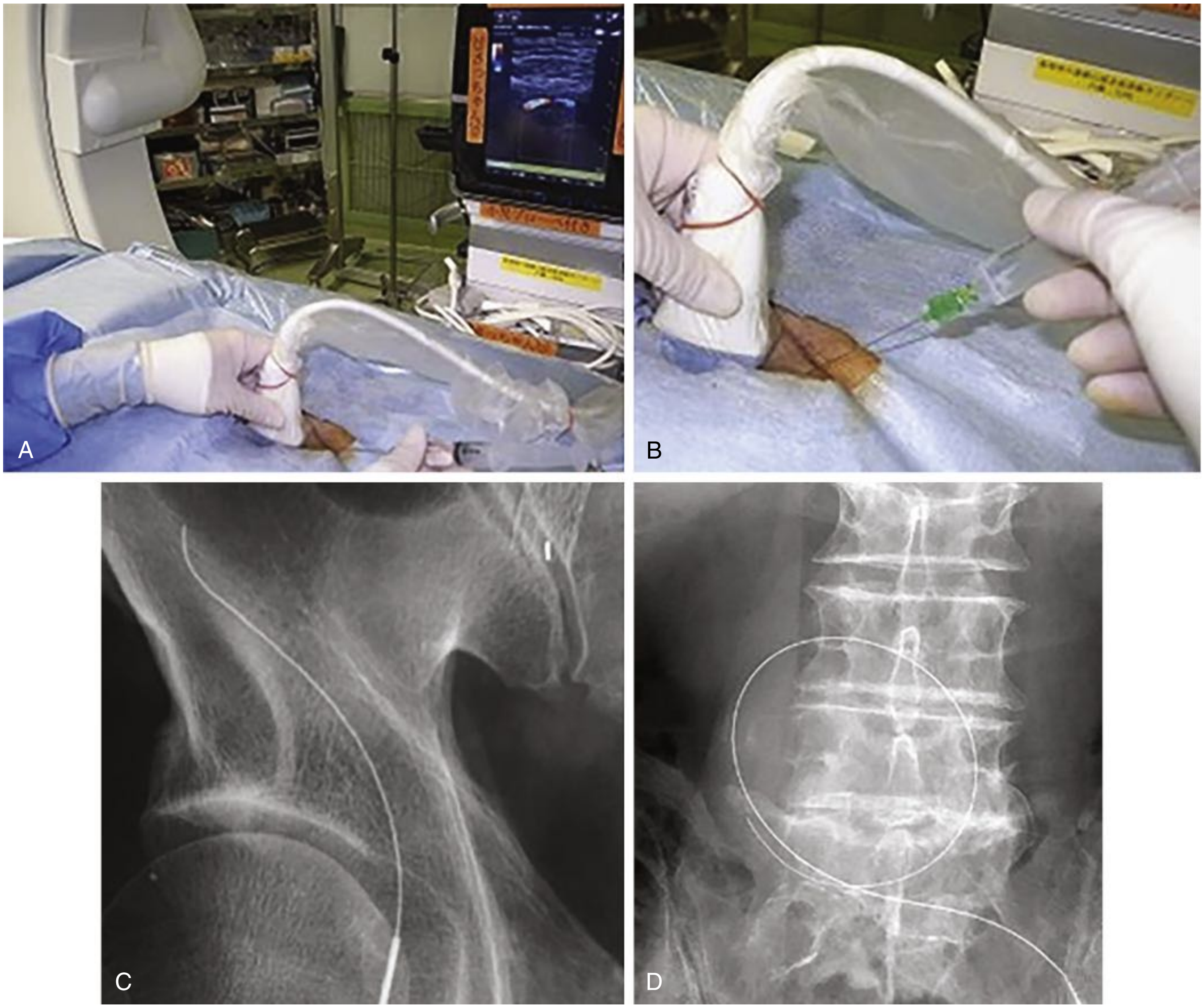

Figure 63.12 (**A**) A puncture with ultrasound guidance for the deep subcutaneous tissue. (**B**) The needle attached syringe with local anesthesia results in reduced amounts of anesthetic drugs and safe puncture. (**C**, **D**) The guide wire is advanced into various branches or aneurysms without fluoroscopic guidance. (**C**, The wire is inserted in the circumflex iliac artery. **D**, The wire is rotated in the aneurysmal sac.).

the detector panel must be placed at the appropriate cranial–caudal and oblique angle to obtain a good image and outcome (see Ch. 62, Endovascular Diagnostic Technique). Additionally, to achieve maximal support and effective contrast infusion, the sheath or catheter should be placed as close to the target lesion as possible. Systemic heparinization should be performed once the decision is made to treat the lesion. Typically, 50 to 100 U/kg of heparin is administered by venous bolus infusion, and the activated clotting time (ACT) should be maintained at approximately 200 to 300 sec during the endovascular procedure. For cerebrovascular intervention, the ACT should be kept above 250 sec to prevent thrombus formation and cerebral infarction.

Lesion Crossing

Although there is no single standard technique, the most important principle is to pass the wire through the lesion via the true lumen. Techniques vary based on the location, degree of stenosis, presence or absence of CTO, or nature of the plaque. An 0.014- or 0.018-inch guide wire may be a better choice for highly stenotic or CTO lesions, and the use of support microcatheters can increase the chances of lesion crossing through the true lumen. Intraluminal devices, as previously described, or ultrasound-guided techniques are also useful for passing through the true lumen. Furthermore, if the wire is inserted into the subintimal plane, it is possible to return to the true lumen by using a reentry device. Additionally, intravascular ultrasound (IVUS) is a useful device to identify whether the wire is in the true lumen or not. Once the lesion is crossed, and the wire enters the distal true lumen, as indicated by backbleeding, contrast injection via the catheter is performed to confirm that the wire is intraluminal. Successful antegrade or retrograde CTO crossing is a flexible procedure, and the retrograde technique can be considered after antegrade techniques have failed.

Antegrade Techniques

Sliding/Drilling/Penetration Technique

The antegrade approach requires ipsilateral antegrade femoral access for use with shorter devices and higher performance levels of pushability, crossability, trackability, and greater torque. The initial approach for CTOs is the use of a 0.014- or 0.018-inch hydrophilic or non-hydrophilic guide wire through an OTW system. For example, a 0.014-inch Gladius (Asahi Intecc, Aichi, Japan) or tapered 0.010-inch Wizard PV (Japan Lifeline, Tokyo, Japan) can be used in the sliding technique because of their inherent ability to cross soft lesions, microchannels, or subtotal occlusive lesions. The guide wire is advanced using sliding, drilling, penetration, or a combination of these techniques to cross the CTO. Drilling is performed by controlled rotation of the guide wire in both directions. Penetration consists of guide wire advancement, intentionally directing the wire along different planes. This maneuver is often best done using a stiff wire (Astato XS9-12, Asahi Intecc, Aichi, Japan) to penetrate the cap of the occlusion.

Double Wire Technique

If cannulation of the target vessel cannot be accomplished with the wire, or the risk of nearby vessel occlusion due to plaque shift is anticipated, a double wire technique may be an effective option. For example, when cannulation of the SFA is attempted, the wire would be advanced first into the DFA, without entering the SFA. In this case, the sheath is inserted into the DFA first, and then withdrawn to the bifurcation of the SFA and the DFA, maintaining the position of the DFA guide wire. A second thin wire is then inserted to cannulate the SFA. This technique has been applied to other lesions, such as renal interventions, and is known as the non-touch isolation technique. For lesions at a bifurcation, the lesions are cannulated by two wires, and a kissing balloon technique is used to prevent occlusion from plaque shift (Fig. 63.13).

Subintimal Angioplasty Technique

The first subintimal angioplasty for an occlusive femoropopliteal artery lesion was reported by Bolia and colleagues in 1989.[90] Subintimal angioplasty has become popular as a means of overcoming long occlusive segments. With this technique, a guide wire is intentionally inserted into the subintimal plane to create a new track. The tip of a hydrophilic guide wire is formed into a loop shape above the level of the occlusive lesion. The wire is then advanced with a support catheter along the subintimal plane until the occlusive lesion is passed. The wire and catheter will naturally reenter the true lumen distal to the occlusion, where the intimal flap is thin and is broken by the wire loop. The resistance to the guide wire in the subintimal plane disappears once it reenters into the true lumen. Recanalization of the true lumen is confirmed by injecting contrast from the tip of the catheter or by IVUS. The recanalization segment is then dilated with an appropriately sized balloon. Typically, stenting is not required with this technique, and it should only be used in cases of flow-limiting dissection or severe elastic recoil. Subintimal angioplasty is technically successful in approximately 80% of cases, and limb salvage is achieved in over 80%, with a primary patency rate at 12 months of 60%–70%.[91] However, subintimal angioplasty fails in approximately 20% of patients. The most common reason for failure is the inability to reenter the true lumen. Reentry devices were developed to overcome this.

Retrograde Techniques

The retrograde technique requires careful assessment of wound healing and limb salvage considerations because failure of the procedure or complications could result in the worsening of foot ischemia and a catastrophic outcome. Tibio-pedal access for revascularizing critical PAD is safe and increases the procedural success rate in patients with CLI.[92,93] While current reports support the safety of 4-Fr sheaths and 4-Fr compatible devices through tibiopedal access, it remains unknown if the use of a larger introducer for contemporary interventional therapy is safe. The technical success rate of the retrograde approach has been reported to be in the range of 85%–86.3%.[94,95] Furthermore, the transcollateral technique and transpedal arch technique have been reported in challenging cases. Using the transcollateral technique, Fusaro et al.[96] first reported the successful crossing of an occlusion in the

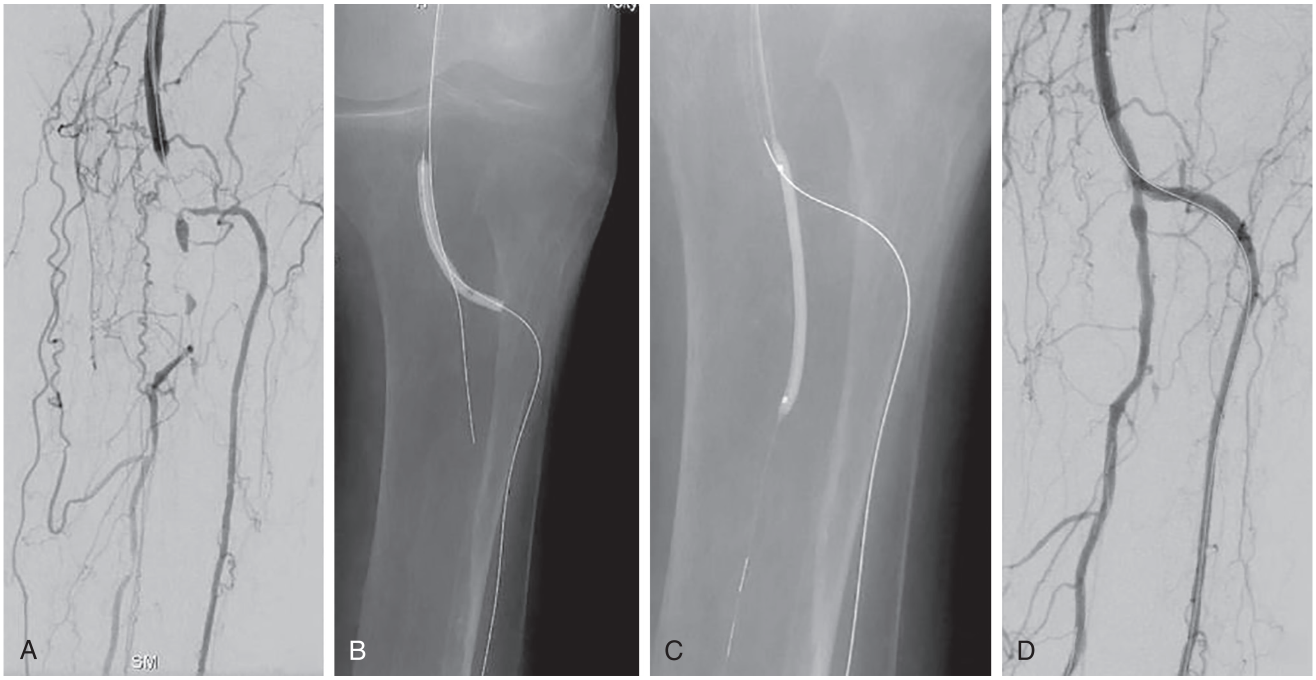

Figure 63.13 (**A**) Initial angiography shows a complex occlusive lesion of the below-the-knee arteries. (**B**, **C**) The wire is inserted to prevent an occlusion by a plaque shift. (**D**) Completion angiography shows an improvement in run-off.

tibioperoneal trunk in a retrograde direction. They passed a 0.014-inch hydrophilic guide wire through the developed collateral vessels of the anterior tibial artery into the peroneal artery. Leaving the first wire in place as a marker, the occlusion in the tibioperoneal trunk was crossed in an antegrade manner with another 0.014-inch wire and dilated with a balloon catheter. Even though no distal vessels for retrograde puncture are available in severe infrapopliteal artery disease, initial success in one antegrade tibial recanalization can provide an opportunity to cross another tibial artery in a retrograde manner. Using the transpedal arch technique, Kawarada et al. reported complete revascularization of an extensive CTO in the posterior tibial artery in a retrograde manner.[97] According to Manzi et al., this technique was attempted in 10.1% (135 patients) of 1331 consecutive patients, and the success rate was 85%, while the limb salvage rate was 86%.[98]

Controlled Antegrade and Retrograde Subintimal Tracking Technique

If reentry into the true lumen is not possible or if reentry devices are not available, the controlled antegrade and retrograde subintimal tracking (CART) technique may be useful, in which two wires are simultaneously inserted via antegrade and retrograde access. For example, in an SFA CTO lesion, the wire is first passed into the subintimal plane in an antegrade manner. If it is impossible to redirect the wire into the true lumen, then a retrograde wire is inserted from a site distal to the lesions, such as the distal SFA, tibial, or pedal artery to approach the target lesion. The distal, antegrade wire is also placed into the subintimal space using directional catheters until both wires cross each other. Then, PTA balloons are inserted over each wire and placed next to each other. Inflating both balloons breaks the intimal flap or septum separating them, allowing the antegrade wire to enter the subintimal plane that leads to the distal true lumen. PTA and stenting should be performed in the same manner as described above (Fig. 63.14).

Balloon Selection

A balloon is typically chosen based on the diameter of the reference vessel and the length of the lesion. The balloons available for various lesions are shown in Table 63.2. Currently, balloons are available up to 30 cm in length and can be used to treat long segments of the SFA or BTK lesions with a single inflation. Most interventionists first verify the ease of expansion and stiffness of the lesion using an undersized diameter balloon and then upsize to an appropriate diameter balloon. In severely calcified lesions, a conservatively sized dilation balloon may be required to avoid rupturing the artery. Measurement of the reference vessel diameter is important in choosing an appropriate balloon. Measurement with digital subtraction software, preoperative CT, IVUS, catheters with graduated markers, or using a predilatation balloon as a reference are also useful for selecting the appropriate balloon size. Balloon shafts come in 50 to 175 cm. A shorter shaft is suitable for the treatment of visceral, iliac, and proximal contralateral SFA lesions when approached from the CFA. Conversely, cerebral, contralateral popliteal, and BTK interventions via the CFA or visceral and iliac intervention via the brachial artery require a longer shaft.

Balloon Placement

Contrast is injected through the sheath or catheter to accurately identify the lesion just before the balloon is placed. If balloon passage is difficult due to severe stenosis or tortuosity

Figure 63.14 (**A**) Initial angiography shows an occlusive lesion of the proximal superficial femoral artery. (**B**) Two wires and balloons are inserted via both antegrade femoral artery and retrograde distal superficial femoral artery access sites (CART technique). (**C**) Completion angiography.

TABLE 63.2 Commercially Available Balloon Size for Specific Artery

Lesion Location	Balloon Diameter (mm)	Balloon Length (cm)
Internal carotid artery	4–6	2
Common carotid artery	6–8	2–4
Vertebral artery	3–5	2
Subclavian artery	6–10	2
Axially artery	5–7	2–5
Brachial artery	2–4	2
Aorta	10–40	2–8
Celiac artery	5–8	2–4
Superior mesenteric artery	5–8	2–4
Renal artery	5–7	2–4
Common iliac artery	6–10	2–4
External iliac artery	6–8	2–10
Superficial femoral artery	5–7	2–15
Popliteal artery	4–6	2–4
Tibial artery	2–3	2–30

of the access vessel, it may be necessary to use a stiffer wire, advance the sheath or guide catheter closer to the target lesion, or switch to a balloon with a lower profile, or greater pushability.

Balloon Inflation and Completion Angiography

It is important to prepare the balloon to avoid air embolization from balloon rupture and to enhance visualization of the balloon under fluoroscopy. The guide wire lumen of the balloon catheter is flushed with heparinized saline solution in the OTW balloon. For RX balloons the guide wire lumen should be flushed from the distal end hole. The balloon is prepped by replacing any air inside the balloon with 25% to 50% strength contrast. The balloon should be positioned so that the most severe stenotic lesion aligns with the center of the balloon. However, there is a difference in the expansion force between the center and edge of the balloon. When a lesion is expanded by the center of the balloon, it may be difficult to obtain full expansion because it sandwiches the surrounding tissue. On the other hand, when a lesion is expanded by the balloon edge, it is more likely to expand because it expands the surrounding tissue outward.

Based on a reference screen or by marking the reference vessel diameter on the screen, the operators should avoid excessive expansion beyond the reference vessel diameter. Zorger et al.[99] investigated the influence of 30-second inflations compared to 180-second inflations. They demonstrated that all procedural success endpoints (bailout stenting, the incidence of major dissections, and need for further intervention) were improved by the longer inflation time. The balloon is deflated and inflated again for the same amount of time. While deflating, the balloon catheter should not be retracted into the sheath immediately since the remaining wings of the balloon may be caught by the tip of the sheath. It should be noted that a vessel may have ruptured if a patient complains of severe pain during dilation of the balloon. It is important to maintain a guide wire position across the dilated lesion in case additional treatment is required.

Vessel Preparation

Vessel preparation minimizes the risk of dissections, maximizes the luminal gain, and prepares the vessel bed for stents, vascular

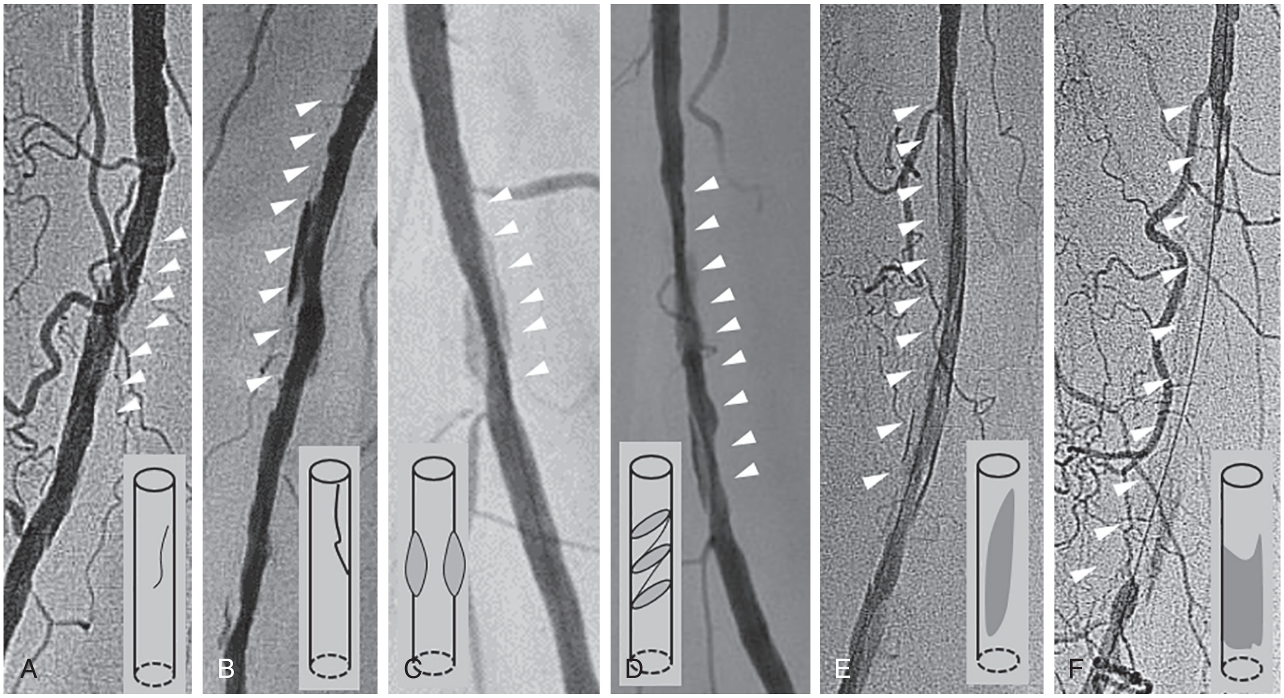

Figure 63.15 **Dissection Grade.** (**A**) Type A has minor radiolucent areas. (**B**) Type B is a linear dissection. (**C**) Type C has contrast outside the lumen. (**D**) Type D is a spiral dissection. (**E**) Type E has persistent filling defects. (**F**) Type F is a total occlusion without distal antegrade flow.

mimetic implants, or local drug delivery. Vessel preparation should be considered regardless of whether the lesion is stenotic or occlusive and is especially crucial if calcium is present.[100] Vessel preparation consists of predilatation with an undersized balloon, angioplasty with scoring or cutting balloons, or atherectomy. Scoring or cutting balloons may be considered in calcified or very fibrotic lesions, and vessel preparation is often needed before delivering adjunctive therapies, such as DCB. An atherectomy system debulks and aspirates multiple lesion morphologies, including calcium, plaque, and thrombus. The DEFINITIVE AR trial[101] was a pivotal feasibility trial to investigate combination therapy, directional atherectomy (DA) and DCB, compared to DCB only. The results suggest that in longer and more calcified lesions, there is a trend toward the superiority of combining DA and DCBs. Patency was improved compared to using DCBs alone, especially in patients who underwent effective DA vessel preparation. In another study, the final 3-year outcomes of SUPERB which evaluated the interwoven nitinol biomimetic Supera stent showed that optimal vessel preparation is essential for precise stent deployment.[102]

Dissection Grade

Arterial dissection often occurs after PTA, and stent placement may be required. Dissections following PTA are classified into six grades.

Grade A is a small radiolucent area within the lumen of the vessel, disappearing with the passage of the contrast material. *Grade B* is a filling defect parallel to the lumen of the vessel, disappearing with the passage of contrast material. *Grade C* is a dissection protruding inside the lumen of the vessel, persisting after the passage of contrast material. *Grade D* is a spiral-shaped filling defect with delayed run-off of the contrast material in the distal vessel. *Grade E* is a persistent luminal filling defect with delayed antegrade flow. *Grade F* is a filling defect accompanied by total occlusion. Stenting is typically required with Grade C to F dissections (Fig. 63.15).[103]

STENTING

Indications

In treating iliac lesions, the primary patency for primary stenting at 5 years was superior to selective stenting. This difference was significant in complex lesions categorized as TASC C or D lesions.[104] Selective stenting or provisional stenting is performed as a bailout procedure for dissection, residual stenosis, the presence of a residual pressure gradient, or acute occlusion following the PTA.

Dissection

Some degree of dissection commonly occurs following PTA. Angiography and IVUS are useful for the assessment of dissection. If the contrast flow is impeded by a flow-limiting dissection, or if a false channel is created, a stent should be placed. Extension of the dissection into the disease-free segment beyond the target lesion also requires stenting.

Residual Stenosis

Residual stenosis is typically defined as over 30% stenosis of the lesion by angiographic measurement following PTA. In such cases, a repeat PTA with a longer inflation time or additional stenting should be considered.

Pressure Gradient

A systolic pressure gradient that exceeds 10 mmHg across the lesion after PTA usually requires a repeat PTA or stent placement.

Acute Occlusion

If an acute occlusion is encountered during endovascular therapy, stent placement is usually necessary. If an acute occlusion occurs in a lesion in the so-called no stent zone, including the CFA, popliteal artery, or BTK lesions, the justification for stent placement is controversial. Therefore, it is best to perform interventions for such lesions where surgical back-up is available.

In-Stent Restenosis

In-stent restenosis (ISR) is usually secondary to intimal hyperplasia. Various treatments have been performed, including the use of cutting balloons, atherectomy, stenting, and covered stent placement. However, due to the absence of good quality data, it is difficult to make solid recommendations.

Stent Fracture

Stent fracture is more common in longer stented segments (over 80 mm), in areas of stent overlap, and arterial segments subjected to longitudinal, bending, and torsional forces, such as the popliteal artery. Stent fracture depends on the ability of the stent to handle axial compression. Stiffer stents fracture more easily when placed in the SFA. A fracture can lead to restenosis, which may or may not be hemodynamically significant. Stent strut fractures are categorized into five types. *Type 0* means that there are no strut fractures. *Type I* is a single strut fracture. *Type II* involves multiple single strut fractures that can occur at different sites. *Type III* involves multiple strut fractures resulting in complete transection of the stent, without displacement of the stent segments. Finally, *type IV* involves multiple strut fractures resulting in the displacement of the segments of the stent, including spiral fractures.

Stent Selection

The pros and cons of using a BES versus an SES are outlined in Table 63.3. Short or focal lesions are best treated with BESs because they can be placed accurately, expanded further using a larger balloon, and have a high radial force that may be necessary to treat a calcified lesion. BESs are often selected to treat ostial lesions of the visceral or aortoiliac artery since these lesions require accurate placement of the stent, and plaques are often calcified. When treating common iliac bifurcation lesions, a "kissing stent" technique may be necessary to prevent obstruction of the contralateral artery resulting from plaque shift. In contrast, the SESs, which have flexibility and kink resistance, are suitable for long and tortuous lesions and superficial arteries that are subjected to external compression. SESs are typically used for internal carotid, external iliac, SFA, and dissections secondary to stent-graft insertion.

TABLE 63.3 Characteristics of Balloon-Expanding and Self-Expanding Stents

	Balloon-Expanding Stent	Self-expanding Stent
Pros	Precise deployment High radial force Further expansion with larger balloons Radiopaque	Flexibility Long length Kink resistance Ability to clamp
Cons	Rigid Short length Prone to fracture Less kink resistance	Low radial force Less precise deployment Insufficient radiopacity
Indications	Ostial lesions Focal lesions Calcified lesions Resistant lesions	Superficial lesions Long lesions Tortuous vessels Dissections

Technique for Balloon-Expanding Stents

The stent size is selected based on the reference vessel diameter. Although the stent diameter should typically be 5% to 10% oversized compared to the reference vessel, the nature of the lesion, including the degree of calcification or thrombus, should be considered. There is a risk of dislodgment of the balloon-mounted stent and the lesion should be adequately predilated to prevent this. This can be done by advancing the tip of the long sheath beyond the lesion, using the sheath dilator or the PTA balloon as a dilator. After insertion of the sheath, the wire is advanced under fluoroscopic guidance. Once beyond the lesion, contrast is injected from the sheath, or IVUS interrogation is performed, to confirm that the wire is in the true lumen. The location of the lesion is then marked. In severe stenotic or CTO lesions, an undersized predilation balloon is often used to facilitate insertion of the stent and is also useful in selecting the appropriately sized stent. After additional contrast has been injected through the sheath to confirm proper stent location, the sheath is withdrawn to expose the stent. Then, under fluoroscopic monitoring, the balloon is inflated to expand the stent with adequate pressure. During inflation, a "doggie bone" shape, with the proximal and distal ends of the balloon expanding first, confirms that the stent has not dislodged. If a stent is not mounted properly on the balloon, then it should be replaced with a new stent. IVUS may be useful where visualization with fluoroscopy is difficult. The wire purchase must be maintained until the procedure has been completed. BESs can be further dilated to a degree with a larger balloon if necessary.

Technique for Self-Expanding Stents

The best features of SESs are their flexibility and long length. The selected stent should have a 1 to 2 mm larger diameter than the reference vessel because the stent cannot be expanded beyond the stated diameter. As with BESs, after the wire has crossed the lesion, predilation is performed. Unlike the BES, the introducer sheath is not always required to cross the lesion since SESs are stored in a covering sheath, and there is no risk of stent dislodgement. The stent is deployed by withdrawing the covering sheath. Fluoroscopic guidance is necessary during deployment because most SESs tend to "jump" forward as they are unsheathed. SESs cannot be re-sheathed once deployed, except for the Wallstent (Boston Scientific, Natick, MA). After stent placement, post-dilation with appropriate diameter and length is required.

The Viabahn (W.L. Gore & Associates, Flagstaff, AZ), a newer endograft for SFA lesions, has been indicated for the treatment of long lesions due to its better results. In the VIASTAR trial,[105] as previously described, the primary patency of this endoprosthesis was superior to bare metal stents even if the lesion exceeded 20 cm. The Viabahn may become an alternative for bypass surgery for patients with serious comorbidities and long, complex lesions.

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A complete reference list can be found online at www.expertconsult.com.

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CHAPTER 64

Laparoscopic and Robotic Aortic Surgery

JEAN-BAPTISTE RICCO and FABIEN THAVEAU

INTRODUCTION

Vascular surgery has evolved with the introduction of endovascular procedures. Minimally invasive laparoscopic techniques have also been developed, with a number of reports describing laparoscopic aortic repair for occlusive and aneurysmal disease.[1–3] There are no large randomized trials to support laparoscopic aortic repair over open or endovascular surgery for abdominal aortic aneurysm (AAA) or aortoiliac occlusive disease (AIOD). The lack of trained vascular surgeons with the skills to perform laparoscopic aortic repair and the improved outcomes after aortoiliac stenting and after endovascular aneurysm repair (EVAR) led to question the need for laparoscopic aortic repair. There is, however, a subset of patients that will benefit from a potentially less invasive alternative to open repair when EVAR or iliac stenting is not achievable. In this setting, laparoscopic aortic surgery may be considered as an option.

We describe in this chapter the current laparoscopic techniques used for aortic reconstruction, including hand-assisted and robot-assisted laparoscopic surgery, their results, and the conditions required to master these procedures.

TOTAL LAPAROSCOPIC AORTIC SURGERY

Four techniques have been described to perform total laparoscopic aortic bypass:

- Retrocolic prerenal transperitoneal approach
- Retrocolic retrorenal transperitoneal approach
- Combined transperitoneal and retroperitoneal approach
- Retroperitoneal approach.

Retrocolic Prerenal Transperitoneal Approach for Aortoiliac Occlusive Lesions

The transperitoneal procedure described by Dion et al.[4] and followed by Coggia et al.[2] involves exposure of the aorta by a

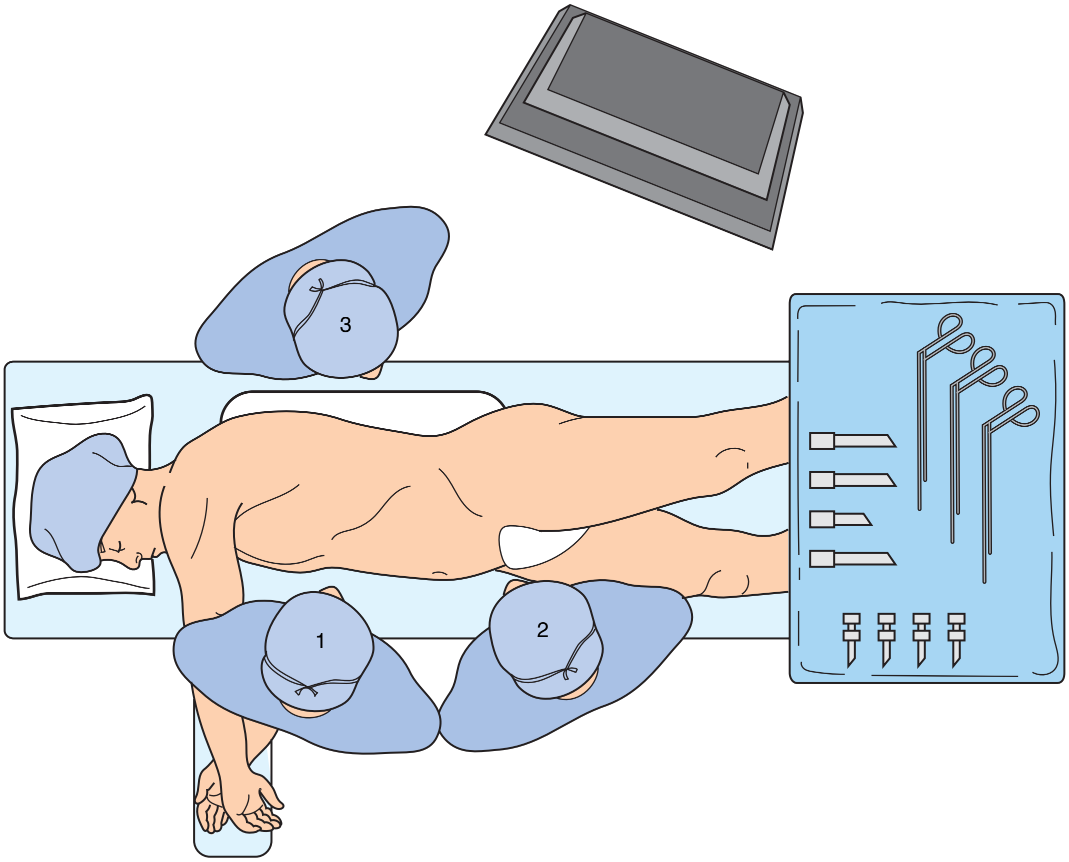

Figure 64.1 Patient in right lateral decubitus position for a total laparoscopic retrocolic transperitoneal approach. *1*, operating surgeon; *2*, first assistant; *3*, second assistant.

left prerenal approach. The patient is placed in the dorsal decubitus position with an inflatable pillow under the left flank. The left arm remains free and the right arm is placed on an armrest. The lower extremities are flexed and attached parallel to each other. Two supports are placed on the right side of the thorax and flank in order to retain the patient when the table is tilted to the right (45 degrees) and the pillow is inflated (35 degrees). After these maneuvers, the patient is in the complete right lateral decubitus position (Fig. 64.1). It is possible to change the patient from the right lateral decubitus position, used during exposure of the aorta, to the dorsal decubitus position for exposure of the femoral arteries, simply by tilting the operating table.

The operating surgeon and first assistant stand on the right side of the operating table, in front of the patient's abdomen, and the second assistant stands opposite the operating surgeon. A pneumoperitoneum is insufflated up to 14 mm Hg through a Veress needle inserted in the left hypochondrium. A 45-degree endoscope is positioned on the left anterior axillary line below the costal margin. Five trocars are introduced under visual control after establishing a pneumoperitoneum. Two operating ports are placed 6–7 cm apart on the left transrectal line parallel to the midline (port #2 for scissors and needle holder and port #3 for fenestrated forceps). Two trocars for the first assistant are introduced in the left iliac fossa and on the midline 5 cm from the pubis (port #4 for suction catheter and port #5 for fenestrated forceps followed by distal clamp). The last trocar (port #1) is positioned on the midline, 2 cm below the xiphoid process for proximal aortic clamp) (Fig. 64.2).

The left latero-colic approach involves left colic dissection to achieve prerenal exposure of the aorta. The table is tilted to the right (i.e., 45 degrees) and the pillow is inflated to enhance the right lateral decubitus position by 30 degrees. The Toldt fascia is incised from the left colic angle to the meso-sigmoid to allow complete dissection of the left mesocolon. After identification of the genital vein, prerenal dissection is continued to the left renal vein. Because the patient is in the right lateral decubitus position, the small bowel and left mesocolon drop to the right side of the abdomen (Fig. 64.3). The mesocolon is then attached to the abdominal wall with transparietal sutures to form an apron providing stable exposure of the aorta.[4] In case of extensive infrarenal aortic calcifications, mobilization of the renal vein is necessary to gain access to the juxtarenal aorta (Fig. 64.4).

For exposure of the femoral arteries the table is rotated to the left and the pillow deflated. After conventional femoral exposure, the table is again tilted to the right to allow introduction of the bifurcated prosthesis through one of the ports. The right branch of the prosthesis is tunnelled in the anatomical position before making the proximal anastomosis. The extremity of the left branch is ligated and left in the abdomen.

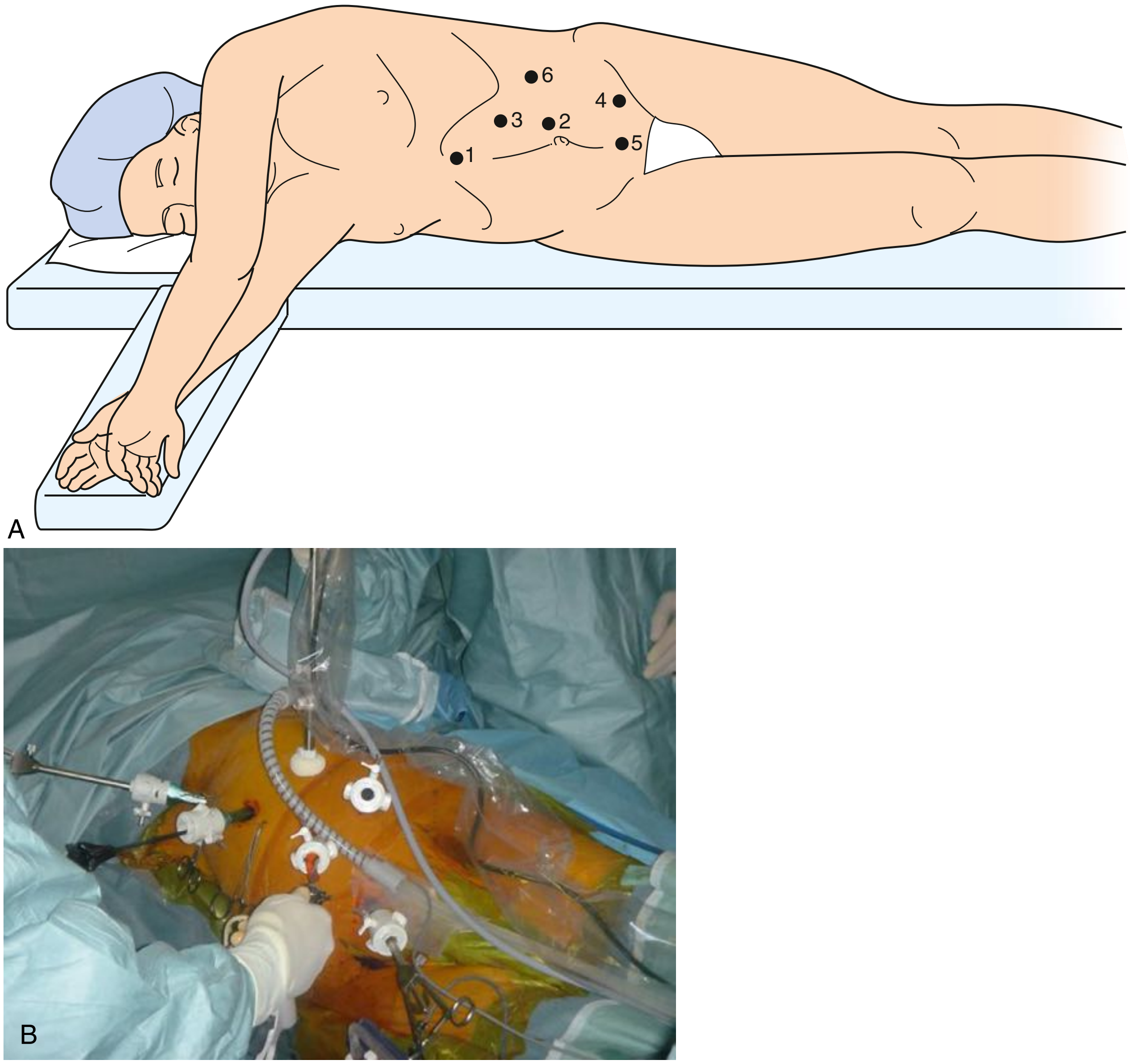

Figure 64.2 (**A**) Position of the ports for retrocolic transperitoneal approach. *1*, retractor – proximal clamp; *2*, coagulating scissors – needle holder; *3*, blunt grasping forceps; *4*, suction system; *5*, blunt grasping forceps – distal clamp; *6*, 30-degree angled viewing endoscope. (**B**) Operative view: operator and position of ports for total laparoscopic retrocolic prerenal transperitoneal approach.

Aortic clamping is performed with laparoscopic clamps introduced through ports #1 and #5, which stabilize the left colon during completion of the proximal anastomosis. The anastomosis between the aorta and prosthetic graft is made using 18-centimeter-long polypropylene 3/0 suture with one end previously sutured to a pledget to avoid tying the first knot (Figs. 64.5 and 64.6). In case of an end-to-end aortic anastomosis, the closure of the infrarenal aorta is performed with a double running polypropylene 3/0 suture. One alternative is the use of an automatic stapler without cutting knife (Endopath ETS-Flex 45, Ethicon) which saves time but requires a moderate calcified aortic wall.

The left branch of the prosthesis is then tunnelled with the help of an aortic clamp introduced through the left groin. The tip of the clamp is located under laparoscopic control and routed behind the left ureter. Femoral anastomoses are performed conventionally on a patient in the dorsal decubitus position. After removing the clamp, the surgeon decreases the gas pressure to 6 mm Hg to check the hemostasis of the aortic anastomosis and to reveal any venous bleeding hidden by the high-pressure pneumoperitoneum. The mesocolon is then repositioned under laparoscopic control to separate the graft from the bowel. This retrocolic prerenal approach achieves an adequate aortic exposure and provides a large operating space with the small bowel falling to the right part of the abdomen and the left mesocolon acting as a peritoneal apron (Video 64.1A).

Retrocolic Retrorenal Transperitoneal Approach

The retrocolic prerenal transperitoneal approach is used in most standard cases of aortic occlusive disease. However, in very thin patients, where dissection of the Toldt fascia is impossible, or in patients with previous left kidney or colon surgery or for suprarenal aortic clamping, and in patients with an abdominal aortic aneurysm, a transperitoneal left retrorenal approach is preferred (Video 64.1B).[5] In these cases, the dissection is conducted by elevating the left colon and the left kidney with section of the reno-azygos lumbar vein to achieve a right medial visceral rotation.

Specificity for Abdominal Aortic Aneurysm

The retrocolic retrorenal transperitoneal approach is used most often for total laparoscopic aortic aneurysm repair, particularly in patients with a juxtarenal AAA.[5] After clamping the aorta, a stitch is placed into the aneurysm wall and pulled-out through the abdominal wall to maintain the aneurysmal sac open. The right iliac clamping is performed through an infra-umbilical trocar, and left iliac clamping through another trocar inserted in the left iliac fossa. A bulldog clamp serves to occlude the inferior mesenteric artery. Mural thrombus is removed in a container. Lumbar arteries are controlled with 3/0 polypropylene stitches as described in the Creech technique or by external hemoclips or staples. Anastomoses are performed as previously described.[6]

Combined Transperitoneal and Retroperitoneal Approach

This approach was first described by Dion.[7] The main feature of the technique is the creation of a peritoneal apron that retains the intestinal loops without reducing the size of the operating cavity. A 10-mm trocar is introduced at the level of the

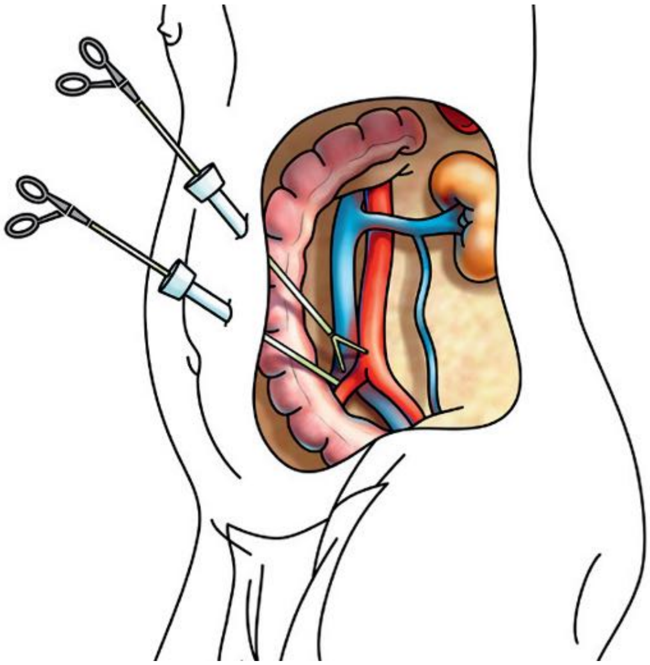

Figure 64.3 Aortic exposure through a left retrocolic prerenal approach. The patient is in right lateral decubitus. The intestinal loops collect on the right side of the abdomen with the mesocolon forming an apron. This technique provides a stable exposure of the aorta.

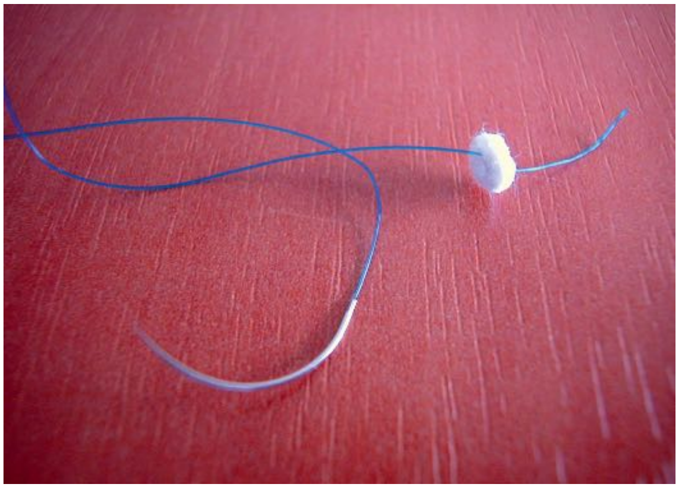

Figure 64.5 Prepared 18-cm-long polypropylene 3/0 suture for aortic anastomosis with one end sutured to a pledget to avoid having to tie the first knot.

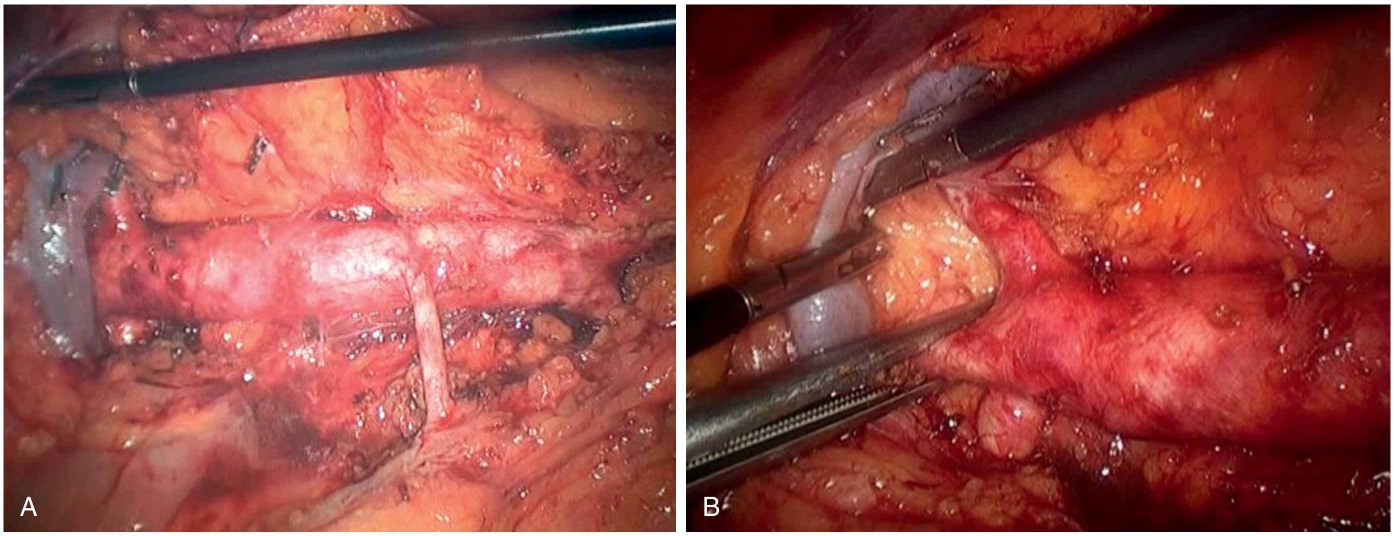

Figure 64.4 (**A**) Complete exposure of the aorta, iliac arteries and inferior mesenteric artery through a left retrocolic prerenal approach. (**B**) Cross-clamping of the suprarenal aorta for extensive occlusive disease and calcification of the infrarenal aorta (same approach).

umbilicus to establish the pneumoperitoneum at a pressure of 12 mm Hg. The patient is then placed in the Trendelenburg position at 10 degrees with the table tilted to the right. As initially described by Dion, the technique involved two distinct retroperitoneal and transperitoneal maneuvers for dissection of the left parietal peritoneum and attachment to the wall by three transparietal sutures to form a peritoneal apron (Video 64.1C). The procedure begins with an incision of the left parietal peritoneum about 8 cm anterolateral to the Toldt fascia. Dissection is followed in front of the kidney up to the renal vein. The infrarenal aorta proximal to the inferior mesenteric artery is then dissected. The surgeon moves to the patient's left side to complete the procedure. The apron is then attached to the wall to keep the bowel out of the operating field. As previously described, this technique was subsequently simplified by Coggia.[8]

Retroperitoneal Approach

This laparoscopic assisted technique with a short laparotomy to facilitate the aortic anastomosis was first described by Said et al.[9] and developed by Edoga et al.[10] for abdominal aortic aneurysm repair. The patient is placed in a right lateral decubitus position as for the retrocolic transperitoneal approach. The viewing endoscope is introduced through a 15-mm incision above and medial to the iliac crest using the open retroperitoneoscopic technique with a prior hand dissection of the retroperitoneal space. This dissection should be extended up to the midline to avoid peritoneal tears. Although rarely used, the retroperitoneal procedure is a suitable alternative when the transperitoneal procedure is contraindicated in patients with hostile abdomen or when a complete exposure of the left common iliac artery is needed.[11] The main advantage of the retroperitoneal route is to exclude the visceral organs from the operating field albeit at the expense of a smaller working space with the risk of peritoneal tears. One reason that this approach is rarely used for aortoiliac procedures is diffusion of the gas through the peritoneum, thus creating a "passive" pneumoperitoneum which progressively replaces the pneumo-retroperitoneum, reducing the working space.

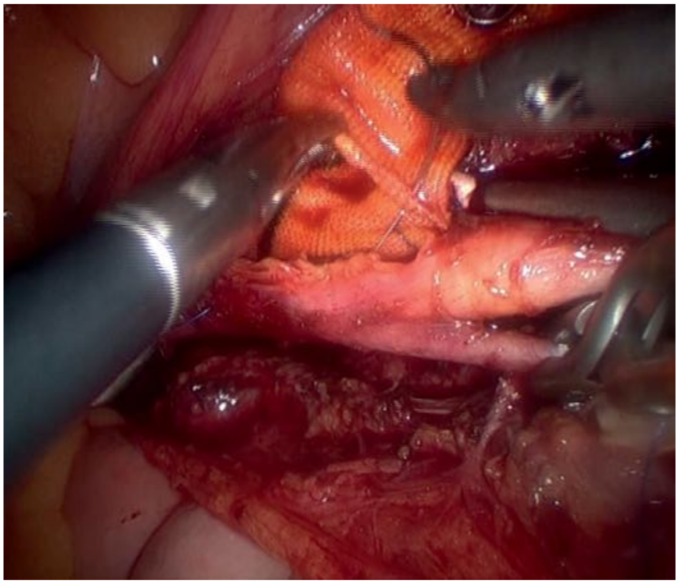

Figure 64.6 End-to-side totally laparoscopic aortic anastomosis with a 3/0 polypropylene running suture using curved jaws and axial handle needle holder.

HAND-ASSISTED LAPAROSCOPIC AORTIC SURGERY

Hand-assisted laparoscopic surgery (HALS), which enables the surgeon to introduce his nondominant hand through a special port while maintaining the pneumoperitoneum, has been routinely used by some authors for aortic occlusive lesions or AAA repair.[12–15] The patient is placed in the supine position. A midline incision of 7–8 cm is performed to allow placement of the port-site device. Through this port, the hand of the surgeon is introduced into the abdominal cavity without any carbon dioxide loss. A 10-mm trocar is then placed along the midline below the umbilicus with introduction of a 30-degree laparoscopic optic and for carbon dioxide insufflation to create a 12-mm Hg pneumoperitoneum. At that point, with the nondominant hand, the surgeon pushes away the bowel loops to the right by tilting of the operating table to the right and in Trendelenburg position. A trocar is then introduced lateral to the border of the left rectus abdominis muscle for dissection of the infrarenal aorta and another trocar is inserted lateral to the border of the right rectus abdominis muscle. After laparoscopic dissection of the aorta, the abdominal cavity is deflated, the special port-site device removed, the bowel being left in place in the right abdomen with the aid of laparoscopic sponges. The incision is kept open with an autostatic retractor. The proximal anastomosis between the aorta and the graft is performed under direct vision with conventional instruments. If a distal anastomosis on the external iliac is planned, an oblique suprainguinal incision is done to expose the artery. HALS has proven in many studies to be a reliable technique to overcome the technical challenge of total laparoscopy aortic surgery, mainly the performance of vascular anastomoses. It may have increased the feasibility of this type of surgery but its invasiveness compared with total laparoscopic aortic repair is a drawback.

TOTALLY ROBOTIC AORTIC AND ROBOT-ASSISTED PROCEDURES

The robot may be used in laparoscopy-assisted procedures as well as in total laparoscopic surgery.[16] Its usefulness becomes more evident when suturing the aortic anastomosis because robotic arms support five degrees of freedom. Optimal placements of the robot's arms are usually in ports located on the left axillary line.[17–21] The use of robots in vascular surgery is thought to result in a better surgical performance by overcoming the long learning curve of vascular suturing. But the system also has some disadvantages, including its complexity and high cost. The robot may be used in laparoscopy-assisted procedures as well as in total laparoscopic surgery. With more than 5000 da Vinci robots (Intuitive Surgical, Sunnyvale, CA) in use around the world in 2020, robotic surgery has become unavoidable in the surgical field.[22] Using the robot to perform aortic surgery takes the fundamentals of laparoscopic surgery.

The initial uses of robots have focused on the achievement of anastomoses[23] and arterial reconstructions, and the system is now increasingly used for the realization of the whole intervention, from the incision to aortic reconstruction.

Totally Robotic Aortic Surgery

The da Vinci surgical system is composed of three main parts: one patient-side cart with four articulated arms; one instrument tower with video command; and the surgeon's workstation with the operating console. The fundamental difference between laparoscopic and robotic techniques is that the latter provides the surgeon a surgical theatre similar to that of open surgery. Indeed, with the robot, the surgeon uses his hands in the same manner as in open surgery. In addition, it provides seven degrees of freedom for the tips of the robotics instruments following rotational movements of the hands and wrists. Added to a three-dimensional-like vision, these characteristics explain why there is a faster learning curve with the robot.

Patient installation is similar to that described for total laparoscopic techniques. Only the trocars require a different strategy.

With the patient under general anaesthesia, an 80-degree rotation of the patient is obtained by addition of a 45-degree right tilt to the table and placing a 35-degree inflated Pelvic Tilt pillow (O.R. Comfort) placed under the patient's left flank. One support is placed on the right side of the thorax, leaving the area below the xiphoid free for placement of a proximal aortic clamp trocar; the second trocar is placed facing the right hip, leaving the surgical approach of the right groin free in case aortobifemoral reconstruction should be required. Both lower limbs are maintained in line with the body, only the right leg is attached to the table, and the left leg is flexed to 30 degrees to avoid any psoas elongation. In the case of aneurysm repair, the patient is immediately installed on the operating table as well and the robot is docked. In case of aortobifemoral reconstruction for occlusive disease, the patient is first placed in the dorsal position to achieve femoral exposure, then rotated on the right side.

A pneumoperitoneum of 14 mm Hg is performed by an open technique at the umbilicus using a 12-mm trocar that will be used later as assistant. Two other 12-mm trocars are inserted respectively below the xiphoid and above the pubic symphysis, used as an assistant or for proximal and distal clamping of the abdominal aorta (Fig. 64.7).

As opposed to basic laparoscopy, the main problem encountered with the robot is the external conflict between the articulated arms. For this reason, robotic trocars of three main arms, right and left surgeon's hand and camera, are placed on the left axillary line and spaced as far as possible from each other. The right hand (arm 1) is close to the left iliac spine shifted 5 cm below, the left hand (arm 3) is close to the left costal margin. The Camera trocar (Camera arm) is placed midway between the remaining two trocars, on a slightly lower line left pararectal. With the S and Si models, which are mostly used, placement of the robot is decided by the placement of the camera articulated arm. The last articulated arm (arm 2) is placed when a last trocar is used, close to the trocar of arm 3, shifted to the patient's back. One 5-mm trocar can be added between the proximal clamp trocar and the umbilicus on the median line.

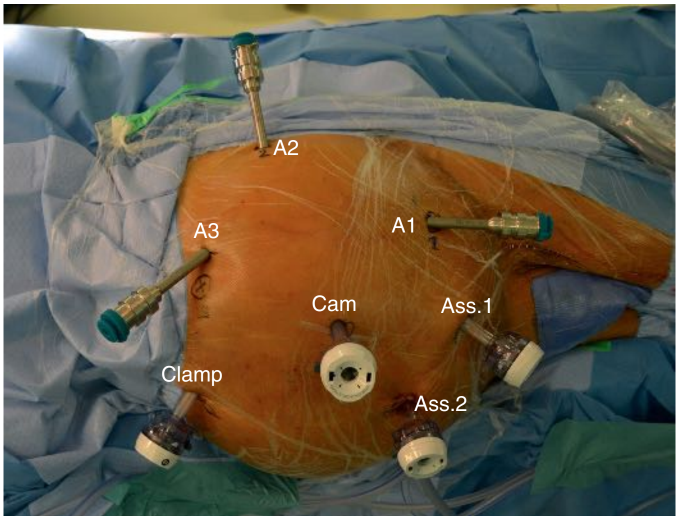

Figure 64.7 Placement of trocars for robotic aortoiliac surgery. *Clamp*: a 12-mm laparoscopic trocar placed just below the xiphoid, on the abdominal median line is used by a surgeon's assistant during the surgical approach and dissection of the aorta, and for the proximal laparoscopic clamp. *Ass.1*: 12-mm laparoscopic trocar placed up to the pubic symphysis, used by a surgeon's assistant during the surgical approach and dissection of the aorta, and for the distal laparoscopic clamp. *Ass.2*: 12-mm laparoscopic trocar at the umbilicus, introduced by open technique, used in the creation of the peritoneum and for the surgical assistance. *A1*: 9-mm robotic trocar docked on the articulated robotic arm 1, inserted close to the left iliac spine shifted 5 cm below, used by the right hand of the surgeon. *A2*: 9-mm robotic trocar docked on the articulated robotic arm 2, inserted close to the robotic trocar of the arm 3, shifted to the patient back, used by the left hand of the surgeon alternatively with the arm 3. *A3*: 9-mm robotic trocar docked on the articulated robotic arm 3, inserted close to the left costal margin, on the left axillary line, used by the left hand of the surgeon. *Cam*: 12-mm laparoscopic trocar inserted on a slightly lower line left pararectal, midway between the trocars A1 and A2 with triangulation and docked on the robotic Camera arm.

The patient side cart is docked from the left side of the patient, placed at 90 degrees relative to the central axis of the operating table (Fig. 64.8) (Video 64.2A). The assistant and operative nurse face the patient, the surgeon is installed on the operating console at a remote place. The main dissection is done with monopolar scissors on the right hand (arm 1) and bipolar fenestrated forceps on the left hand (arm 3). Another arm can be used as a robotic assistant with second fenestrated forceps (arm 2). Most of the time, a 0-degree endoscope is used with the camera (Camera arm), but a 30-degree endoscope may also be used, especially for obese patients with difficult exposure due to the intraperitoneal fat.

With total robotic technique, both retrocolic prerenal and retrocolic retrorenal approaches are achieved using the same principles as the total laparoscopic technique described above.

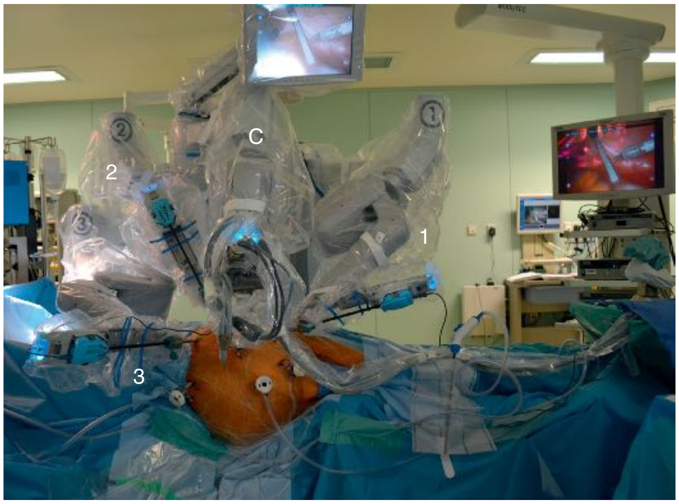

Figure 64.8 Side-docking method for robotic aortoiliac surgery. The robot is docked from the left side of the patient at an approximately 90-degree angle to the central axis of the table. *1*, articulated robotic arm 1, used by the left hand of the surgeon. *2 and 3*, articulated robotic arm 2 and arm 3 are used alternatively by the right hand of the surgeon. *C*, camera articulated robotic arm, with a 0-degree or 30-degree endoscope providing three-dimensional vision and used by both hands of the surgeon independently of the operative robotic arms.

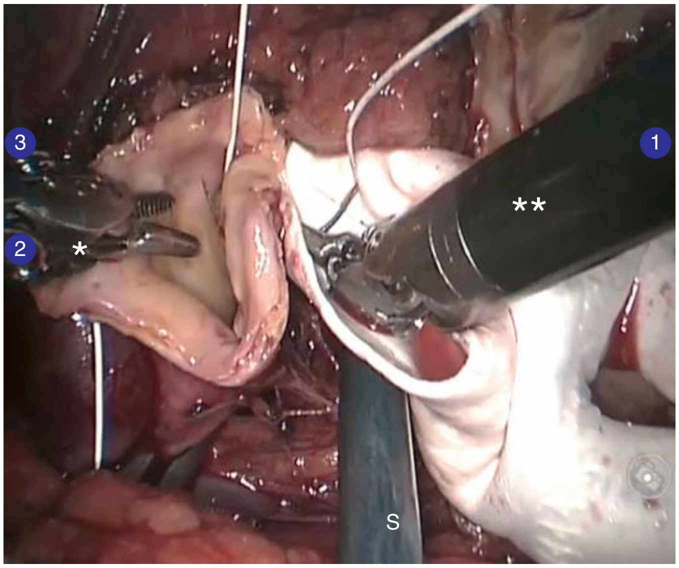

Figure 64.9 Robotic proximal anastomosis for abdominal aortic aneurysm repair with a PTFE bifurcated graft. *Left robotic needle holder, used by the left hand of the surgeon. **Right robotic needle holder used by the right hand of the surgeon. *S*, laparoscopic surgical suction. See Fig. 64.8 for 1,2,3 arms.

However, there are some striking differences between the two techniques that give advantage to the robot in performing aortic surgery. Because of the stable three-dimensional vision and capability of the instrument's movements in a close and deep space, the robot pushes the limits of laparoscopic dissection. The suprarenal aorta, origin of the superior mesenteric artery, origin of the right renal artery, and the left renal artery are dissected. This offers the opportunity of temporary suprarenal aortic clamping for extensive aortic occlusive disease close to the renal arteries or for an aneurysm with a short aortic neck. Similarly, the right iliac bifurcation can be easily reached and dissected to perform the distal anastomosis in case of an aortoiliac aneurysm.

The retrocolic retrorenal approach is mostly performed for occlusive disease, and the retrocolic prerenal approach is preferred in the case of AAA repair (Video 64.2B). In this case, after clamping the proximal neck of the aneurysm, the lumbar arteries are clipped, helping to mobilize the aneurysmal sac with a fenestrated grasp (arm 2) without any risk of distal embolization. The distal aorta is clamped by a laparoscopic clamp through the distal trocar, and common iliac arteries are clamped selectively by removable bulldog clamps. In case of severe calcifications of the iliac arteries, transparietal aortoiliac clamps may be used instead of ineffective bulldogs.

Aortic and iliac anastomoses are carried out with 3/0 or 4/0 Gore-Tex suture, which provides more strength than polypropylene. Robotic suturing with the help of a shorter learning curve provides better dexterity and pushes the limit of laparoscopic suturing (Videos 64.2C and 64.2D). Proximal and distal aortic anastomoses are carried out with a unique running suture 25 cm long, blocked at one end by a pledget (Fig. 64.9) (Video 64.2E). The same technique is applied for iliac anastomoses, with a 15-cm running suture. One challenge during robotic suturing is the degree of tension needed on the suture line, as the tactile sensation is not transmitted to the hands of the surgeon from the robotic arms and is acquired with experience.

Robot-Assisted Aortic Surgery

Some surgical teams have decided to use the robot only to perform one part of the aortic surgery with minilaparotomy for graft implantation. In these cases, the robot is installed after completion of aortic exposure with a classic laparoscopic technique[19–21] and used to perform arterial sutures, while reducing the clamping time.

PUBLISHED STUDIES

Clinical studies eligible for inclusion in this chapter were identified by a thorough research of the PubMed bibliographical database from 1995 to 2020. Two investigators (J-BR, FT) worked independently using the following keywords: *laparoscopy, laparoscopic, endoscopy, aortic aneurysm, aortic occlusive disease, robot,* and *robotic*. After excluding cardiac surgical procedures, 52 studies were found to be eligible with 24 reporting total laparoscopic aortic surgery (TLAS), 14 reporting HALS and minilaparotomy-assisted laparoscopic surgery, and 10 reporting robot-assisted laparoscopic aortic surgery.

Total Laparoscopic Aortic Procedures

Total laparoscopic aortic procedures for aortoiliac occlusive disease (AIOD) were analyzed in 16 studies regrouping 932 patients (Table 64.1). Total laparoscopic procedures for abdominal aortic aneurysm (AAA) were reported in 9 studies regrouping 410 patients (Table 64.2).

TABLE 64.1 Total Laparoscopic Surgery for Aortic Occlusive Disease

Authors	Year	Patients	Operative time (minutes)	Clamping time (minutes)	Hospital stay (days)	Mortality	Conversion
Barbera[40]	1998	24	250	70	7	0/24	4/24
Dion[29]	2004	51	290	99	5	1/51	5/51
Coggia[2]	2004	93	240	68	7	4/93	2/93
Olinde[41]	2005	22	267	90	4	1/22	2/22
Lin[24]	2005	68	199	85	6	1/68	3/68
Rouers[42]	2005	30	244	66	5	0/30	6/30
Remy[25]	2005	21	240	60	7	0/21	1/21
Dooner[27]	2006	13	390	45	7	0/13	3/13
Cau[43]	2006	72	216	57	8	0/72	2/72
Fourneau[26]	2008	50	328	69	5	0/50	11/50
Di Centa[44]	2008	150	260	81	7	4/150	5/150
Tiek[45]	2012	14	273	48	4	0/12	0/12
Segers*,[46]	2014	12	265	0	6	0/12	0/12
Ghammad[47]	2015	173	205	50	7	4/173	21/173
Lecot[48]	2016	87	327	NR	6	1/87	18/87
Ricco[36]	2016	52	250	50	6	2/52	7/52

*Clampless and sutureless aortic anastomosis using a covered stent graft, no aortic clamping, median time for aorto-prosthetic connection was 60 seconds. Sixteen studies (932 patients) of total laparoscopic surgery for aortic occlusive disease. Operative time, clamping times and length of stay in the hospital are presented as median values. *NR*, value not reported.

TABLE 64.2 Total Laparoscopic Aortic Aneurysm Repair

Author	Year	Patients	Operative time (minutes)	Clamping time (minutes)	Hospital stay (days)	Mortality	Conversion
Edoga[10]	1998	22	391	146	6	2/22	2/22
Kolvenbach[3]	2006	131	265	95	5	4/131	6/37
Coggia[49]	2004	30	290	78	9	2/30	2/30
Coggia[50]	2005	30	255	80	9	1/30	1/30
Cau[43]	2006	23	251	101	6	1/23	7/23
Coggia[5]	2008	13	260	77	10	0/13	0/13
Javerliat[51]	2011	99	210	81	6	0/99	5/99
Coscas[52]	2014	31	289	75	13	3/31	3/31
Ricco[36]	2016	31	273	110	8	1/31	9/31

Nine studies (410 patients) with total laparoscopic aortic repair for AAA.
Operative time, clamping times and length of stay in the hospital are presented as median values. *NR*, value not reported.
Coggia[5] reported this series of juxtarenal aortic aneurysms
Javerliat,[51] from Coggia group, reported a subgroup of laparoscopic aortic aneurysm repair in patients with standard surgical risk.
Coscas,[52] from Coggia group, reported a subgroup of laparoscopic aortic aneurysm repair in octogenarians with anatomic criteria amenable to EVAR.

Hand-Assisted and Laparotomy-Assisted Laparoscopic Surgery

Hand- or minilaparotomy-assisted laparoscopic aortic procedures for AIOD (Table 64.3) and for AAA (Table 64.4) were reported in 14 studies regrouping 794 patients in total.

Robot-Assisted Laparoscopic Surgery

Robotic-assisted laparoscopic aortic procedures were reported in 12 studies regrouping 529 patients (Table 64.5).

Robot-Assisted Laparoscopy

Results of robot-assisted aortic laparoscopy have been analyzed separately with regard to the specificity of robotic technologies. As shown in Table 64.5, results obtained from these studies showed that the robotic system was effective in performing aortic anastomoses with the surgeon operating from a console away from the operating table. Comparison of the performance of robot-assisted and standard laparoscopic surgery revealed the superiority of the former with a shorter

TABLE 64.3 Hand- and Minilaparotomy-Assisted Laparoscopic Surgery for Aortic Occlusive Disease

Author	Year	*N*	Operative time (minutes)	Clamping time (minutes)	Hospital stay (days)	Mortality	Conversion
Lacroix[33]	1999	10	350	NR	7	0/10	1/10
Alimi[32]	2004	58	238	54	8	2/58	1/58
Kolvenbach[53]	2000	41	149	36	4	1/41	3/41
Silva[54]	2002	18	191	44	7	0/18	1/18
Wijtenburg[55]	2003	25	180	37	7	1/25	2/25
Debing[56]	2003	13	230	29	6	0/13	1/13
Fourneau[34]	2005	46	208	28	6	2/46	1/46

Seven studies (211 patients) with hand-assisted or minilaparotomy-assisted procedures.
Operative time, clamping times and length of stay in the hospital are presented as median values. *NR*, value not reported.

TABLE 64.4 Hand- and Minilaparotomy-Assisted Laparoscopic Aortic Aneurysm Repair

Author	Year	Patients	Operative time (minutes)	Clamping time (minutes)	Hospital stay (days)	Mortality m/*n*	Conversion c/*n*
Kline[57]	1998	20	245	NR	6	0/20	2/20
Castronuovo[15]	2000	60	462	112	6	3/60	3/60
Alimi[58]	2003	14	195	NR	4	1/14	1/14
Kolvenbach[3]	2006	215	175	55	7	4/215	11/215
Berchiolli[14]	2019	173	NR	NR	4	2/173	3/173
Veroux[35]	2010	50	178	NR	4	0/50	NR
Howard[59]	2015	51	330	90	5	1/51	NR

Seven studies (583 patients) with hand-assisted or minilaparotomy-assisted procedures.
Operative time, clamping times and length of stay in the hospital are presented as median values. *NR*, value not reported.

TABLE 64.5 Robot-Assisted Laparoscopic Aortic Surgery

Author	Year	Patients	Robot	Operative time (minutes)	Clamping time (minutes)	Hospital stay (days)	Mortality (30-day)	Conversion
Aneurysm Repair								
Kolvenbach[60]	2004	10	Zeus	242	96	7	0/10	2/10
Stádler[61]	2009	17	da Vinci	215	76	5	0/17	1/17
Lin*[,62]	2012	6	da Vinci	396	86	7	0/20	1/6
Stádler[21]	2016	61	da Vinci	253	93	7	1/61	8/61
Colvard**[,37]	2019	4	da Vinci	383	143	4	0/4	0/4
Aortic Occlusive Disease								
Desgranges[63]	2004	5	da Vinci	188	75	8	0/5	1/5
Nio[18]	2005	8	Zeus	405	111	7	1/8	2/8
Diks[23]	2007	17	Zeus + da Vinci	365	86	4	1/17	3/17
Stádler[61]	2009	115	da Vinci	215	40	5	0/130	2/115
Novotný[64]	2011	40	da Vinci	295	60	NR	0/40	2/40
Lin*[,62]	2012	12	da Vinci	493	86	7	0/20	0/12
Stádler[21]	2016	224	da Vinci	194	37	5	0/224	2/224

Twelve studies of robot-assisted laparoscopic aortic surgery.
Operative time, clamping time of the aorta and length of stay in the hospital are presented as median values. *NR*, value not reported.
*In this series of Lin,[62] total robotic aortic surgery was performed in 3 patients with aortoiliac occlusive disease (AIOD), robotic-assisted with a mini-laparotomy was performed in all patients with AAA and in 9 remaining patients with AIOD.
**In this series total robotic technique was used to treat complex iliac aneurysms with preservation of internal iliac vascularization in young and healthy patients.

TABLE 64.6 Main Data for Eligible Series of Laparoscopic Aortic Surgery

	TLAS (AIOD)	TLAS (AAA)	HALS (AIOD)	HALS (AAA)	ROBOT (AIOD)	ROBOT (AAA)
Patients	932	410	211	649	421	94
Operative time (min)	[199–390]	[210–391]	[149–350]	[175–330]	[188–405]	[215–396]
Clamping time (min)	[45–99]	[75–146]	[28–54]	[25–112]	[37–111]	[76–96]
Hospital stay (days)	[4–8]	[5–13]	[4–8]	[4–7]	[4–8]	[5–7]
Conversion	85 (9.1%)	35 (8.5%)	10 (4.7%)	17 (2.6%)	12 (2.8%)	12 (12.7%)
Death	18 (1.9%)	14 (3.4%)	6 (2.8%)	9 (1.4%)	2 (0.4%)	1 (1.1%)

Operative time, clamping time (aortic) and length of stay in the hospital are presented in each category as median values of the series with the shorter and the longer time periods.
AAA, aortic abdominal aneurysm; *AIOD*, aortoiliac occlusive disease; *HALS*, hand or minilaparotomy-assisted laparoscopic aortic surgery; *ROBOT*, robot-assisted laparoscopic aortic surgery; *TLAS*, total laparoscopic aortic surgery.

suturing and clamping time. Only one comparative study of TLAS and robotic-assisted procedures[24] demonstrated advantages in the time taken to complete the aortic anastomosis, 40.8 ± 4.1 minutes for robot-assisted procedures versus 52.7 ± 9.0 for total laparoscopic procedures (P <0.05), although the total procedure time was increased because of the robot set-up time.

PERIOPERATIVE OUTCOMES

Operative Time

Total operative times, excluding robot-assisted aortic laparoscopy, varied widely from 149 minutes to 390 minutes (Table 64.6). HALS had the shortest median operating time but with a wide range of values (149 to 350 minutes).

Closing Time

Aortic clamping extended from 28 minutes with HALS for AIOD to 146 minutes with TLAS for AAA with a wide range of values for the same pathology and also for the same technique within different centers (see Table 64.6).

Conversion to Open Surgery

Conversion to open surgical repair with TLAS for AIOD was 9.1% (95% CI, 7.4–11.1) and 8.5% (95% CI, 6.1–11.6) in patients with AAA (P = 0.75). Rate of conversion was significantly higher with TLAS than with HALS or minilaparotomy-assisted laparoscopy for AIOD (9.1% vs. 4.7%, P = 0.03) and also for AAA (8.5% vs. 2.6%, P = 0.001), respectively. Reasons for conversion were multiple including calcified aorta, bleeding from the lumbar veins or from the aortic anastomosis, and self-imposed operative time or aortic-clamping time limits.[24–26]

A significant number of specific complications occurred during laparoscopic aortic procedures including bleeding lumbar veins that quickly retract behind the spine, retroperitoneal hematoma due to extended laparoscopic dissection, ureteral lesions in relation to dissection, and acute occlusion of the prosthetic graft in some patients due a long aortic clamping time or an inadequate tunneling of the graft.

Mortality

Thirty-day postoperative mortality rate was 1.8% [95% CI: 1.4–2.4] for the whole series. Postoperative mortality among patients with a AAA treated by TLAS (3.4%, 95% CI: 2.1–5.3) was not significantly different than in patients treated by HALS (1.9%, 95% CI, 0.7–3.0, P = 0.10).

Morbidity

Hemorrhage and acute kidney insufficiency were the most frequently reported operative and postoperative complications occurring during the first 30 days after the procedure. Other complications were lower limb ischemia, ischemic colitis, thrombosis of the prosthesis, and myocardial infarction. These complications occurring more often after TLAS for AAA. However, many of the studies do not define criteria for their complications and these data should be viewed with caution.

Hospital Stay

In all 48 studies, median hospital stays varied from 4 to 13 days regardless of the laparoscopic technique used (see Table 64.6).

SUMMARY

Almost all surgical specialties incorporated laparoscopic techniques many years ago. Although several studies have demonstrated the feasibility of laparoscopy in aortic surgery,[4,27,28] vascular surgeons have been slow to adopt laparoscopic aortic techniques. One of the reasons is that the best way to start laparoscopic aortic surgery is in dealing with aortic occlusive disease. However, even for iliac artery occlusion, traditional bypasses have been replaced by stenting with a low morbidity and excellent results. Therefore, aortoiliac bypasses are now reserved for complex aortoiliac occlusion or endovascular failure. This reduces the workload and increases the technical challenge of laparoscopic procedures.

The concept of laparoscopic aortic surgery is to combine the excellent and durable results observed after conventional open arterial repair with the advantages of a less invasive laparoscopic approach. For most authors, initial laparoscopic procedures were performed with HALS or with the assistance of a minilaparotomy through which the aortic anastomosis was performed under direct vision. Following this initial experience, some authors have developed total laparoscopic aortic procedures to enhance the advantage of minimally invasive surgery with easier and faster recovery.

After the pioneer efforts of Dion et al.,[29,30] the key to total laparoscopic technique for aortoiliac disease was presented by Coggia et al.,[8] who described the transperitoneal left retrocolic approach of the abdominal aorta. This technique with a patient in right lateral decubitus provides a large workspace allowing dissection of the abdominal aorta and completion of the aortic anastomosis.

Total laparoscopic bypass is safely performed by a few centers of expertise for complex aortoiliac occlusive disease or infrarenal aortic aneurysm.[31] Despite these encouraging results, the importance of prior training to obtain the required level of expertise to perform laparoscopic aortic anastomoses, has been emphasized[26,32] with the option of assisted laparoscopy to lessen the risk of totally laparoscopic aortic anastomosis.[32–34] Because of these technical challenges, and the associated steep learning curve, no large randomized controlled trial has been done so far to prove the benefit of laparoscopic aortic surgery as compared to open or endovascular techniques.

We observed in these series a trend toward a decrease of pulmonary complications as compared with open surgery probably related to avoidance of large abdominal incision and reduced pain. However, data from these series showed that even for well-trained surgeons, operative time and aortic clamping time were longer than usually observed during open aortic surgery. Specific operative difficulties were observed with TLAS in treating aortic aneurysmal disease, leading to a higher rate of conversion than with HALS or other laparoscopy assisted techniques (see Table 64.6). Among all series, median blood loss was comparable to that reported for open aortic surgery. Extreme blood loss was observed in some patients with AAA or with AIOD and a severely calcified aorta. Infrarenal circumferential aortic calcifications are not a contraindication for TLAS if suprarenal clamping is possible through a left transperitoneal retrorenal approach. Concerning AAA repair, one small randomized trial with a 12-month follow-up[35] concluded that laparoscopic-assisted (HALS) could be a less invasive alternative for sexually active males who are unsuitable for EVAR. Coggia et al.[5] reported a prospective cohort study of 148 patients undergoing TLAS for juxtarenal AAA repair with no mortality and low morbidity. However, limitations of this study included strict patient selection before TLAS was considered; therefore, it may not be truly applicable to the general population. Ricco et al.[36] published results of a cohort of 228 consecutive cases using propensity score matching comparing the outcomes after open and TLAS for aortic surgery through a composite primary end point of pertinent adverse events (AEs). Logistic regression analysis of the groups adjusted for propensity score showed that only two variables, TLAS (OR 4.50; $P = 0.01$) and coronary artery disease (OR 4.67; $P = 0.02$) were independently related to the occurrence of an AE during the postoperative period. In this study, the occurrence of AEs during follow-up was analyzed using the Cox model and again the same variables, TLAS (HR 4.40; $P = 0.02$) and coronary artery disease (HR 2.70; $P = 0.02$), were independently associated with the occurrence of an AE during follow-up. In this series, the small number of patients prevented a separate analysis with regard to AAA and AIOD. This study suggests that even with a well-trained team, TLAS increases the risk of AEs observed in the course of aortic surgery.

To overcome these technical difficulties, robotic systems have been recommended to facilitate advanced laparoscopic techniques, such as suturing, knot-tying and the performance of aortic anastomosis. Laparoscopy creates a closed space in two-dimensional vision with a dissociation between eye-hand coordination, the robotic technology should compensate for these restrictions with a virtual three-dimensional image, providing improved depth perception compared with traditional laparoscopy. These advantages have improved the ability of surgeons to perform complex operations. Use of the robot allows the surgeon to push the limits of laparoscopy through improved dexterity to perform complex iliac aneurysm procedures in young and healthy patients.[37] Robotics provide a durable solution without the problem of endoleaks with potential reinterventions or parietal complications such as incisional hernia.

We have identified eight studies on robot-assisted laparoscopic aortic surgery (see Table 64.6). The conversion rate ranged from 2.8% for AIOD to 12.7% for AAA, with technical problems related to the robotic system and bleeding from the lumbar arteries. Despite these limitations, robotic assistance goes beyond the making of the aortic anastomosis; robotic techniques allow greater visualization and facilitate aortic dissection. There are several limitations to robotics in laparoscopic aortic surgery, the most obvious being the high cost of the system. In addition, the set-up of the system may be time-consuming before the staff is fully trained. The robotic learning curve seems to be quicker and easier than that of laparoscopic surgery for developing the technical skills to perform an aortic anastomosis.[38] Robotic aortic surgery can also be used to resolve type II endoleaks following EVAR with a mini-invasive technique.[39]

In addition, the postoperative length of stay ranges from 4 to 13 days, with the majority being 6 days or greater, which is comparable to that with open aortic surgery and much longer than that with any endovascular procedure. Furthermore, endovascular procedures can be performed under regional or even local anaesthesia, whereas laparoscopic and robot-assisted procedures require general anaesthesia. Therefore, the development of robotic-assisted aortic laparoscopy has not yet been widely adopted and experience is restricted to a few centers worldwide.

CONCLUSIONS

Our review shows that laparoscopic aortic surgery can be performed safely with low mortality and morbidity provided that patient selection is adjusted to experience and conversion liberally performed. The future of this technique is still unknown, and it is time for multicentre randomized trials to demonstrate the potential benefit of laparoscopic aortic surgery for aortic occlusive and aneurysmal disease not amenable to an endovascular treatment.

SELECTED KEY REFERENCES

Coggia M, Javerliat I, Di Centa I, et al. Total laparoscopic bypass for aortoiliac occlusive lesions: 93-case experience. *J Vasc Surg*. 2004;40(5):899–906.

The authors describe a new technique of total laparoscopic bypass surgery to treat aortoiliac occlusive lesions with 93 total laparoscopic bypass procedures for TASC grade C or D aortoiliac occlusive lesions. The authors used a transperitoneal left retrocolic or retrorenal approach to the infrarenal abdominal aorta. Median operative time was 240 minutes (range, 150–450 minutes). Median aortic clamping time measured to unclamping of the first prosthetic limb was 67.5 minutes (range, 30–135 minutes). Median hospital stay was 7 days (range, 2–57 days). The authors demonstrated the feasibility of total laparoscopic aortic bypass in patients with TASC C and D aortoiliac occlusive lesions.

Dion YM, Katkhouda N, Rouleau C, Aucoin A. Laparoscopy-assisted aortobifemoral bypass. *Surg Laparosc Endosc*. 1993;3(5):425–429.

A seminal paper. The authors described the first case of laparoscopy-assisted aortobifemoral bypass. The patient's postoperative period was uncomplicated; the patient had minimal pain that allowed for a quick return to ambulation. This procedure appeared to be of interest for some patients with aortoiliac disease.

Lucereau B, Thaveau F, Lejay A, et al. Learning curve of robotic-assisted anastomosis: shorter than the laparoscopic technique? An educational study. *Ann Vasc Surg*. 2016;33:39–44.

The da Vinci robot could theoretically minimize the technical challenge of laparoscopic surgery. The aim of this study was to compare the learning curves of performing vascular anastomoses on an expanded polytetrafluoroethylene (ePTFE) abdominal aortic graft as model by trainees with no experience in using laparoscopic versus robotic techniques. The trainees were randomly assigned to the laparoscopic or robotic groups. Minimally invasive laparoscopic technique training demonstrates a learning curve to perform vascular anastomoses. The robotic learning curve seems to be quicker than that of laparoscopic surgery. The robot allowed faster, more accurate, and easier learning of technical skills on the first anastomoses. The authors conclude that robotics may offer the opportunity for surgeons to more easily acquire skills to perform laparoscopic aortic anastomosis and may provide better reproducibility.

Nio D, Diks J, Bemelman WA, et al. Laparoscopic vascular surgery: a systematic review. *Eur J Vasc Endovasc Surg*. 2007;33(3):263–271.

The objective of this early systematic review was to evaluate the results of clinical studies on laparoscopic surgery for aortoiliac disease. Thirty studies were identified. These were all descriptive and included nine comparative studies. Operative times varied widely, the shortest being for hand-assisted procedures and the longest for totally laparoscopic procedures. The conversion rate varied from less than 5% up to 16% in smaller series. The mortality rate was approximately 5%. This systematic review has shown that the observational, noncomparative character and selection bias of most published series are their major limitations. More data are required to define the value of laparoscopic vascular surgery in comparison with endovascular and open surgery.

Ricco JB, Cau J, Biancari F, et al. Outcomes after open and laparoscopic aortic surgery in matched cohorts using propensity score matching. *Eur J Vasc Endovasc Surg*. 2016;52(2):179–188.

This propensity score-matched cohort suggests that even in a well-trained laparoscopic surgical group, a total laparoscopic approach increases the risk of adverse events observed in the course of aortic surgery. This negative result contrasts with those reported in most observational studies, probably because the propensity score avoids the heterogeneity of the previous studies published on this subject and limits the confounding and selection biases.

Stádler P, Dvorácek L, Vitásek P, Matous P. Robot assisted aortic and non-aortic vascular operations. *Eur J Vasc Endovasc Surg*. 2016;52(1):22–28.

This study evaluates the results of a large experience with 310 robot-assisted vascular procedures. The authors demonstrate that robotic systems provide a real opportunity for minimally invasive surgery in the field of vascular surgery. The authors have shown that robotic systems remove fundamental disadvantages of laparoscopy and suggest the possibility of expanding robot-assisted laparoscopic surgery in this area.

A complete reference list can be found online at www.expertconsult.com.

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SECTION 9 GRAFTS AND DEVICES

CHAPTER 65

Autogenous Grafts (Including Vein Harvest, Surgical and Endoscopic)

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Based on a previous edition chapter by Scott A. Berceli

BACKGROUND

Autogenous vein remains the conduit of choice for infrainguinal revascularization and has been shown to be superior to alternatives above and below the knee in patients with claudication and chronic limb-threatening ischemia (CLTI).[1,2] The first report on the use of autogenous vein for the treatment of arterial occlusive disease came in 1944 by Dr. Dos Santos, who performed a vein patch during a superficial femoral endarterectomy, and then soon after by Dr. Kunlin, who utilized reversed great saphenous vein as a conduit to bypass a superficial femoral artery occlusion.[3] Kunlin's techniques were continued in the United States by the likes of Drs. Linton and Darling, who replicated his earlier success with autogenous vein grafting.[4] From there, great saphenous vein use was extended below the knee to tibial and inframalleolar targets. Interest in extending the use of autogenous vein in these locations was furthered by the observation of poor outcomes with prosthetic graft use below the knee.[5] Other autogenous options have been explored including arm vein and small saphenous vein, with mixed results. With these options available, an autogenous conduit is possible in most patients.[6] A detailed review of venous biology including the anatomy of these options as well as the histology and physiology can be found in Chapter 3 (Vessel Wall Biology).

PREOPERATIVE VEIN MAPPING

Preoperative assessment of autogenous vein is essential in planning an arterial reconstruction. Its value has been recognized since the 1970s when preoperative assessment was performed with venography.[7] In the 1980s ultrasound was introduced. Ultrasound offers the advantage of being noninvasive, and also better characterizes vein diameter, depth, and location relative to surrounding structures, while still providing important information on anatomic variation, varicosities, fibrosis, calcification, and areas of extensive branching that may prohibit use as a conduit. With advances in technology and increased familiarity with its use, along with reports on its accuracy and predictive value, ultrasound has become the gold standard in venous imaging.[8–10] In addition to its role in preoperative planning, duplex vein mapping has been shown to decrease the rate of surgical site infection, frequency of readmission, and cost. This is presumably due to avoiding unnecessary or excessive vein exploration.[11,12] CT angiography is sometimes already available for patients being planned for revascularization, and has also been shown to be a reliable method of measuring GSV diameter that correlates well with duplex. CTA has good specificity but relatively poor sensitivity for this indication, therefore if CT shows inadequate vein it should be followed up with an ultrasound exam.[13]

Diameter measurements of the great saphenous vein should be taken from inner wall to inner wall at multiple levels; high thigh near the saphenofemoral junction, mid-thigh, low thigh, knee, high calf, low calf, ankle. Anatomic variation, varicosities, fibrosis, calcification, and areas of extensive branching should be noted.[9]

There are numerous reports on the relationship between vein diameter and graft function, and the minimum acceptable vein diameter for bypass grafting has been debated. In PREVENT III, vein grafts <3 mm (along with non-GSV) were designated as high-risk conduits, comprising 24% of conduits used. These grafts demonstrated 1-year primary and secondary patency rates of 44% and 69%, respectively, as compared to 72% and 87% in grafts with a diameter >3.5 mm.[6,14,15] Wengerter et al. showed superior patency with veins >3 mm compared to those <3 mm (1-year patency rates of 53% and 20%, respectively).[16] In a prospective multicenter study, Buth et al. found that vein diameter <3.5 mm was the only factor that significantly correlated with subsequent graft stenosis.[17] A designation of high risk or sub-optimal becomes relative when considering the alternative options (prosthetic graft, cryopreserved vein) in the open surgical management of patients with CLTI. While inferior, the results in high-risk conduits in PREVENT III still showed reasonable secondary patency of 69% with no difference noted in limb salvage of 84.7% at a year.[15] Slim et al.[8] extended the use of reversed vein to as small as 2 mm in patients with CLTI and they have shown acceptable patency rates. The use of grafts as small as 2 mm has also been reported to be acceptable with *in situ* bypass.[9] These results highlight that with close surveillance and secondary intervention for threatened grafts, successful outcomes are feasible even with marginal conduit diameter.[8] Ultimately, every effort should be made to use an autogenous conduit when feasible. Each patient presents with unique circumstances and the most appropriate conduit will depend on the clinical scenario, patient-specific risks factors, and their anatomy.

VEIN GRAFT PREPARATION

Vein Handling Considerations

As is the case in most areas of surgical technique, precise, atraumatic dissection is critical in vein handling during harvest. Minimal direct handling of the vein helps avoid injury to endothelial cells, which function as a barrier between blood and the highly thrombogenic subendothelial tissue, and also house and produce a number of vasorelaxant, anti-inflammatory, and antithrombotic factors.[18] Traumatic dissection and loss of endothelial integrity can expose subendothelial tissues, which not only induces platelet deposition, but can alter the media and lead to the elaboration of growth factors that cause smooth muscle cell proliferation and production of a fibrous matrix. This environment, coupled with the recruitment of inflammatory mediators, has the potential to develop an occlusive arterial lesion.[19] Study of animal models support this notion by demonstrating that smooth muscle cells are maintained in a contractile (nonproliferative) phenotype and that leukocyte infiltration is reduced when endothelial injury is avoided.[18,20] Direct evidence linking endothelial integrity to improved clinical outcomes is lacking, however given the indirect evidence and limited downside, the general consensus is to strive for precise, atraumatic dissection and minimal direct manipulation of the vein. This can be performed via a “no-touch” technique, which has been demonstrated to reduce endothelial damage during harvest (Fig. 65.1). Though somewhat a misnomer, the “no-touch” technique involves limited handling of the vein without direct application of forceps or vascular clamps. Major branches should be ligated away from the wall to avoid narrowing of the lumen or crimping of the endothelium and to promote outward remodeling after implantation, but not too far away as to leave a long stump, which may be a nidus for thrombus formation.[14,18,19]

Distention Pressure

Cannulation of the vein is required before implantation to evaluate the potential diameter of the graft, assess for leaks, and identify adventitial bands impinging on the lumen. A number of investigations have examined the effect of distention pressure on endothelial integrity and almost uniformly have observed that pressure in excess of 100 mm Hg causes patchy endothelial denudation and that pressure in excess of 500 mm Hg leads to disruption of the media.[21,22] The intrinsic biomechanical properties of the graft are negatively impacted, with a resultant decrease in wall compliance secondary to disruption

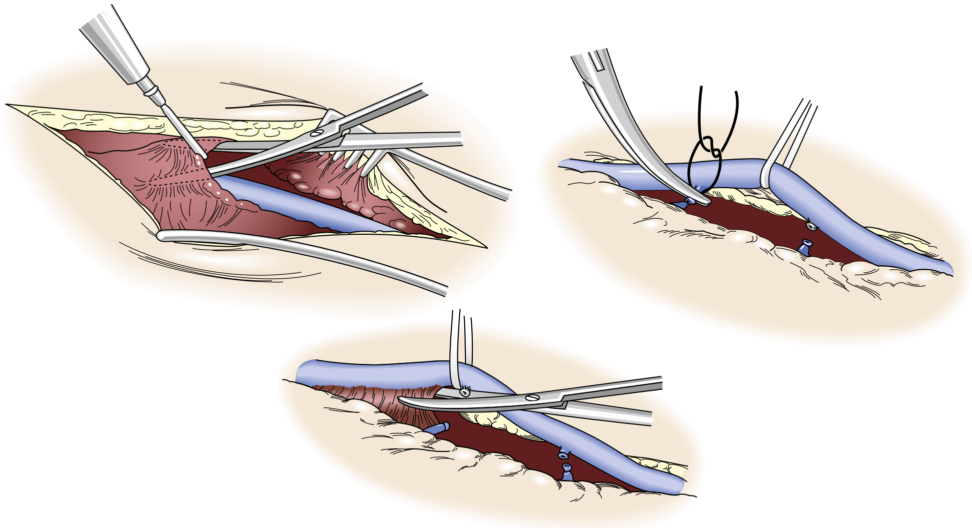


Figure 65.1 **"No-Touch" Technique Used in the Harvest of Autogenous Vein.** Side branches are identified and ligated several millimeters away from the wall to prevent luminal narrowing after implantation and outward remodeling of the vein graft. Using a Silastic vessel loop to control the vein without direct manipulation with surgical instruments, the periadventitial tissues are divided and the vein is excised.

of the elastic elements within the wall.[23] Biologic function is also influenced, with distention injury initiating an increase in *c-fos* expression, an upstream regulator of platelet-derived growth factor production.[24] Use of a standard small-volume syringe can produce intraluminal pressure in excess of 700 mm Hg.[22] A variety of pressure-sensing devices have been developed to allow the surgeon to monitor or control distention pressure. Ranging from syringes with intrinsic pressure transducers to reservoir inflation bulbs that generate a fixed pressure, these devices have undergone only sporadic testing and have not yet been accepted into widespread clinical use. Improving outcomes by minimizing vein graft intimal hyperplasia via external mechanical support or altering the makeup of the vessel wall is an area of ongoing research.[25]

Irrigating Solution

A number of preservation solutions continue to be used for temporary storage after vein harvest, and include crystalloids, autogenous blood, and solutions containing ions for pH buffering with different pharmacologic additives. Current opinions and use of these solutions still vary. The bulk of the literature suggests that unbuffered, isotonic crystalloid solutions are most damaging to the endothelium and can increase the likelihood of graft failure.[18] Simple buffered and modified crystalloid solutions have demonstrated reductions in endothelial denudation and improvements in both cell viability and contractility when compared with an unbuffered solution.[26,27] Using data from PREVENT IV, researchers found that in patients undergoing coronary bypass, veins that were preserved in a buffered solution had a lower likelihood of graft failure at 1 year compared to the saline group (OR 0.59; CI 0.45–0.78; P<0.001) or blood group (OR 0.62; CI 0.46–0.83; P<0.001).[28] For these reasons, buffered crystalloid seems to be the best option for short-term storage of excised vein, however institutional availability, cost, and previous practices vary as evidenced by the high rate of continued use of saline and blood in PREVENT IV, at 44.4% and 32.2%, respectively.[28]

Temperature

With conflicting experimental evidence, delineation of the most favorable storage temperature is difficult, and reasonable arguments for either cold- or room-temperature treatments can be crafted. Although no definitive recommendation can be proposed, the increased effort required to supply and maintain cold perfusate in the operating suite has prompted most clinicians to favor the use of room-temperature solutions.

Pharmacologic Adjuncts

Unfractionated heparin has universally been included in most vein harvest solutions. Aimed at reducing fibrin deposition and the formation of microthrombi, doses ranging from 4 to 10 U/mL are typically used.[29] Pharmacologic agents have been used in vein harvest in an attempt to prevent vasospasm and maintain an intact endothelium. The most widely studied vasodilator for this purpose is papaverine. Percutaneous injection of papaverine (120 mg/L) along the outside of the vein before skin incision has been described as a step to minimize spasm, although this can prove challenging in all but the thinnest patients.[18] Application of papaverine along periadventitial tissues and within the lumen perfusate is more easily accomplished and continued throughout vein harvest. Though not rigorously studied as an independent variable, most regimens containing papaverine have shown reduced endothelial injury in comparison to controls.[18,27] Other vasodilators have been examined, and a combination of glyceryl trinitrate (8.3 mg/L) and verapamil (16.7 mg/L) appears to be particularly beneficial. In direct comparison to papaverine, glyceryl trinitrate/verapamil demonstrated notable improvement in endothelial coverage.[30]

The majority of published regimens have sought to optimize variables to maintain an intact endothelial monolayer or reduce smooth muscle cell injury at the time of implantation; few reports have challenged their techniques to extended exposure in an *in vivo* environment. Among the clinical investigations in this area was the PREVENT III trial, which was a prospective, randomized controlled trial that sought to evaluate the efficacy of an edifoligide, an E2F inhibitor expected to block

BOX 65.1 Recommended Vein Graft Harvest Protocol

Handling

- Precise atraumatic technique
- Ligation of tributaries away from the wall
- Lysis of adventitial bands
- Minimization of time from vein excision to implantation

Solution

- Buffered isotonic crystalloid (e.g., Plasma-Lyte)

Temperature

- No definitive recommendation

Distention

- Maximum pressure of 100–150 mm Hg

Pharmacologic Adjuncts

- Heparin (4000–10,000 U/L)
- Papaverine (120 mg/L) or glyceryl trinitrate (8.3 mg/L)/verapamil (16.7 mg/L)

cellular proliferation, in improving vein graft patency following infrainguinal revascularization for CLTI. Ultimately, they concluded that treatment of vein grafts with the E2F inhibitor prior to bypass did not confer protection from clinically meaningful outcomes such as reintervention for graft failure.[6,31]

Though extensive research has been conducted in this area, no consensus has been reached regarding the optimal techniques for vein graft harvest, with each variable demonstrating unique advantages and shortcomings. Box 65.1 provides a practical summary protocol for the preparation of autogenous vein conduit.

ENDOSCOPIC AND MINIMALLY INVASIVE VEIN HARVEST

Among the complications associated with a single continuous incision for lower extremity vein harvest are wound infection and dehiscence, which can lead to significant morbidity. Minimally invasive approaches to saphenous vein harvest have been developed to reduce incisional length and diminish the associated morbidity. Early investigations of this technique were with series of small, sequential incisions overlying the vein. The use of such “skip incisions” significantly improved primary wound healing, with wound complications developing in 28% of patients with a continuous incision, as opposed to 9.6% of patients in the “skip incision” group.[32] The concept has evolved with the availability of endoscopic visualization and specialized instrumentation to facilitate an even less invasive vein harvest. Several different devices have been developed for this purpose, all using the basic concept of three small incisions in order to access the vein, ligate side branches through the access point, and then ligate the vein proximally and distally before removing it. Additional incisions are utilized as necessary in order to free up any vein branches not accessible during endoscopic harvest or to release troublesome adherent fibrous bands. Used predominantly for harvesting of vein for coronary bypass surgery, prospective randomized human trials have demonstrated significant reductions in wound morbidity when compared with single-incision saphenectomy,[33–35] Increased manipulation of the vein is typical with this approach, and this raises concern about increased endothelial damage and accelerated graft failure. Blinded morphologic examination of harvested human vein specimens and clinical outcome studies have demonstrated no significant differences in vein injury or graft patency.[35–37]

Probably related to the long segments of vein required for lower extremity bypass and the prolonged learning curve inherent in this approach, endoscopic vein harvest for peripheral revascularization has not been uniformly embraced. A small number of centers have championed its use, with mixed results. With no randomized trials comparing single-incision with endoscopic saphenous vein harvest for peripheral bypass, experiences have predominantly been reported through case series with retrospective controls.[38–41] These reports generally support the observations in the cardiac literature and suggest that endoscopic harvest offers reduced wound complications with no notable deterioration in short- and long-term graft patency or limb salvage. Not all reports have been favorable, however, with some teams detailing inferior patency rates with little improvement in wound complications after endoscopic or minimally invasive vein harvest.[42,43] Compilation across centers, within the context of the Vascular Quality Initiative database and a meta-analysis of 18 published studies, has underscored this observation, where the primary patency was reduced in patients undergoing endoscopic harvest (vs. either continuous or skip incision techniques) with no associated improvement in the incidence of surgical site infection.[44,45]

Among the important conclusions in these studies is the significant learning curve inherent in this technique, some suggesting up to 100 cases necessary to become proficient.[39,46] There are some concerns about increased cost of the procedure secondary to additional equipment expenses, however these are likely more than offset by decreased length of stay during the primary admission and a reduction in the number of readmissions for wound complications.[47] In the absence of a prospective randomized controlled trial it is not clear which technique is superior, but it seems that in experienced hands the outcomes are comparable.

AUTOGENOUS GRAFT CONFIGURATIONS

Reversed Vein Grafts

Excision of the vein with orientation in a reversed configuration while maintaining antegrade flow through intact valves offers the most straightforward method for vein graft implantation and is suitable for most clinical situations. Difficulty may arise when significant tapering of the saphenous vein in the distal part of the limb creates a size mismatch between the artery and vein graft at both the proximal and distal anastomoses.

The proximal vein graft appears to be a common site for luminal narrowing and vein graft failure, and use of small-diameter conduit at this location may accentuate this problem.[48] The size mismatch can be most problematic, and anastomoses most challenging, however, when performing a tibial or pedal artery anastomosis, where significant differences in diameters may be encountered. If the mismatch cannot be overcome by tailoring the vein graft, the valves may be lysed and the vein graft implanted in a nonreversed fashion.

Nonreversed Vein Grafts

The most common challenge in performing a reversed-configuration vein graft is significant proximal-to-distal tapering of a vein and the resulting size mismatch at the proximal and/or distal anastomoses. The combination of complete excision of the vein, lysis of the valves, and orientation in a nonreversed configuration offers a solution to this issue. Although this requires increased manipulation with the potential for injury during valve lysis, it has proved to be as durable as others, and some feel this shortcoming is offset by a potential improvement in vein graft biology and subsequent hemodynamics via valve disruption.[49–52] In the low-flow, non-pulsatile hemodynamic environment that normally characterizes the superficial venous system, the mild to moderate stenosis created by partially open valves does not translate into a significant loss of pressure or impediment to flow. After implantation into the arterial system, the hemodynamic significance of the valves becomes more pronounced. Though not significantly narrowing the lumen during peak systole, a transition to turbulence with localized regions of stasis is noted within valves.[53] Lysis of valves has been shown to lead to a 15% decrease in resistance and a 15%–30% increase in graft flow.[54,55] Intact valves may also serve as a nidus for the development of a hyperplastic lesion. Vesti et al. prospectively evaluated long-term remodeling of valves in reversed and nonreversed saphenous vein grafts and found that only 2.5% of these grafts progressed to a critical stenosis requiring operative intervention, all of which occurred in reversed grafts with intact valves. Despite this, they found that valve morphology may be dynamic, with 60% of the hemodynamically significant valve lesions showing regression to less than 20% stenosis in a mean period of 3 months. No specific valve features were identified as high risk for graft failure.[56] Long-term valve remodeling and diameter mismatch remain the most common reasons to use a nonreversed conduit.

In Situ Vein Grafts

The concept of using the great saphenous vein as a graft with mobilization of only the proximal and distal segments while maintaining the interval region within its subcutaneous bed was initially suggested by Rob's group in the 1950s.[57] In general, this technique involves three key steps: (1) mobilization of the proximal and distal segments for construction of the anastomoses, (2) removal of the valvular obstructions to arterial flow, and (3) interruption of the venous side branches to prevent the formation of hemodynamically significant arteriovenous fistulae. Early success and widespread use were most limited by the technique of valve excision, which was initially performed by opening the valve at multiple locations and lysing the valves. The development of efficient instrumentation for valve lysis provided the opportunity to reduce vein manipulation and maintain an intact vasa vasorum and fueled renewed enthusiasm for the *in situ* approach.[57] In a large single center series, Shah et al. reported cumulative secondary patency rates of 91%, 81%, and 70% at 1, 5, and 10 years, respectively, with limb salvage rates of 97%, 95%, and 90% at 1, 5, and 10 years, respectively, using *in situ* vein grafts.[49] Contemporary comparisons of *in situ* versus reversed or nonreversed grafts show no significant differences in long-term outcomes.[58]

Proximal and Distal Anastomoses

The common femoral artery serves as the most common source of inflow for infrainguinal revascularization, and the relative position of this artery and the confluence of the saphenofemoral junction dictates construction of the proximal anastomosis. Mobilization of the proximal great saphenous vein is accomplished by ligation of the superficial branches, placement of a side-biting vascular clamp across the common femoral vein, transection of the great saphenous vein flush with the wall, and repair of the femoral vein with running nonabsorbable suture. Lysis of the most proximal great saphenous valve can be difficult with standard valvulotomes, but localized eversion of this segment permits excision of the valve under direct vision. Intrinsic atherosclerotic disease in the common femoral artery may dictate more proximal placement of the anastomosis. Additional proximal vein length can be obtained by harvesting a segment of the superficial epigastric vein and extending the venotomy proximally along the posterior surface of this vein to provide an autologous patch for repair of proximal common femoral artery disease. Extensive common femoral or profunda femoris origin disease may necessitate endarterectomy with patch angioplasty or graft replacement of the common femoral artery. In the absence of significant proximal artery occlusive disease, defined as greater than a 50% reduction in lumen diameter, the superficial femoral, profunda femoris, or popliteal artery can be used for placement of the proximal anastomosis.

The posterior tibial, peroneal, and dorsalis pedis arteries provide the most straightforward options for placement of the distal anastomosis. Although the below-knee popliteal artery can also be used, fashioning the anastomosis can be problematic because of the nearly 90-degree angle that is formed between the graft and artery. With most hemodynamic analyses detailing an increase in flow separation and activation of proliferative metabolic pathways with right-angle anastomoses, grafts configured to this segment of the popliteal artery may benefit from excision and placement in an anatomic tunnel. Distal anastomoses to the above-knee popliteal artery do not offer the same constraints on their configuration; however, after mobilization of the proximal and distal graft, the segment that remains *in situ* can be quite short and of limited benefit.

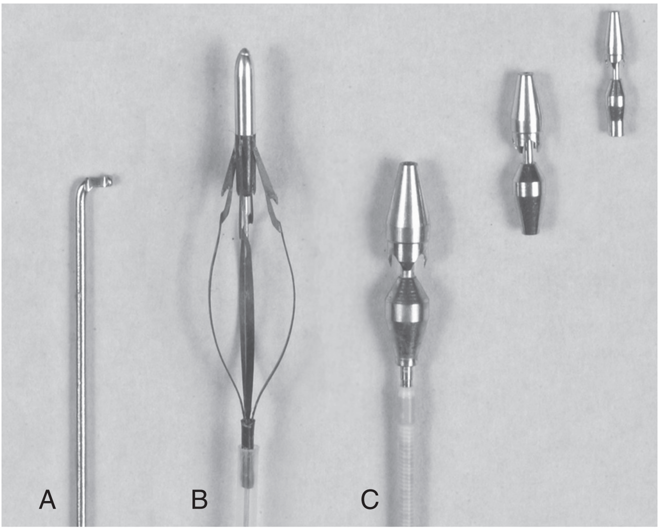


Figure 65.2 **Valvulotomes.** (**A**) Modified Mills. (**B**) LeMaitre adjustable. (**C**) Uresil fixed with 2-, 3-, and 4-mm cutting heads.

Valve Lysis

Valvulotomes have undergone a variety of revisions over the last several decades, and the current generation of devices can be classified into three categories – the modified Mills valvulotome, the adjustable valvulotome, and the fixed valvulotome (Fig. 65.2). The modified Mills valvulotome (see Fig. 65.2A) was initially described in 1976 for application to coronary artery bypass surgery.[59] With limited modification, this device was rapidly adopted for use in peripheral vascular surgery. Introduced into a side branch or the distal end of the vein, the device is advanced through the valve leaflets (Fig. 65.3). The proximal vein graft is distended by arterial inflow or manual infusion to induce valve closure, and the valvulotome is slowly withdrawn until the reverse cutting blade engages the valve leaflet. The tip of the valvulotome is maneuvered toward the center of the lumen, and a short burst of inferior traction is applied to transect the valve.[57]

Popularized by LeMaitre and Arakelian the expandable valvulotome offers four cutting blades encompassed within a self-centering series of wire hoops (see Fig. 65.2).[60] With the blades encased in a protective sheath, the device is advanced to the proximal end of the vein graft. The vein is distended, the cutting system deployed, and the device slowly withdrawn. Because of the mobility of the wire hoops, the position of the cutting blades is self-adjusting to accommodate vein diameters between 1.8 and 6 mm.

Fixed-diameter valvulotomes were developed from the original work of Hall, in which a blunt-tipped vein stripper was passed proximally to distally through the graft to avulse the valve leaflets and render them incompetent.[61] The addition of cutting blades and detachable heads of varying size led to the current generation of devices (see Fig. 65.2C).[62] A 2-, 3-, or 4-mm head is secured to a flexible shaft and reintroduced into the lumen of the vein. As with the other devices, the proximal vein is distended and the valves are lysed with a rapid burst of inferior traction.

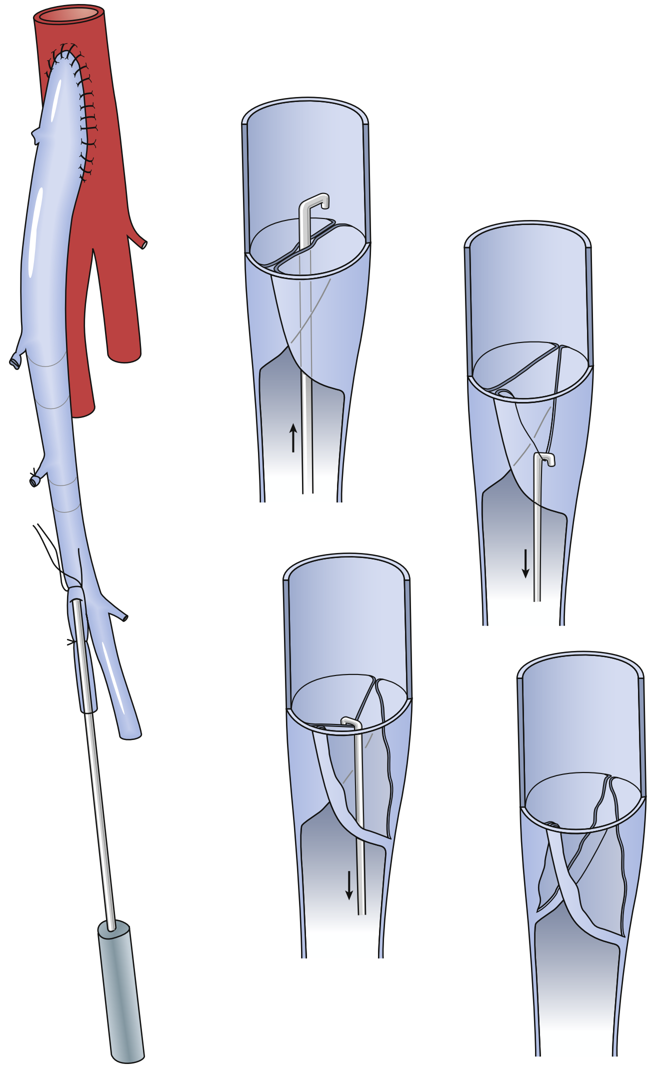


Figure 65.3 **Valve Lysis Using the Modified Mills Valvulotome.** The valvulotome is inserted into a long side branch and advanced into the proximal vein. Competent valves within the graft are maintained in closed position by arterial inflow pressure, and the valvulotome is withdrawn until resistance is encountered. After ensuring that the instrument has not engaged a side branch, a short burst of inferior traction is delivered and the valve leaflet transected. Short advancement and 180-degree rotation of the valvulotome permit division of the opposite valve in analogous fashion.

Visualization studies after the application of valvulotomes report that complete disruption occurs in approximately 70% to 95% of the treated valve leaflets.[63,64] Proximal segments of the vein, where the size mismatch is most pronounced, are most likely to demonstrate only partial valve disruption; thus careful attention to this region seems warranted.[63] There are a few studies comparing these devices directly, and in general there seems to be no significant differences in patency.[65]

Side Branch Ligation

Without the need to mobilize the vein from its subcutaneous bed, multiple options are available for treatment of the venous side branches. The standard approach is complete exposure of the great saphenous vein with a single continuous

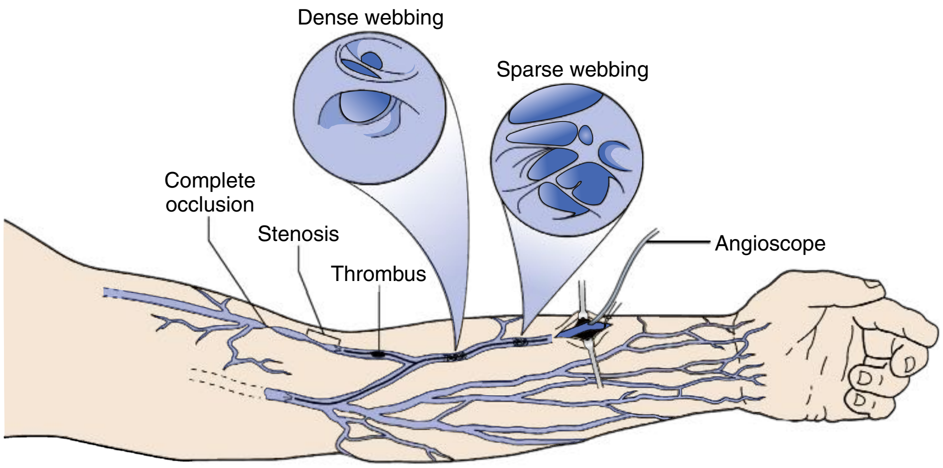


Figure 65.4 Iatrogenic injury to upper extremity veins leading to stenosis or segmental occlusion is common. Although preoperative duplex vein mapping can be helpful, intraoperative angioscopy offers the potential for precise localization of those compromised areas.

incision that extends the length of the leg. Although this open approach simplifies side branch ligation and valve lysis; it has been associated with a wound complication rate in excess of 40% in some reported series.[66] Noninvasive identification of the major side branches offers the opportunity for a limited-incision or semi-closed *in situ* technique. Intraoperative venography and duplex scanning with marking of major side branches are two readily available options for this task, but these methods can be surprisingly inaccurate and fail to recognize almost 50% of the side branches. Using an angioscope to identify the orifice and transcutaneous illumination to guide the location of the skin incision has proved somewhat more successful, with detection of approximately two-thirds of patent side branches.[67] Graft patency rates are relatively unaffected by complete vein exposure or skip incisions, but an increased incidence of persistent arteriovenous fistulae has been documented with most semi-closed techniques. Studies examining persistent fistulae have generally recommended their ligation; however, such an aggressive approach has been called into question. Conservative management of these fistulae results in spontaneous closure in a third of cases, with eventual revision for reduced distal graft velocity in a third, and a third remaining stable without intervention.[68,69]

OTHER AUTOGENOUS CONDUITS

Arm Vein

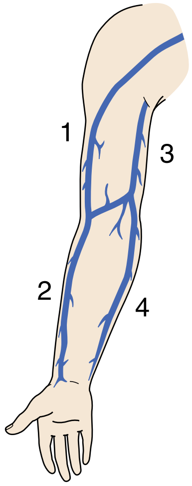
Use of single-segment or composite arm grafts provides an important alternative in patients in which great saphenous vein conduit is unavailable. The most extensive experience with arm vein conduit use for lower extremity bypass is detailed through a series of reports from the Beth Israel Deaconess Hospital.[70–72] Preoperative duplex evaluation of the upper extremity veins is critical in the operative planning for patients with inadequate or previously harvested ipsilateral saphenous vein. To take advantage of the larger veins in the upper part of the arm, the basilic–cephalic loop graft has been proposed.[73] Using the median cubital vein as the connecting segment, the cephalic and basilic veins are harvested in a continuous loop from the antecubital fossa to their termination in the axillary vein.

Similar to the approach when using lower extremity veins, single-segment arm vein is preferable. Through extensive use of the median antecubital vein as a bridge, success can be achieved in up to 80% of cases requiring the use of arm vein.[70] Limiting this effort, however, is the inherent iatrogenic injury that occurs from repeated cannulation in this area (Fig. 65.4). Veins that are most superficial and anatomically accessible, such as the forearm cephalic and median antecubital, are most frequently damaged, with 30% to 50% of these veins demonstrating a variety of pathologies.[74] For this reason, the use of angioscopy in the assessment of arm veins offers distinct advantages in assessing conduit quality and the potential need for excluding a segment that has extensive webbing or related to prior cannulations. A summary of the advantages and disadvantages of available arm vein conduits, along with an estimate of their relative frequency of use, is provided in Figure 65.5.[70]

Small Saphenous Vein

Although much shorter than the great saphenous vein, the small saphenous vein can be a useful source of autogenous conduit in the vein-limited patient. Arising from tributaries lateral to the calcaneus and terminating in the popliteal fossa at the saphenopopliteal junction, this conduit is predominantly used in combination with other vein segments in a composite configuration but can also be used as a single segment. Preoperative duplex evaluation is critical to evaluate adequacy, with a lumen diameter of at least 3.0 mm generally considered suitable for grafting. Small saphenous vein is usually the third choice of autogenous vein (behind great saphenous and arm vein) because of the inherent difficulties in surgical exposure and harvest. Options for exposure include the development of a subfascial plane along the enveloping fascia of the superficial posterior compartment, or a posterior leg incision.[75–80]

Patients with isolated tibial artery occlusive disease may be candidates for *in situ* bypass using the small saphenous vein. Employing a posterior approach for exposure of the proximal and distal anastomotic sites, popliteal–crural bypasses to each



Upper extremity vein segment	Frequency of use	Comment
1. Cephalic vein (arm)	70%	Uniform diameter 4–6 mm Implant reversed due to thin walls for lysis Can be harvested within the deltopectoral groove
2. Cephalic vein (forearm)	45%	Intraluminal webs and phlebitis common Wall thickness adequate for valve lysis
3. Basilic vein (arm)	50%	Significant diameter change along the length Valve lysis difficult due to large proximal diameter Located subfascial in its proximal portion
4. Basilic vein (forearm)	2%	Smallest caliber of the upper extremity veins Posterior position minimizes previous iatrogenic injury

Figure 65.5 Superficial upper extremity veins available for use in bypass grafting, including individual considerations and relative frequency of their use. (From Hölzenbein TJ, Pomposelli FB Jr, Miller A, et al. Results of a policy with arm veins used as the first alternative to an unavailable ipsilateral greater saphenous vein for infrainguinal bypass. *J Vasc Surg*. 1996;23(1):130–140.)

of the three tibial arteries can be performed. Cumulative 1- and 3-year primary patency for these grafts has been reported at 75% and 60%, respectively, approximating the same results observed with *in situ* grafting using the great saphenous vein.[78–80] The durability of small saphenous vein used in a composite fashion is notably inferior, with 1- and 3-year primary patency reported at 50% and 35%, respectively.[79]

Femoral–Popliteal Vein

Although primarily used for intraabdominal vascular reconstructions in most current day treatment algorithms, the femoral–popliteal vein was initially investigated as the potential conduit of choice for lower extremity bypass procedures.[81–83] With promising results demonstrated in a retrospective review of their clinical practice, Schulman et al. initiated a prospective, randomized trial comparing autogenous femoral–popliteal vein to saphenous vein as the preferred conduit for infrainguinal bypass.[81] Based on a total enrollment approaching 100 patients, no significant differences in 5-year primary patency (55%) or limb salvage rates (70%) were observed. Thirty-day mortality and early postoperative complications were also similar in both groups. Follow-up examination to evaluate the long-term sequelae of deep vein harvest demonstrated chronic calf swelling and an obstructive pattern on venous plethysmography, but no significant increase in stasis dermatitis or venous ulceration.[84] Although no objective differences were observed between the femoral–popliteal and saphenous vein groups, the authors concluded that the increased complexity associated with femoral vein harvest made the saphenous vein the preferred conduit for lower extremity revascularization.

Superficial Femoral Artery

Patency of an occluded segment of excised superficial femoral artery can be restored via an eversion endarterectomy, providing an autogenous conduit that is suitable for short interposition or composite grafting.[85] Although conceptually these conduits were thought to be useful in the salvage of patients with prosthetic graft infection, rupture of the anastomosis was observed in 75% of those grafts placed in an infected field.[86] When used in combination with an autogenous vein, patency rates for these composite grafts have demonstrated marginal 1-year primary patency rates (60%).[86,87] Frequently the mechanism of failure for these conduits was acute thrombosis in the absence of a stenotic lesion, which is different from what is usually seen in autogenous vein grafts.[87]

Hypogastric Artery

Facilitated by the rich collateral network in the pelvis, the hypogastric artery offers an available source of autogenous conduit for short segment, intraabdominal reconstructions. With a cascade of associated branches, this graft offers the ability to create several distal anastomoses from the primary graft, an advantageous configuration for use in complex aortic reconstructions. Although historically it has been used sporadically in the adult population, this segment of artery is the conduit of choice for renovascular reconstructions in the pediatric population.[88–90] Autogenous vein is less commonly used in pediatric patients because of the propensity for late aneurysmal dilation. Although no detailed analysis of hypogastric artery patency has been performed, these anecdotal experiences across multiple centers support its use.[89,90]

AUTOGENOUS GRAFT FAILURE

Broadly speaking, vein graft failure can be split into three categories; early (0–30 days), midterm (30 days–2 years), and late graft failures (beyond 2 years). In general, early graft failure is attributable to technical factors, intermediate graft failure to intimal hyperplasia, and late graft failure is felt to be the result of recurrence or progression of atherosclerotic disease.

Early Graft Failure

Graft failures within 30 days are thought to be technical if they are associated with one of four categories: inadequate inflow, inadequate outflow, extrinsic lesions, and intrinsic lesions. The incidence of early failure is about 5%.[6,31] Inadequate inflow may be secondary to an unrecognized lesion in the proximal arteries or inflow graft. More common is the scenario in which the importance of the proximal lesion is underestimated, only to have its hemodynamic significance unmasked after placement of the distal graft. The resulting increase in flow leads to an accentuated drop in pressure across the lesion and converts a previously innocuous lesion into one that now has important hemodynamic implications. Cardiovascular compromise, such as systemic hypotension or a low cardiac output state can also be the cause of inflow-related graft failure. Inadequate outflow as a result of extensive, preexisting tibial and inframalleolar occlusive disease is an established risk factor for early graft failure.[91] Extrinsic causes of early graft failure include compression from tunneling errors, compressive hematoma, hypercoagulability, or other systemic factors. Intrinsic vein graft defects include endothelial damage, focal, flow-limiting lesions such as a retained valve leaflet, an intimal flap, or inappropriate placement of anastomotic sutures. Limitations in flow can result from the use of an undersized conduit, as previously discussed. Independent of luminal narrowing, intrinsic vein graft defects, such as sclerosis and calcification, also contribute to graft thrombosis.[92] Early graft failure is typically managed with open exploration and revision to treat the underlying cause, with good outcomes including 90% 1-year patency reported.[93]

Midterm Graft Failure

Surgical manipulation of the vein combined with the exposure to elevated shear and tensile forces elicits a complex series of biologic events in the vein wall that begins immediately on implantation. Repair of the damaged vein graft is initiated by the local synthesis of a wide variety of cytokines and growth factors. Chemokines induce the recruitment of neutrophils and mononuclear cells, which further amplifies these pathways. Activated by these chemoattractants and mitogens, smooth muscle cells begin to dedifferentiate from a contractile to a synthetic phenotype and replicate within the media. By tracing the gradient of chemokines, liberated smooth muscle cells migrate from the media to the intima, where continued proliferation and abundant matrix deposition are stimulated. Progressive thickening of the intima can lead to narrowing of the lumen, a reduction in graft flow, and intraluminal thrombosis (Fig. 65.6).

Despite the relative uniformity of the surgical trauma and hemodynamic insult, vein graft lesions demonstrate a strong tendency to be focal rather than diffuse.[94] Up to 30% of autogenous grafts will fail or require revision secondary to significant narrowing of the lumen within 2 years.[6,95] Stenotic lesions are more likely to be associated with the proximal or distal anastomosis but occur not infrequently in the midbody of the graft.[48] It has been postulated that midgraft lesions are associated with valve leaflets; detailed evaluation of this issue

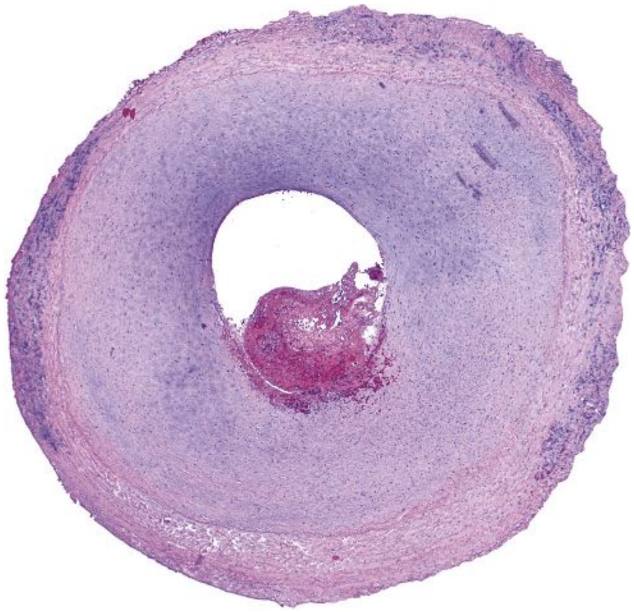


Figure 65.6 Cross-sectional histologic image of an 8-month-old vein graft demonstrating severe intimal hyperplasia. Adherent thrombus is present within the severely compromised lumen.

demonstrated substantial remodeling within valve sites, but progression to high-grade stenosis was rare and accounted for less than 20% of intrinsic graft lesions requiring repair.[56] Using CT angiography to study adaptation and remodeling in the form of cross-sectional area throughout the length of 56 vein grafts, He et al. found cross-sectional area was heterogenous throughout the graft and dynamic during follow-up. Certain parameters including black race and initial lumen diameter were associated with negative, inward remodeling while others, namely cilostazol use, were associated with outward remodeling.[96] The underlying biologic mechanisms for development of this segmental pattern of intimal hyperplasia remain poorly understood. Although the local flow environment plays a significant role, physical forces in isolation fail to explain these observations. More likely, critical lesion development occurs at the intersection of localized trauma, ongoing hemodynamic stress, an altered ability for local repair after injury and is influenced by patient-specific clinical factors such as race, specific medications, smoking status, and degree of ischemia and infection at the time of surgery.[96,97]

Late Graft Failure

Although the peak incidence of vein graft failure occurs within the first year, delayed progression of intrinsic lesions can lead to ongoing loss of graft patency. This is commonly attributed to progression of the atherosclerotic disease process, which can occur in the inflow vessel, outflow vessels, or develop in some form within the graft itself. Insight into the pathology of delayed lesion development in peripheral vein grafts is limited and most of our understanding is derived from coronary bypass grafts examined at the time of autopsy.[98] Histologically, there is replacement of the fibrotic wall with lipid-laden macrophages and intramural calcification is common.[99–101] Degeneration of the vein graft wall with intramural thrombus formation, characteristic of ruptured atherosclerotic plaque, is also described.[102] Supporting these observations is the clinical impact of lipid-lowering therapy on coronary artery graft patency, where reductions in total serum LDL significantly enhance vein graft durability.[103] Examination of these events in peripheral bypass grafts is limited to the analysis of sporadic samples obtained at the time of graft revision. An initial report published by Szilagyi et al. in 1973 identified atherosclerotic changes in 8 of 21 grafts ranging in age from 8 to 96 months.[94] These observations are supported by Walton et al., who described apolipoprotein B deposits, ulceration, calcification, and aneurysm formation in the majority of failed grafts that had been implanted for more than 2 years.[104] Other reports present a more variable picture and predominantly describe a fibrocellular hyperplastic intima with rare atherosclerotic degeneration as the cause of late failure.[105] Although investigators have speculated that modulation of early intimal hyperplasia will have an impact on cholesterol-driven atherogenesis and provide an avenue to improve graft patency, this view remains speculative with limited data to support it. Surveillance remains an important method of studying vein grafts over time and identifying those at risk for failure.

Autogenous Graft Modifications to Improve Durability

The prevailing concept in vein graft biology has been that the initial stages of adaptation are critical in defining the long-term future of the conduit. Specifically, it has been hypothesized that inhibition of the early wave of smooth muscle cell proliferation would mitigate the development of stenotic lesions following implantation. Emanating from this strategy, edifoligide emerged as a promising approach to improve vein graft durability. The regulation of cell cycle kinetics and DNA replication are under the control of the E2F pathway, and the double-stranded oligodeoxynucleotide edifoligide was designed to bind and inactivate the E2F family of transcription factors. Applied to the harvested vein, this therapeutic agent was developed to inhibit the burst of smooth muscle cell proliferation that is initiated in the first several days following implantation. Two phase III clinical trials have investigated the use of edifoligide in infrainguinal and coronary artery revascularization. Following randomization of 4400 patients, treatment with edifoligide was demonstrated to have no influence on vein bypass graft durability.[6,28] Although these were landmark trials in their attempts to directly modulate the biology of an implanted vein graft, the lack of a significant clinical effect has led to a reassessment of the fundamental paradigms in the field and the current wave of investigative research.

GRAFT ASSESSMENT

Intraoperative Graft Assessment

In general, technical adequacy can be judged intraoperatively by the external appearance of the graft, each anastomosis and by the quality of distal pulses or signals with continuous wave Doppler. If these results are not satisfactory, a more detailed assessment to ensure technical success and to optimize short- and intermediate-term graft patency has been advocated and most commonly is performed with contrast-enhanced angiography. Duplex scanning has developed into the next most commonly used intraoperative method for evaluation of vein grafts. Selective versus routine intraoperative completion imaging varies by practice, and there is no consensus as to whether this makes a difference in outcomes. Other described means of intraoperative assessment include angioscopy, intravascular ultrasound, pressure measurements, plethysmography, photoplethysmography, and transcutaneous oxygen measurement. More information and discussion of prevention of graft failure by intraoperative assessment can be found in Chapter 48 (Graft Thrombosis).

Postoperative Management, Surveillance

Although vein grafts remain the gold standard, they are at risk for failure and development of complications. For this reason, the concept of surveillance has been used in an attempt to periodically evaluate grafts and identify high-risk lesions before graft failure occurs. Physical examination with physiologic assessment of distal perfusion are the key components of surveillance. Patient history is elicited to detect new onset of claudication or ischemic pain at rest, and physical examination is performed to identify notable changes in the lower extremity pulse. The ankle–brachial index (ABI) is used as the quantitative measure of perfusion. A successful postoperative ABI is considered to be >0.9 or an increase in 0.15 from baseline. On surveillance, a reduction of >0.15 is considered significant. Duplex is commonly utilized in surveillance protocols. The utility of duplex comes from the measurement of flow velocities and peak systolic velocity (PSV) within the graft. A normal PSV is >45 cm/s, with low resistance outflow waveforms. A focal increase in PSV can be used to calculate a velocity ratio (Vr), which is the PSV at the stenosis relative to that in a normal proximal graft segment. Grafts at increased risk for failure are classified as having a focal increased PSV between 180 and 300 cm/s, with a Vr of 2–3.5. The highest risk grafts have a focal PSV >300 cm/s and a Vr of >3.5, with graft PSV <45 cm/s. Changes in any of these parameters as outlined should prompt further evaluation to identify the lesion or lesions that have precipitated the hemodynamic deterioration.[106,107]

Whether or not duplex offers an additional benefit remains unclear. A number of retrospective case series have shown duplex surveillance is associated with improvement in primary assisted patency.[108,109] A prospective randomized controlled trial supported these findings, showing improvement in assisted primary and secondary patency in duplex surveilled grafts (78%, 82%) as compared to non-surveilled grafts (53%, 56%).[110] On the other hand, numerous studies, including randomized controlled trials and a recent meta-analysis have failed to demonstrate any difference in patency, limb salvage, or mortality between exams with ABI and the addition of duplex ultrasound.[91,93,94,107,111] A systematic review and meta-analysis as well as the current Society for Vascular Surgery

(SVS) clinical practice guidelines maintain that evidence supporting duplex surveillance of infrainguinal vein grafts is low quality. Despite this, duplex ultrasound provides an opportunity for early detection of threatened grafts, is noninvasive, and relatively low cost. With this in mind, the current SVS guidelines recommend clinical examination, ABI, and duplex ultrasound for infrainguinal vein graft surveillance on a schedule of early postoperative, 3, 6, and 12 months, and annually thereafter.[106]

Evidence regarding the ideal antithrombotic regimen after autogenous bypass is limited. Vascular Quality Initiative registry data looking at the relationship between oral anticoagulants and patency of infrapopliteal bypass grafts found no difference in primary autogenous graft patency with anticoagulants, either alone, or in combination with aspirin.[112] Current SVS guidelines recommend antiplatelet therapy, with no recommendation for routine use of anticoagulation.[113]

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66 CHAPTER

Prosthetic Grafts

RICHARD F. NEVILLE

INTRODUCTION

Arthur Voorhees and colleagues first described the use of a prosthetic graft to bridge arterial defects in 1952.[1] Since then, numerous advances have been made in fabric technologies, and a large variety of prosthetic grafts are currently available on the market. Currently, vascular surgeons use prosthetic grafts for several different indications, including aortic aneurysm repair, arterial bypass in the upper and lower extremities, and dialysis access creation.

Prosthetic grafts can play an important role in the management of vascular disease for those patients who do not have adequate autogenous conduit. Although surgical bypass with autogenous vein has a well-established record with documented long-term patency rates, a growing proportion of patients needing bypass surgery lack suitable autogenous venous conduit.[2,3] Reasons for this include previous harvesting of the veins for coronary artery bypass or prior lower extremity revascularization procedures, small vein caliber, active infection at the vein harvest site, and vein varicosities or thrombosis.

The advent of endovascular technology has resulted in a corresponding reduction in the number of surgical bypasses performed in patients with arterial occlusive disease, with a concomitant increase in the complexity of patients that do require bypass such as the scenario of failed endovascular intervention.[4] As such, lower extremity bypass with a prosthetic conduit continues to serve as a therapeutic choice in the revascularization of patients with limb ischemia.

BASIC PRINCIPLES

Materials

The ideal prosthetic conduit would be impermeable, compliant, biocompatible, durable, easy to sterilize, facile to implant, available in different sizes, resistant to thrombosis and infection, and cost-effective. Properties such as surface electronegativity, graft porosity, endothelial seeding, and heparin bonding have all been evaluated for their potential to improve graft function. Electronegativity on the graft surface plays a role in the inhibition of platelet aggregation with theoretic enhancement of this property by carbon coating of the luminal surface of the graft. Graft porosity has not been shown to significantly affect the rate of graft thrombosis but may be implicated in tissue ingrowth. Currently, the most commonly used prosthetic materials for revascularization surgery are Dacron and expanded polytetrafluoroethylene (ePTFE), although there are several commercially available graft materials (Table 66.1).

Dacron

British chemists Whinfield and Dickinson developed the polyester fabric Dacron in 1941, and it is one of the oldest continuously used fabrics on the market.[5,6] Dacron grafts can be knitted or woven and can also be reinforced by external rings for support (Fig. 66.1). Knitted grafts have the advantage of better compliance but have larger pores that tend to leak and require pre-clotting. As such, modern versions of knitted Dacron grafts

TABLE 66.1 Selected Commercially Available Vascular Grafts in the United States

Material Type	Company	Product	Description
Standard			
ePTFE	Angiotech/Edwards Life Sciences (Irvine, CA)	Lifespan	Re-enforced
	Atrium Medical Corporation (Hudson, NH)	Advanta VXT	Softwrap technology
		Advanta SST	Trilaminate, allows pulsation
		Advanta VS	60/20-μm through-pore design
		Flixene	Laminated with biomaterial film
	Bard Peripheral Vascular, Inc. (Tempe, AZ)	Impra CenterFlex	Unmodified
	Boston Scientific (Natick, MA)	Exxcel Soft Vascular Graft	Unmodified
	B. Braun (Melsungen, Germany)	VascuGraft	Unmodified
	Vascutek, Ltd. (Renfrewshire, United Kingdom)	Maxiflo Ultrathin	Thin wall, external ePTFE wrap
		Maxiflo Wrap	Regular wall, external ePTFE wrap
	W.L. Gore & Associates Inc. (Flagstaff, AZ)	Gore-Tex	Unmodified
		Gore-Tex Stretch	Stretch
		Gore Intering	Unibody, intrawall radially supported
Dacron	Braun	Protegraft	Knitted, double velour
	InterVascular, Inc. (Mahwah, NJ)	InterGard Ultrathin	Unmodified
	Vascutek, Ltd.	VP1200K	Unmodified
Sealed			
ePTFE	Vascutek, Ltd.	SealPTFE Ultrathin	Gelatin sealed, thin wall
		SealPTFE Wrap	Gelatin sealed, regular wall
		Taperflo	Gelatin sealed, tapered
Dacron	Atrium Medical Corporation	Ultramax	Knitted, gelatin sealed, double velour
	Bard Peripheral Vascular, Inc.	Vasculour II	Knitted, albumin sealed
	Boston Scientific	Hemashield Gold Microvel	Knitted, collagen sealed, double velour
		Hemashield Platinum	Woven, collagen sealed
	B. Braun	UniGraft	Woven, gelatin sealed, single/double velour
	InterVascular, Inc.	InterGard Woven	Woven, collagen coated
		InterGard Knitted	Knitted, collagen coated
	Vascutek, Ltd.	Gelseal	Knitted, gelatin sealed
		Gelsoft	Knitted, gelatin sealed
		Gelsoft Plus	Köper knitted, gelatin sealed
Heparin Modified			
ePTFE	W.L. Gore & Associates, Inc.	Propaten	Carmeda bioactive heparin coating
Dacron	InterVascular, Inc.	InterGard Heparin	Knitted, collagen coated

Continued

TABLE 66.1 Selected Commercially Available Vascular Grafts in the United States—cont'd

Material Type	Company	Product	Description
Carbon Modified			
ePTFE	Bard Peripheral Vascular, Inc.	Impra Carboflo	Carbon coated
		Distaflo	Preformed cuff at distal end
		Dynaflo	Preformed cuff at distal end
Silver Modified			
Dacron	B. Braun	SilverGraft	Antibacterial
	InterVascular, Inc.	InterGard Silver	Antibacterial
Others			
Collagen based	Artegraft (North Brunswick, NJ)	Artegraft	Cross-linked bovine carotid artery
Polyurethane	Bard Peripheral Vascular, Inc.	Vectra	Self-bonded, trilayer Thoralon design for hemodialysis vascular access

ePTFE, expanded polytetrafluoroethylene.

are coated with albumin to prevent leakage from such pores.[7] Dacron is a highly resilient fabric that is estimated to last over 30 years, but these grafts are at a higher risk of dilation compared with other graft materials.[8] It is currently used primarily as a large-diameter graft in aortic and lower-extremity bypass surgery.

Expanded Polytetrafluoroethylene

ePTFE was described by Matsumoto and colleagues from Japan in 1973.[9] It is configured on a mandrel process with a nodal–fibril porous configuration with carefully constructed inter-nodal distances to optimize function and healing properties. ePTFE grafts are available in several configurations: thin walled, ringed, and pre-cuffed (Fig. 66.2). The pre-cuffed configuration was an attempt to optimize graft hemodynamics, but this has been difficult to confirm.[10] The graft is produced by extruding a low porosity tube producing a graft that is compliant, easy to suture, and does not need to be pre-clotted, in contrast to knitted Dacron grafts.[11]

Polypropylene and polyurethane

Developed in the early 1990s, the early experience with the use of this hydrocarbon material was promising. Polypropylene's high tensile strength and relative inertness gave it an advantage over other prosthetic materials.[12] It also had a long history of successful use in suture and hernia mesh. Polyurethane grafts are produced by the reaction of isocyanates with an alcohol group.[5] The main advantage of polyurethane is high elasticity, but this material demonstrates poor biostability and loss of compliance after implantation limiting widespread clinical use.[6]

Composite Grafts and Allografts

The successful implementation of prosthetic grafts has triggered the development of novel materials such as composite grafts including biologic materials using human umbilical vein, or bovine collagen.[13] While this type of material has yet to be used for lower extremity bypass, the conduit has been used in a hemodialysis access.[14,15]

Cryopreserved Vein and Human Umbilical Vein Grafts

Cryopreserved vein and human umbilical veins are alternative conduits that were first utilized in the 1960s. Cryopreserved grafts are relatively expensive compared with other prosthetic conduits and have a greater incidence of aneurysmal degeneration and thrombosis from late rejection. The current data from multiple centers reported a 30%–58% patency rate at 1 year using cryopreserved veins for infrapopliteal bypass, which is inferior to autologous conduits and heparin bonded ePTFE grafts.[16–20] However, given the biologic nature of the material, this graft may have value in bypasses that traverse infected fields in the absence of any autogenous conduit options, particularly as a temporizing procedure.

CLINICAL APPLICATIONS

Peripheral Bypass Grafts

Numerous studies have been carried out to compare Dacron and ePTFE grafts for lower-extremity bypasses, primarily in femoral–popliteal bypasses with both above- and below-knee distal anastomosis sites. Rychlik and colleagues published a meta-analysis in 2014 that reviewed 91 publications and assessed 1192 patients who underwent above-knee femoro-popliteal bypass using Dacron versus ePTFE.[21] The authors reported similar 10-year primary patency between the grafts at up to 10 years and no difference in the incidence of amputation, morbidity, or mortality between the patient populations. A Cochrane Review published in 2010 found that patency of vein grafts was superior to prosthetic grafts in the above-knee position but that long-term outcomes using Dacron or standard ePTFE in the lower extremities were similar.[22] In this study, PTFE with a vein cuff improved primary patency when compared to PTFE alone for below-knee bypasses.

The long-term patency of Dacron and ePTFE grafts is limited by the inherent thrombogenicity of available polymeric materials and the subsequent stimulation of neointimal hyperplasia. The later phenomenon is especially important at anastomotic

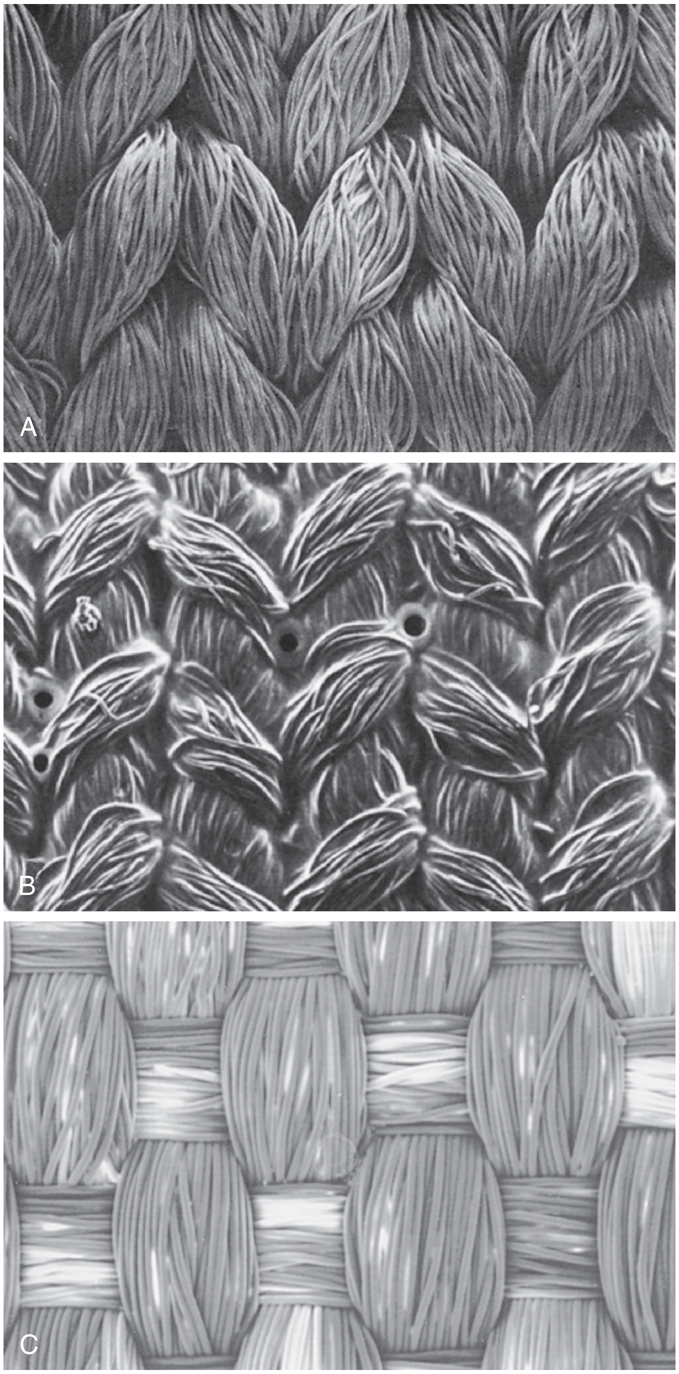


Figure 66.1 Dacron Structure. Scanning electron microscopy of typical yarn configurations in Dacron grafts. (**A**) DeBakey standard-knit Dacron vascular prosthesis (original magnification ×37). (**B**) Vascutek Gelsoft Köper knitted prosthesis sealed with gelatin (×40). (**C**) Woven Dacron (×50). (Source: Figure 93.1 in *Rutherford's Vascular Surgery*, 8th Edition.)

sites eventually leading to critical stenosis and graft failure. With regards to polypropylene, a study of 4 mm lower extremity polypropylene grafts implanted in dogs by Greisler and colleagues reported a 16-month patency of 81% compared with 69% and 20% for Dacron and ePTFE, respectively.[12] Due to susceptibility to oxidation, however, polypropylene is only used as part of multi-component grafts that render the polypropylene inert.[5] The use of human umbilical vein grafts has been impeded by aneurysmal degeneration of the graft material. This complication

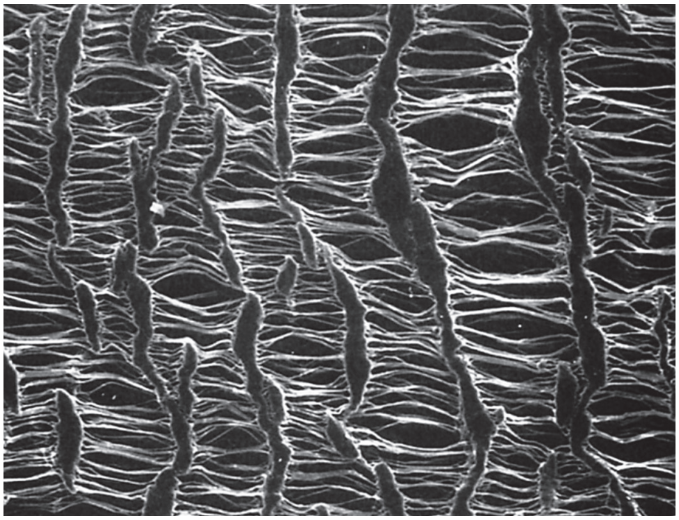


Figure 66.2 PTFE Structure. Scanning electron microscopy of node–fibril structure in expanded polytetrafluoroethylene grafts (original magnification ×500). (Source: Figure 93.1 in *Rutherford's Vascular Surgery*, 8th Edition.)

has been addressed with recent modifications of the graft design, resulting in 61% patency at 36 months.[23] In a large National Surgical Quality Improvement Program (NSQIP) database, human umbilical vein composite grafts had a higher 30-day failure rate of 15.4% compared to 10.5% in ePTFE grafts and 7.5% in GSV conduits.[24] These grafts have also been met with limited success when used for tibial bypass.[25]

Hemodialysis Access

Since the Fistula First Initiative in 1996, the use of AV fistula creation has improved substantially with a subsequent decrease in catheter use.[26] Prosthetic grafts for arteriovenous (AV) access, however, may remain an option in patients with failed native AV fistulae and lack of venous conduit. The 2019 National Kidney Foundation updated guidelines also acknowledge that, while autogenous access is ideal, the use of early cannulation grafts as central venous line–sparing strategies may be appropriate.[27]

The most commonly used grafts are constructed from ePTFE with early-access grafts having the advantage of earlier use and decreased need for catheter access.[28,29] Advantages of prosthetic AV grafts include ease of placement, shorter time from operation to utilization, and a potentially large surface area for cannulation. Graft failure due to stenosis related to intimal hyperplasia at the venous anastomosis as well as graft thrombosis and infection occur at higher rates compared with native conduit AV fistulae.[30,31]

Use of bovine carotid artery grafts during fistula revision procedures may provide an alternate option for patients without autogenous options.[32] Early results suggest bovine carotid artery may have superior primary and assisted primary patency rates compared to PTFE with earlier cannulation for hemodialysis access.[33] In addition, the early cannulation of bovine grafts obviates the need for a tunneled dialysis line, thus decreasing catheter use and its associated complications.[34]

Other Locations

Prosthetic grafts can deliver excellent long-term patency for visceral and renal arterial reconstruction due to short conduit length, high flow arterial beds, and the absence of extrinsic mechanical compression. Large-caliber venous reconstruction of the inferior or superior vena cava and the iliofemoral, jugular, and portal veins, including portosystemic shunts, can be performed with externally supported ePTFE grafts.[35–42]

Strategies for Improving Prosthetic Graft Patency

Early clinical outcomes with prosthetic grafts were suboptimal with 1-year patency rates varying between 20% and 50% with 3-year patency 12%–40%.[2,43–45] The results with prosthetic grafts were especially poor for tibial bypass.[46] While autogenous vein remains the acknowledged ideal conduit for distal bypass, there is a growing group of patients with inadequate venous conduit due to previous harvest or anatomic constraints that benefits from the use of prosthetic grafts. This scenario includes those veins with a diameter less than 3 mm, grafts requiring spliced vein segments, or a nonsaphenous venous conduit. The morbidity from vein harvest is also not insignificant, particularly when greater saphenous vein is not available and construction of an autogenous conduit requires harvesting several venous segments including arm and lesser saphenous vein. Vein harvest also increases operative time compared to bypass with a prosthetic conduit through two limited incisions. Ultimately, improvements in outcome with prosthetic grafts may create on option for patients who lack autogenous material or have disadvantaged vein. Strategies for improving patency include venous adjuncts at the anastomosis, heparin bonding to the prosthetic luminal surface, and the addition of a distal arteriovenous fistula.[47]

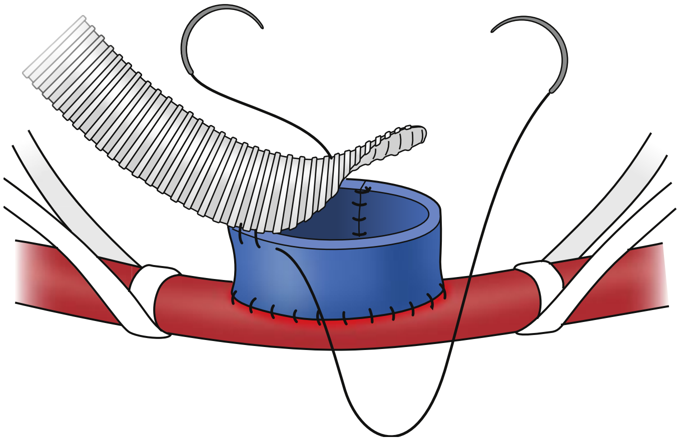


Figure 66.3 The Miller Cuff Technique. A venous cuff is interposed between a prosthetic graft and the target artery. (From *Fischer's Mastery of Surgery*, 7th ed., 2018; Kayssi A, Lee K, Neville RF. Section IX: Vascular Surgery. 198;1–8. Philadelphia, PA: Lippincott, Williams and Wilkins; 2018.)

Vein Patches and Cuffs

Anastomotic techniques utilized to improve prosthetic graft performance have evolved with various techniques since the initial Miller cuff in 1984. The Miller cuff involved interposition of autogenous vein at the distal anastomosis (Fig. 66.3).[48] Miller reported on 114 infrainguinal procedures using this vein cuff technique with a patency rate of 72% noted at 18 months.[48] While this technique demonstrated improved patency, several disadvantages have been recognized with this configuration, including significant turbulence at the anastomotic reservoir and difficulty in achieving an adequate angle between the graft and recipient artery. These factors may explain the immediate and early graft failures reported in Miller's initial series.

Taylor subsequently described a technique to address several of these concerns in which a composite of the prosthetic graft and a vein patch is anastomosed to the target artery (Fig. 66.4). Reporting on 256 grafts including 83 tibial bypasses, Taylor and colleagues' 1-, 3-, and 5-year patency rates were 74%, 58%, and 54%, respectively.[49] Disadvantages of this technique include the direct exposure of the tibial artery to the ePTFE graft for the proximal half of the anastomosis, thereby losing the advantage of venous endothelium for half the anastomosis. There can also be a point of anastomotic constriction where the three suture lines converge between the artery, ePTFE, and vein patch. In addition, a significant length of vein must be available to accomplish the anastomosis using the Taylor technique. Finally, there can be difficulty in placement of this configuration at the inframalleolar position due to anatomic space constraints.

Several authors have studied clinical results and compared these techniques. Kansal and colleagues reported improved patency for prosthetic bypasses with the Miller cuff as compared to historic controls with standard ePTFE.[50] A prospective, randomized trial utilizing ePTFE grafts with and without a Miller vein cuff was reported by Stonebridge, who did not demonstrate a statistically significant benefit for the vein cuff technique in tibial bypasses, although there was a trend toward improved patency

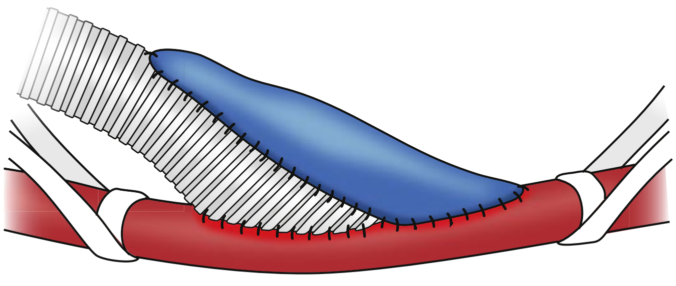


Figure 66.4 The Taylor Patch Technique. The graft is partially sutured onto the target artery, and a vein patch is used to suture the rest of the graft onto the artery and increase the anastomotic surface area. (From *Fischer's Mastery of Surgery*, 7th ed., 2018; Kayssi A, Lee K, Neville RF. Section IX: Vascular Surgery. 198;1–8. Philadelphia, PA: Lippincott, Williams and Wilkins; 2018.)

at 24 months.[51] Kreienberg compared grafts using ePTFE with a vein cuff versus composite saphenous vein grafts and reported a similar primary patency at 2 years of 49% for the vein cuff patients versus 44% for the composite vein patients with secondary patency rates somewhat better for the composite vein group.[52] The Albany group compared all bypasses with spliced vein segments to ePTFE and a Miller vein cuff.[53] The primary patency was better with the vein bypasses although 25% of the spliced vein procedures required secondary revision to obtain these results. Additionally, spliced vein procedures involved increased operative time, longer hospital stays, greater intraoperative blood loss, and greater perioperative morbidity.

The distal vein patch (DVP) technique was developed to take advantage of standard techniques known to all vascular surgeons with the potential benefit of a venous adjunct at the distal anastomosis of the prosthetic graft. While prior procedures were somewhat complex involving multiple intricate suture lines requiring a significant length of vein, the DVP technique incorporates ease of technique with maintenance of the proposed advantages leading to improved outcomes for prosthetic grafts (Fig. 66.5). The initial series of tibial artery bypasses using DVP for patients with limb-threatening ischemia was reported in 1997.[54] The DVP technique resulted in improved 4-year patency (62%) and limb salvage (79%) in a

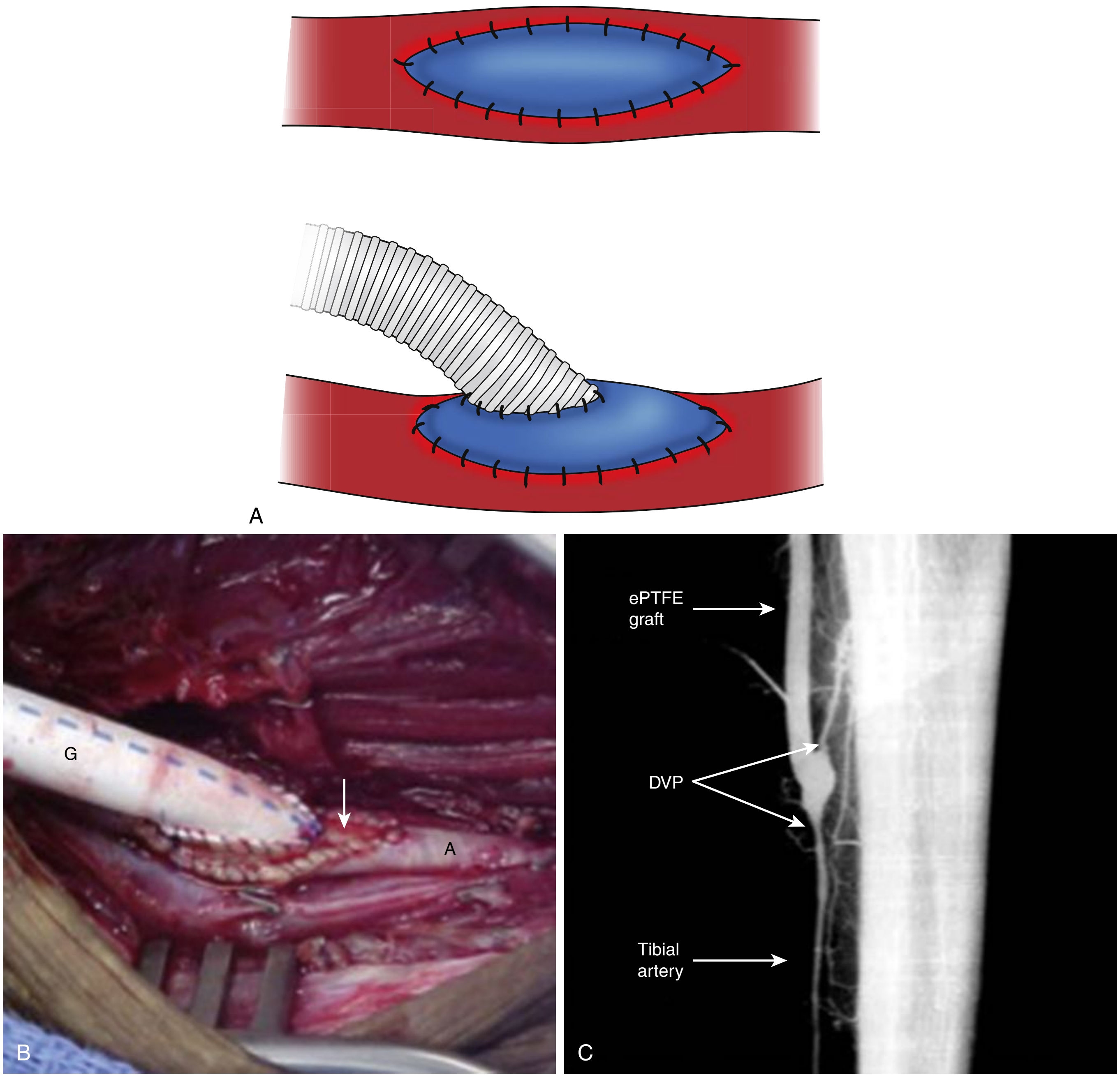


Figure 66.5 Distal Vein Patch Technique. The distal arterial target is patched with a vein, and a prosthetic graft is sewn onto the proximal ⅔ of the patch. (**A**) Schematic of the DVP technique. (**B**) Intraoperative image of a completed DVP anastomosis. (**C**) Completion arteriogram after DVP bypass. (A, Source: *Fischer's Mastery of Surgery*.)

group of patients without adequate saphenous vein conduit options.[55] Since that report, the DVP technique has been used to perform over 400 cases representing 23% of the authors' total tibial experience during that period. A report of this larger cohort resulted in 50% primary patency at 4 years (Table 66.2).[56] Secondary patency following thrombectomy and revision of the distal anastomosis can be obtained under local anesthesia. In these cases, the recipient artery rarely occludes because the hyperplastic response occurs primarily between the vein patch and ePTFE material, leaving the native artery patent and amenable to revision. Extension of the patch to reconfigure the distal anastomosis is often adequate for revision (Fig. 66.6).

The advantages of a venous adjunct at the distal anastomosis derive from both biologic and mechanical factors. Venous endothelium may confer a beneficial effect through fibrinolytic and antiplatelet activity although these effects remain unproven. The mechanical factors of shear stress and compliance mismatch have also been implicated in prosthetic graft failure. Theoretically, vein interposed between a stiff prosthetic graft and a more pliable artery would minimize the expansibility mismatch created with pulsatile flow and thus decrease mechanical injury at the anastomosis. Anastomotic geometry may be altered by the presence of vein at the distal anastomosis thereby positively affecting turbulence and shear forces that play a role in the hyperplastic process. The DVP

TABLE 66.2 Data Regarding Primary Patency and Limb Preservation in an Extended Cohort of Distal Vein Patch Bypass With Long-Term Follow-Up.

Series	*N*	BK Popliteal Versus Tibial	1	2	3	4	5
Miller Cuff							
Miller, 1984	114			72 (18 m)			
Raptis, 1995		BK popliteal 100%			57		
Stonebridge, 1997	96	BK popliteal 100%	80	52			
Kansal, 1999	56	BK popliteal 47% Tibial 53%	62	54	30		
Stonebridge, 2000	89	Tibial 100%	50	32			
Panneton, 2004	44	BK popliteal 21% Tibial 79%	62	44			
Griffiths, 2004		BK popliteal 100%			45		
Oderich, 2005		BK popliteal 35% Tibial 65%	78		54		
Lauterbach, 2005	105	BK popliteal 38% Tibial 62%	79	75	64		
Taylor Patch							
Taylor, 1992	86	BK popliteal	88		77		65
	83	Tibial	74		58		54
Yeung, 2001	44		71	71			
St. Mary's Boot							
Tyrell, 1991	30		40				
Kreienberg, 2000	59	BK popliteal 12% Tibial 88%		45	38		
Kreienberg, 2002	20	BK popliteal 20% Tibial 80%		49			
Distal Vein Patch							
Neville, 2001	80	Tibial 100%	82	77	69	62	
Flis, 2001	86	BK popliteal Tibial					53 vs. 29
Bellosta, 2005	22	Tibial 100%				62 (secondary)	
Neville, 2012 (current)	270	BK popliteal 6% Tibial 94%	79	75	65	51	

Comparative table including data gleaned from articles that reported results on specific data points with the Miller cuff, Taylor patch, St. Mary's boot, and distal vein patch. Data may have been collected in the context of a trial involving other techniques, and only data that could be gleaned from the publication regarding vein interposition techniques were used. While not a statistical comparison, this is as near a comparison of like-kind data as possible.
Source: Neville RF, Lidsky M, Capone A, et al. An expanded series of distal bypass using the distal vein patch technique to improve prosthetic graft performance in critical limb ischemia. *Eur J Vasc Endovasc Surg*. 2012;44:177–182.

anastomosis configuration results in a small vortex of turbulent flow at the heel and a more streamlined flow pattern at the toe (Fig. 66.7).[10] Venous tissue may also simply enlarge the distal anastomosis so that the formation of hyperplasia must encroach on a wider lumen before becoming clinically significant. Finally, venous tissue is also technically easier to suture to small, calcified tibial arteries with a technically easier secondary suture line between the PTFE and vein.

Heparin-Bonded Grafts

The bonding of heparin on the inner surface of a prosthetic conduit has been used in an attempt to reduce graft thrombosis and hyperplasia.[10] End-point covalent bonding of heparin to the luminal surface of the graft maintains the bioactivity of the heparin molecule.[57] This process reduces platelet adherence, acute thrombosis, and anastomotic intimal hyperplasia in canine and primate models.[58] Heparin bonding using the Carmeda bioactive surface technology (CBAS, Carmeda, Uplands Vasby, Sweden) allows binding of the heparin molecule to the luminal surface of ePTFE grafts while maintaining the morphology of the heparin molecule and hence its bioactivity. This process leads to a reduction in platelet deposition on the graft surface in animal and human models. Heparin bonding also reduces thrombus formation on the surface of the graft with a subsequent decrease in graft thrombogenicity in acute and chronic models. A reduction in myointimal hyperplasia at the anastomotic site has been demonstrated with heparin-bonded biomaterial surfaces. Decreased platelet adherence, thrombus formation, and inhibition of myointimal hyperplasia could be hypothesized to decrease both early and late graft failure.

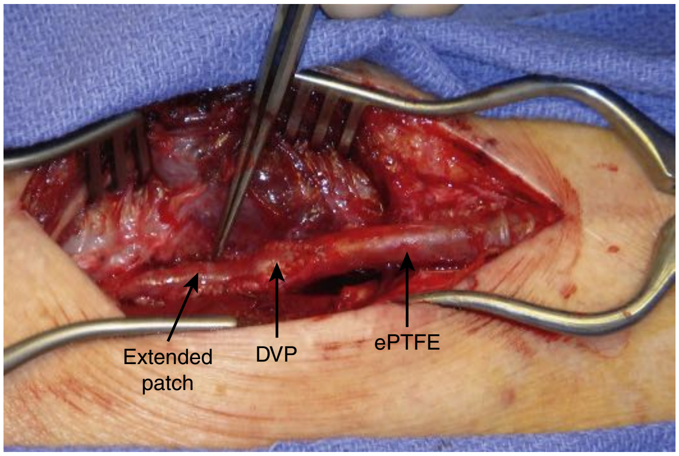


Figure 66.6 DVP Revision. Revision of a DVP graft with opening of the graft hood, thrombectomy, and extension of the patch across the toe of the prior anastomosis onto the target artery.

Initial clinical experience with heparin-bonded grafts was encouraging as compared to historical results with standard prosthetic grafts. Walluscheck reported 80% 1-year patency for below-knee bypasses.[59] Furthermore, Bosiers reported primary and secondary 1-year patency rates of 82% and 97%, respectively, with little difference between popliteal and tibial bypasses.[60] A multicentered randomized controlled trial of heparin-bonded Dacron versus ePTFE for femoropopliteal bypass reported greater patency rates with Dacron than with ePTFE at 3 years, but the advantage was not sustained at 5 years.[61] This was, however, a small study of primarily above-knee bypasses, limiting its generalizability to the infrapopliteal vascular beds. In regards to tibial bypass, recent data suggests that heparin-bonded ePTFE grafts may be statistically noninferior to venous conduit although autogenous vein remains the ideal conduit for lower extremity bypass.[56,62–65] Comparison of primary patency and amputation rates achieved for tibial bypass with heparin-bonded ePTFE and great saphenous vein support the dictum that an intact, quality vein remains the preferred conduit for distal bypass (Fig. 66.8). The results with heparin-bonded ePTFE suggest that prosthetic conduit is an acceptable alternative choice when a quality, intact great saphenous vein is unavailable for tibial bypass.

Heparin-induced thrombocytopenia is a potential concern with implantation of heparin-bonded grafts. This phenomenon has been described in isolated case reports of patients undergoing lower-extremity bypass grafts.[66–69] In these cases, platelet counts were improving prior to graft explantation in

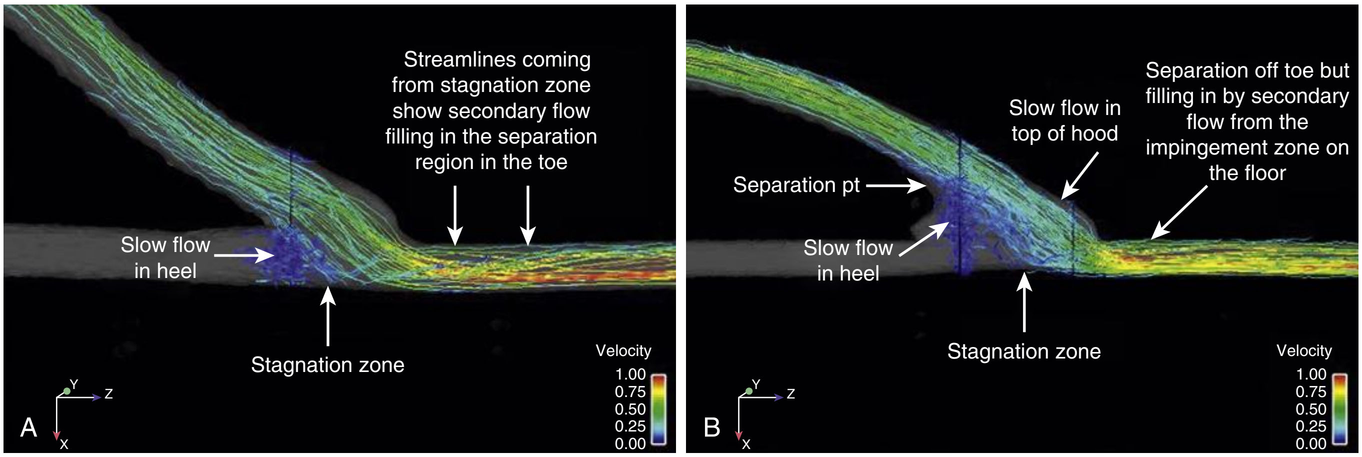


Figure 66.7 Graft Hemodynamics. Magnetic resonance velocimetry images analyzing anastomotic hemodynamics. (**A**) DVP anastomosis. (**B**) Precuffed PTFE anastomosis.

cases where covalently bonded grafts were used, as compared with older grafts that used ionic interaction with the graft surface, leading to subsequent release of the heparin into the bloodstream.[70] Furthermore, a study of covalently bonded grafts found no increase in the systemic markers of hemostasis *in vivo*, and no antibodies against heparin were detected up to 6 weeks after implantation.[71]

Spiral Laminar Flow Grafts

Stonebridge and colleagues have reported that physiologic flow in blood vessels may not be laminar in the conventional sense but rather a spiral laminar pattern of blood flow.[72] It was hypothesized that inducing such a spiral laminar flow pattern in prosthetic grafts may result in an inhibition of formation of neointimal hyperplasia and stabilize flow patterns through stenotic areas. Conceptually, a reduction of the laterally directed forces on the vessel wall would improve shear forces as well as reduce the expression of adhesion molecules thus inhibiting the formation of neointimal hyperplasia.[73,74] A spiral laminar flow graft was developed to reproduce a spiral laminar flow pattern (Vascular Flow Technologies, Dundee, United Kingdom) (Fig. 66.9). Stonebridge and colleagues reported primary patency rates of 86%, 81%, and 81% (12, 24, and 30 months) for above-the-knee bypasses and 73%, 57%, and 57% for below-the-knee bypasses, respectively.[75] To date, there are no published randomized controlled trials comparing the efficacy of spiral laminar flow grafts with ePTFE or Dacron grafts.

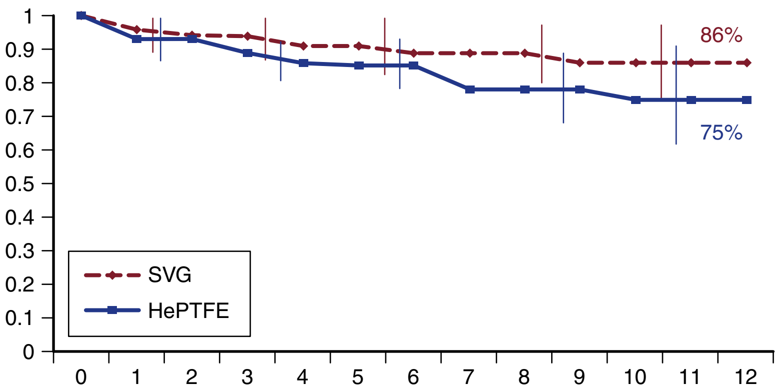
Distal Arteriovenous Fistula

When the target artery outflow of a distal bypass is compromised, the addition of an arteriovenous fistula at the distal anastomosis has been used to increase bypass success. Dardik et al. used a common ostium arteriovenous fistula in an attempt to decrease graft thrombosis by reduction of outflow resistance.[23] Ascer and colleagues described a technique involving construction of an arteriovenous fistula between the target tibial artery and corresponding tibial vein with an ePTFE bypass to the involved vein.[76] Reported patency rates with this technique were 62% at 36 months, despite a fistula thrombosis rate of 37%. A prospective, randomized trial comparing distal bypasses using ePTFE with a Miller vein cuff with and without an arteriovenous fistula demonstrated that the fistula conferred no benefit, but the authors did not stratify patients based on arterial runoff.[77]

The addition of a common ostium arteriovenous fistula to the distal anastomosis of a DVP bypass has also been described. This modification has been performed in patients with no available vein and severely disadvantaged arterial runoff. The target tibial artery is opened longitudinally and a venotomy is created in the corresponding tibial vein (Fig. 66.10). The vein patch is then sutured to the common ostium created by this fistulous connection. An anastomosis is then constructed between the vein patch and the ePTFE, as described in the DVP bypass configuration (Fig. 66.11). Theoretically, the distal arteriovenous fistula decreases outflow resistance, thereby reducing overload on a fixed arterial circuit and increasing flow velocity in the graft above the critical thrombotic threshold to improve graft function and decrease the incidence of thrombosis with bypass in the setting of disadvantaged runoff. Results using this technique have been reported and resulted in a 62% primary patency and 57% limb salvage rate at 24 months in a series of patients who would otherwise have undergone primary amputation.[78]

Deep Venous Arterialization

Deep venous arterialization (DVA) is a technique directed at providing options for patients with a "desert foot" who would otherwise undergo amputation due to disadvantaged arterial runoff.[79–83] In this technique, a fistula is created between the arterial inflow and a distal venous outflow in conjunction with disruption of the vein valves in the foot. Vein wall shear stress promotes a remodeling and neo-angiogenesis creating a new distribution system with at least temporary venous arterialization and perfusion of the foot that can be sufficient for healing. Endovascular, open, and hybrid technique have been described. A 2019 review of all published data demonstrated a 1-year primary patency rate of 44.4% to 87.5% utilizing the open technique.[82] The author's early experience with DVA in conjunction with prosthetic distal bypass grafts demonstrated



HePTFE	62	57	57	52	51	47	47
Vein	50	48	48	43	43	43	43

Figure 66.8 Vein Bypass vs. DVP. Primary patency of tibial bypass using heparin-bonded ePTFE (HePTFE) conduit with a DVP compared to great saphenous vein bypass. Kaplan–Meier survival curves for primary patency over 12 months by graft type**.** (Source: Neville, et al. *J Vasc Surg.* 2012;56(4):1008–1014.)

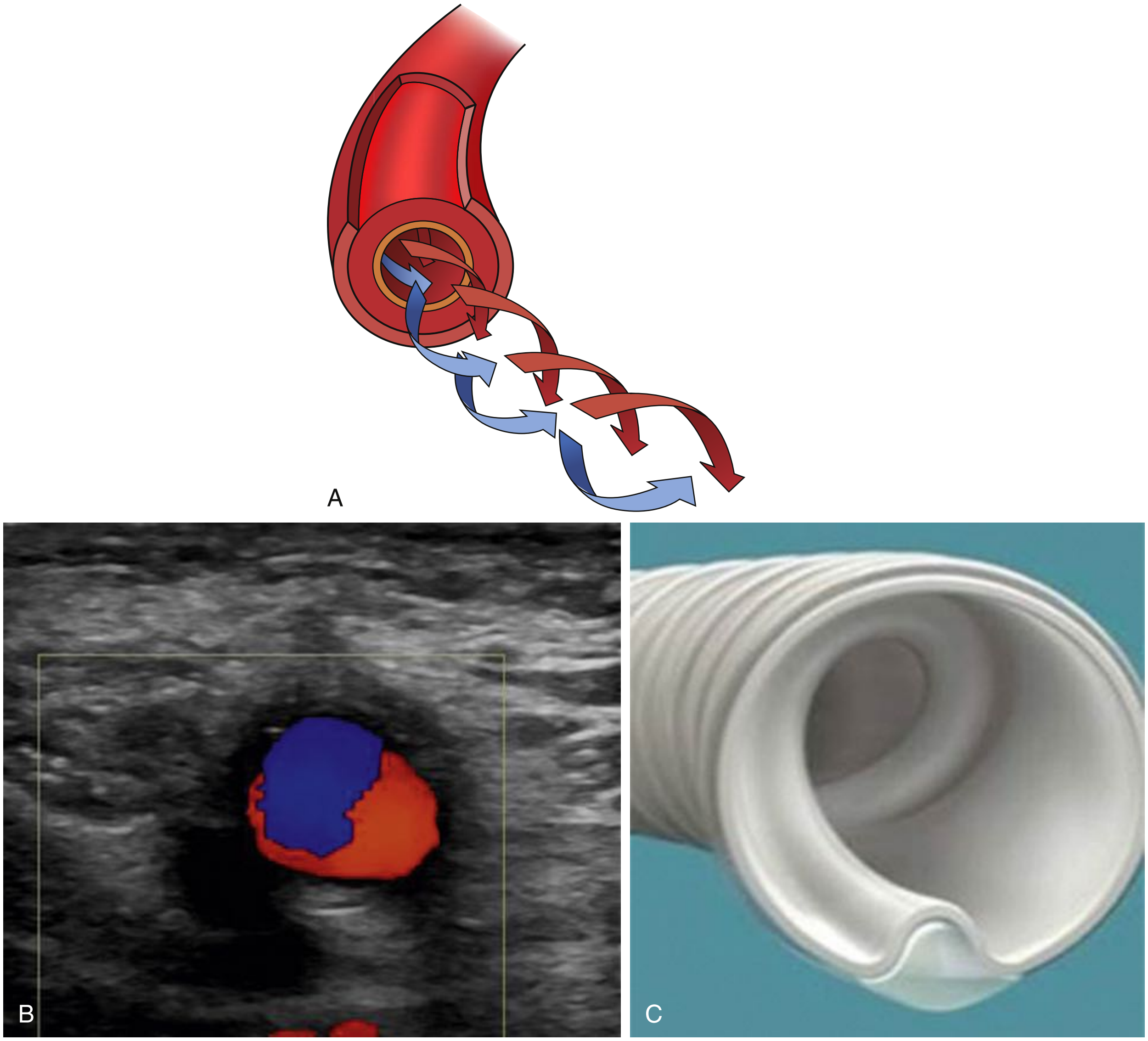


Figure 66.9 **Spiral Laminar Flow.** (**A**) Schematic of the concept of spiral laminar flow in a vessel. (**B**) Duplex ultrasound image of common femoral artery flow consistent with spiral laminar flow physiology. (**C**) Prosthetic graft constructed to reproduce a spiral laminar flow pattern.

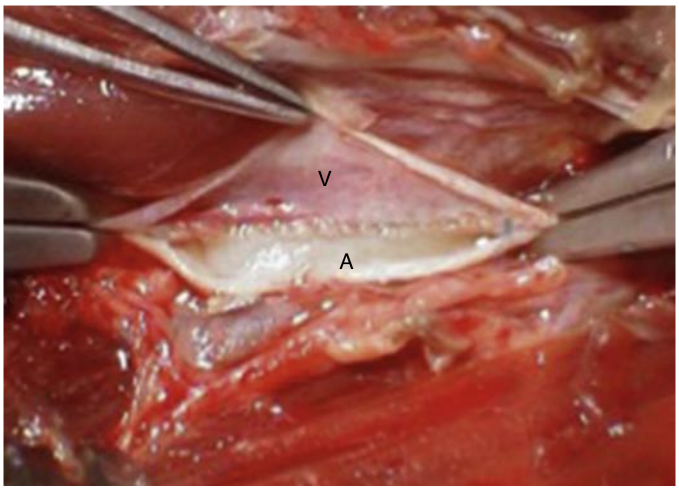


Figure 66.10 **"Patchula" Technique.** The target tibial artery (*A*) and corresponding tibial vein (*V*) are opened longitudinally and a common ostium is created with an onlay patch.

technical feasibility and relief of symptoms and improvement in ABIs[79,80] (Fig. 66.12). Future investigation is warranted to better understand the applicability of this technique in the algorithm of limb salvage strategies.

Adjunct Medical Therapies

The role of adjunct medical therapy in improving prosthetic graft patency has been debated, and there is no clear, consistent data to suggest an ideal adjunct medical therapy to improve prosthetic graft function. A Dutch multicenter randomized study compared 2690 patients who underwent infrainguinal bypass both using vein or prosthetic grafts and randomly assigned patients to aspirin versus warfarin therapy. Overall data did not show any advantage of one therapy over another but when separated into prosthetic conduit versus vein, the prosthetic group had better results with aspirin alone, whereas the vein group had better results with warfarin alone.[84] The Boston Veterans Affairs Hospital Prospective Study compared dual therapy, aspirin and warfarin,

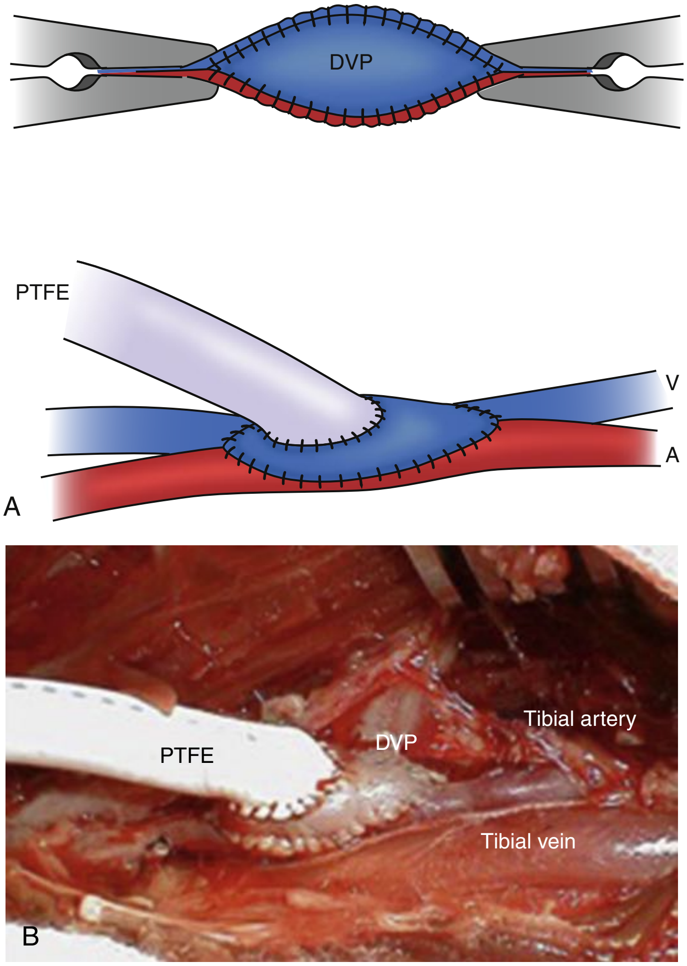


Figure 66.11 **"Patchula" Technique.** A DVP bypass is constructed using the patch over the common ostium in the usual manner. This creates a DVP bypass with concomitant anastomotic arteriovenous fistula.

versus aspirin alone and demonstrated no difference in overall patency between the two groups. The dual therapy seemed to show benefit for smaller (6 mm) prosthetic grafts; however, there was a two-fold increase in major hemorrhagic complications and a higher mortality rate.[85] Finally, the Clopidogrel and Acetyl Salicylic Acid in Bypass Surgery for Peripheral ARterial Disease (CASPAR) trial looked at the efficacy of dual therapy with clopidogrel and aspirin versus aspirin alone in distal bypasses. Dual therapy did not appear to reduce the occlusion rates in venous bypasses. In a subgroup of patients with prosthetic grafts, however, such dual antiplatelet therapy reduced the relative risk of graft occlusion by 35% without any deleterious side effects or major hemorrhagic event.[86] Bedenis and colleagues published a Cochrane Review on the role of antiplatelet medications in preventing postoperative thrombosis after lower extremity bypass and similarly reported an improved graft patency with aspirin for up to 12 months in patients with prosthetic grafts.[87] The role of direct thrombin inhibitors and Factor Xa inhibitors for peripheral bypass graft has not been adequately explored in literature. Some attempts have also been made to develop novel agents to prevent intimal hyperplasia in order to improve graft patency. Thus far, no new agents have efficacy in this regard.[88]

Graft Surveillance

Despite technological advances leading to improved performance of prosthetic conduits, graft failure continues to occur either perioperatively attributable to "technical error," or following a more prolonged period due to development of myointimal hyperplasia or acceleration of atherosclerosis in the proximal or distal arterial bed.[55,89] Detection of a failing graft prior to thrombosis simplifies medical and operative management and improves long-term patency and limb salvage. The addition of

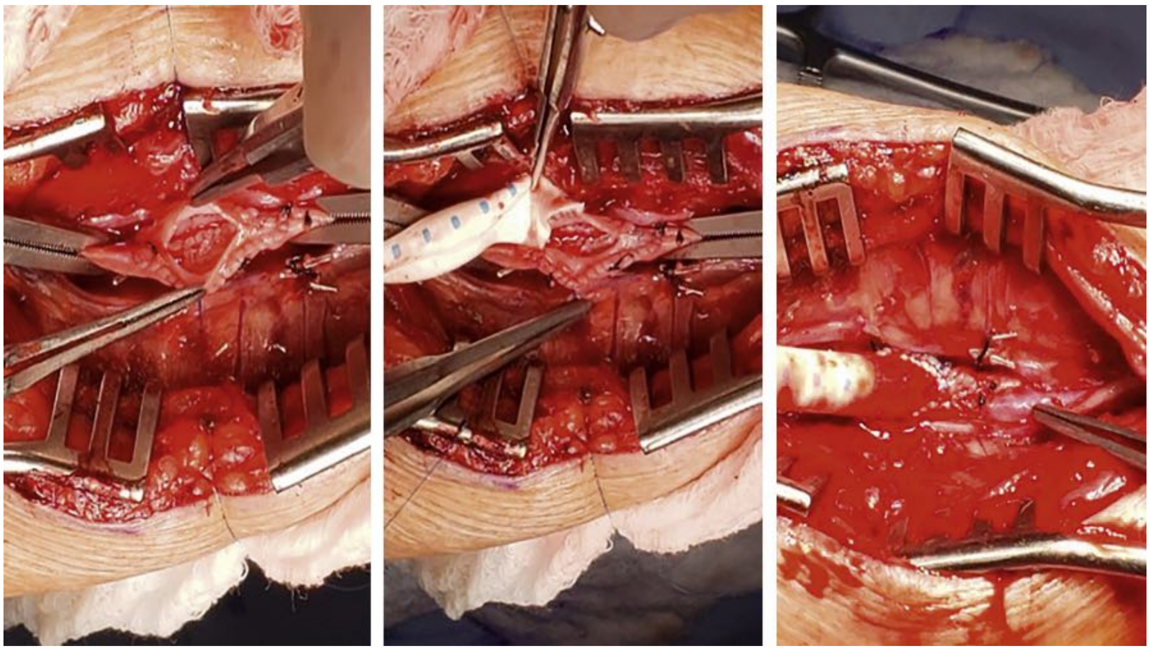


Figure 66.12 Femoral to posterior tibial artery bypass with distal vein patch bypass and deep venous arterialization.

warfarin, for example, has been shown beneficial in patients with low velocity grafts.[90] Detection of graft stenosis allows for early endovascular therapy or simplified surgical revision intervention prior to graft thrombosis. A Dutch study demonstrated near 90% patency rate for infrainguinal bypasses at 2 years using aggressive surveillance and endovascular intervention.[91] As a result, graft surveillance programs have been incorporated into most vascular surgical practices to detect failing grafts thus improving graft function and assisted primary patency rates.

Graft surveillance involves clinical evaluation for recurrent or new symptoms of limb ischemia as well as an examination of pulses and an ankle–brachial index.[92] Clinical assessment alone, however, does not always identify significant stenoses that threaten graft function, especially in patients initially treated for critical limb ischemia. Vascular laboratory imaging has therefore been added to surveillance protocols as a noninvasive assessment of graft function. While the overall benefit of graft surveillance has not been well-documented for prosthetic grafts, regular interval duplex ultrasound studies obtained at 3, 6, and 12 months postoperatively and then annually has been employed in many practices to identify threatened bypasses before they occlude.

Numerous authors have attempted to define the Doppler ultrasound criteria that should prompt further work-up and potential repair of a "failing" graft. Bandyk has suggested that a peak systolic velocity exceeding 300 cm/s on Doppler ultrasound and a peak systolic velocity ratio across the stenosis exceeding 3.5 correlates with more than 70% stenosis in a graft.[93] Another study by Brumberg and colleagues demonstrated that mid-graft peak velocity of 45 cm/s or less was predictive of graft failure.[94] Sanchez and colleagues reported a series looking at surveillance in order to detect failing ePTFE grafts.[95] These authors reported on a 12-year experience with over ninety ePTFE grafts and surmised that ultrasound surveillance was useful despite the observation that the progression of proximal and distal arterial disease was the primary cause of ePTFE graft failure in the series. These authors concluded that frequent graft surveillance may allow for the detection of hemodynamically threatening lesions prior to graft thrombosis and enhance long-term graft patency and function as the 5-year patency and limb preservation rate for treating "failing" ePTFE grafts was substantially improved over that for ePTFE grafts that have gone on to occlude. A smaller study from Sweden randomized 156 patients between clinical surveillance and surveillance that included Duplex ultrasound evaluation. Although only forty of the grafts in the trial were ePTFE grafts, the authors noted improved assisted primary and secondary patency in the group with regular Duplex ultrasound surveillance.[96] More recently, a combined experience from Boston and the Netherlands found ultrasound surveillance to be effective in leading to a reduction in amputation and cost.[97]

LIMITATIONS AND RISKS

Graft Failure Modes

The failure of prosthetic conduits can be classified as early, midterm, or late. Early failures that occur in the first month after surgery are commonly due to technical problems during surgery and the presence of underlying thrombophilia. Technical problems encompass poor/limited choice of inflow or outflow targets and other technically related difficulties. Midterm graft occlusions occur between 6 and 24 months after surgery and are usually due to myointimal hyperplasia at an anastomosis. The interaction between blood, host artery, and graft initiates a complex set of biochemical and cellular responses that ultimately limit implant function. Finally, late graft thrombosis occurs several years after implantation and is frequently secondary to the progression of proximal or distal atherosclerotic disease.

The Blood–Material Interface

Prosthetic grafts with blood-compatible materials attempt to minimize activation of the body's prothrombotic and hyperplastic responses. The full spectrum of this response includes a combination of lipids, proteins, and cells that act in concert to provide localized amplification. A series of negative feedback mechanisms control the propagation and termination of these responses. The inability of current prosthetic materials to replicate these complex systems plays a role in graft failure.

Cellular Interaction and the Coagulation Cascade

When blood encounters an artificial surface adsorption of proteins activates the complement and coagulation cascades. Activation of the complement system may contribute to surface-induced thrombosis through platelet activation as well as monocyte and neutrophil infiltration which also have been implicated in the development of myointimal hyperplasia.[98] Discussion of the coagulation system is beyond the scope of this chapter but binding of plasma factor XII to prosthetic surface results in a conformational change that yields an activated form, XIIa, which catalyzes this cascade.[99,100] Blood flow modulates this process by controlling the rate at which coagulation proteins and activated factors are delivered to or removed from the graft surface. Locally disturbed flow or turbulence at an anastomosis creates recirculation regions that stimulate coagulation factors. Platelets are the major cellular component of the thrombotic response and are involved in both complement-mediated and T cell-mediated immune responses.[101] Increased levels of platelet-generated thromboxane continue to be observed 1 year after graft implantation in animals, and clinical studies have revealed persistent platelet deposition on Dacron grafts for at least several months.[102–105] Antiplatelet agents can reduce platelet deposition onto prosthetic grafts.[106,107] Despite their role in the phagocytosis of foreign material and bacteria, neutrophils recruited to a biomaterial surface do not protect against infection.[108] Activated macrophages express tumor necrosis factor-α as well as growth factors that may stimulate smooth muscle cell (SMC) proliferation and contribute to intimal hyperplasia.[109,110]

Migration of endothelial cells from the peri-anastomotic area results in the formation of a neointima extending no more than a few centimeters from the anastomosis with little coverage of the midportion of the graft. However, scattered islands of endothelial cells have been observed far from the anastomotic regions due to transmural ingrowth of microvessels from perigraft tissue or adherence of blood-borne endothelial progenitor cells (EPCs).[111–117] Endothelial cells that grow onto prosthetic graft surfaces often display a procoagulant phenotype and promote rather than hinder graft thrombosis. Activated endothelial cells may increase growth factor production and thereby encourage SMC proliferation.

Graft Complications

Complications after placement of a prosthetic graft include bleeding, infection, occlusion, seroma formation, pseudoaneurysm, and rarely steal phenomenon secondary to inadequate proximal blood flow. A detailed discussion of all graft-related complications is beyond the scope of this chapter, but the two most important complications, graft thrombosis and infection, are briefly outlined below.

Graft Thrombosis

As previously discussed, implanted prosthetic grafts can develop myointimal hyperplasia and eventually thrombose, leading to graft occlusion. When myointimal hyperplasia results in the development of a hemodynamically significant stenosis prior to graft thrombosis, the bypass is referred to as a "failing graft," with diminished function.[118] Flow in a "failing graft" is hemodynamically compromised but may not result in clinical signs or symptoms of diminished flow. Revision of failed grafts often requires a more complex procedure with increased morbidity and mortality as compared to an intervention to maintain assisted primary patency. Therefore, routine surveillance is often performed to monitor graft function prior to total occlusion.

When graft failure does occur, patients may present with original symptomatology, however increased ischemic symptoms are not uncommon. Prosthetic graft occlusion can lead to significant morbidity and limb loss, a particularly devastating complication in those performed for intermittent claudication.[119] The treatment of lower extremity prosthetic bypass graft occlusion is tailored to the patient and guided by clinical presentation and patient's anatomy. A patient with an occluded graft with a non-threatened limb may benefit from thrombolysis to both restore flow within the graft and unmask any underlying stenotic lesions amenable to endovascular or open surgical treatment. Conversely, a patient with advanced limb ischemia manifesting sensory or motor loss will require more urgent revascularization. Chronically occluded grafts often require operative exploration for open thrombectomy or creation of a new bypass if warranted by symptoms.

Since its introduction in the 1970s as a technique to restore patency of occluded arteries, thrombolysis is now a commonly used and effective modality for treating native arterial and venous thrombosis as well as prosthetic grafts.[120] Thrombolysis can be administered systemically or as part of a catheter-directed or mechanical approach using specialized catheters. Numerous contraindications to this treatment approach exist, including recent surgery, hemorrhagic strokes, bleeding disorders, and a non-viable limb.[121] Several retrospective studies have described an early technical success of 48%–90% and a limb-salvage rate of 56%–82% with thrombolysis.[121–128] The Surgery or Thrombolysis for the Ischemic Lower-Extremity (STILE) trial and the Thrombolysis or Peripheral Arterial Surgery (TOPAS) trial investigators assessed thrombolysis versus thrombectomy for limb ischemia and reported that thrombolysis was superior to surgical thrombectomy in patients with fewer than 2 weeks of symptom duration, whereas surgical thrombectomy was superior to thrombolysis when symptoms lasted for 2 weeks or longer.[129–131]

Graft Infection

Prosthetic graft infection occurs in 1%–6% of patients undergoing lower-extremity bypass and 0.5%–2% of patients undergoing abdominal aortic repair.[132–134] These infections are associated with considerable morbidity, including amputation rates of 10%–70%, and mortality rates up to 20%.[134,135] The most common causative organisms are *Staphylococcus* species, *Staphylococcus aureus* and *Staphylococcus epidermidis*.[133–136] The origin of the graft infection is often microorganisms seeded at the time of the operation or contamination through wound complications, adjacent infections, or a bloodstream infection from a distant source. Predictors of prosthetic graft infection include reoperative bypass, female gender, diabetes, and active infection at the time of bypass.[137] There is no evidence that a particular type of graft material, such as Dacron or ePTFE, is more predisposed to infections compared with other materials.[138]

The diagnosis and management of graft infections is guided by the patient's clinical status and the microbiology and extent of the infection. Patients typically present with fever and malaise, with or without a wound infection and purulent discharge. Elderly, malnourished, and frail patients may not mount an adequate inflammatory response to indicate an active infection. Patients with suspected graft infection should undergo blood cultures and, if applicable, wound cultures should be sent. Patients should then be started on broad-spectrum antibiotics that are reviewed when the culture results and antibiotic sensitivities are reported. Imaging should be obtained in the work-up of patients with a suspected graft infection. Acceptable modalities include CT angiography, ultrasonography, magnetic resonance imaging, Gallium scanning, and rarely labelled white blood cell scanning. Radiologic findings suggestive of graft infection include peri-graft air, fluid or soft-tissue attenuation, and pseudoaneurysm formation.[139]

There are several treatment strategies for graft infections which are guided by the patient's status and the type of infective organism. Graft preservation is sometimes possible in patients with limited infections and no signs of sepsis or extensive graft involvement with sparing of the anastomosios.[129,140] Grafts that are infected with *Pseudomonas* and methicillin-resistant *Staphylococcus aureus* (MRSA) usually require removal of the infected graft due to the particular virulence of those organisms.[132,141] In patients with graft thrombosis and clinical evidence of adequate collateralization, graft excision without revascularization may be sufficient. In patients who require revascularization of the excised graft segment, an *in situ* graft can be placed or an extra-anatomic bypass might be created. Conduit options include autogenous, cryopreserved, and