Which Arteries Are Expendable? The Practice and Pitfalls of Embolization throughout the Body

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ABSTRACT

This article outlines general concepts of, and strategies for, therapeutic embolization throughout the body, touching on all major arterial distributions. Clinical scenarios that allow or prevent safe embolization of vessels are presented. Specific agents are recommended where appropriate, as are alternate approaches when embolization is not an option. Pre-embolization precautions and adjunctive measures are described in high-risk areas.

KEYWORDS: Embolization, trauma, angiography

Objectives: On completion of this article, the reader will (1) understand which vessels can be safely embolized in various arterial distributions, and (2) be able to describe scenarios which would limit or allow embolization in high-risk areas.

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Vascular embolization is a common technique in catheter-based therapy. Although the maintenance and restoration of arterial continuity with angioplasty and stents is alluring and is more often the focus of endovascular development, its counterpart—the deliberate elimination of arterial flow to control pathological conditions—can be equally important and is every bit as rewarding and technically challenging. The safe and effective application of embolization techniques requires a broad knowledge of normal and variant arterial anatomy, as well as recognition of the collateral pathways

that might either compromise the efficacy of embolization or, in contrast, maintain viability of tissues beyond the embolization zone.

For most vascular territories, the operator performing an embolization procedure must choose between two different approaches having two very different final outcomes: (1) embolize widely and/or permanently, with potential compromise of end-organ perfusion; or (2) perform a more localized procedure such that the perfusion of distal territories is preserved. The former is generally less challenging and more rapidly

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applied in emergent situations, but the latter may be preferred to preserve organ function. Most practitioners will, at some point, find themselves in a quandary, wondering: "Can I safely embolize that vessel or do I need to preserve it?" There is a large body of experience and literature concerning the embolic management of individual vascular territories, but, to our knowledge, no comprehensive and concise overview of the entire arterial vasculature has previously been assembled. The following is a consensus document reflecting the pooled knowledge and standard practice at a major multisite institution with extensive, ongoing experience in trauma, transplant, and quaternary referral care. It includes commentary from specialty- and subspecialty-certified experts from the fields of interventional radiology, neurointerventional radiology, cardiology, and vascular surgery. Our goal is to offer guidelines for arterial embolic therapy as applied to specific vascular territories throughout the body.

CORONARY ARTERIES

Embolization is not commonly performed in the coronary vasculature. Occlusion of branch vessels or trunks that feed myocardium will produce ischemia and infarction. However, coronary arteriovenous fistulas (AVFs) are seen in 0.1% of coronary angiograms. These lesions can be associated with myocardial ischemia on the basis of coronary "steal." Coronary AVFs may present clinically as angina pectoris, congestive heart failure, or cardiomyopathy, or may be identified incidentally during coronary arteriography. Small fistulas are usually managed conservatively, but large, discrete fistulas may be closed surgically or with percutaneous techniques (Fig. 1). Although coils are most commonly used, the recent availability of the Amplatzer Vascular Plug (AGA Medical, Plymouth, MN) may see them used

with greater frequency. Some fistulas are not anatomically suitable for closure. Mavroudis et al provide a guide for which fistulas are suitable for percutaneous closure.¹ Safe embolization relies on embolizing only the fistula and preserving all other coronary branches.

INNOMINATE ARTERY

The innominate artery is a critical conduit for blood supply to the brain and right arm. Therefore, embolization therapy is not a first-line treatment for innominate lesions. The optimal endovascular treatment for innominate artery lesions at present is reconstruction with an endograft to stabilize the injured site without compromising distal flow. The innominate artery can be injured by blunt or penetrating trauma. Innominate hemorrhage and pseudoaneurysm have been widely reported and have been treated by both surgical and endovascular techniques.² Unfortunately, in blunt trauma, the injury often involves the vessel origin, near the aorta, which can compromise the proximal seal zone of a simple tubular endograft.^{3,4} In such cases, it would be necessary to use a branched endograft based in the transverse aorta—a device that is not currently available. In the absence of an endograft for definitive endovascular repair, temporary control of innominate hemorrhage can be achieved by placement of an occlusion balloon, with subsequent surgical management.⁵

In some situations, catheter-directed occlusion of the innominate artery may be the only practical mechanism for addressing an injury. Such might be the case in a patient who cannot tolerate a surgical procedure. Although innominate artery occlusion compromises flow in the right common carotid artery, creating the potential for embolic or ischemic stroke, adequate cerebral perfusion can in many cases be derived

Figure 1 Coronary artery-to-coronary sinus fistula, before and after closure with coil embolization. Note the improved visibility of the normal coronary arteries after the fistula was closed; this is due to resolution of the steal phenomenon.

intracranially from the circle of Willis or extracranially from the external carotid.⁶ A balloon occlusion test of the carotid with evaluation of stump pressures and middle cerebral artery flow may help determine which patients can tolerate an occlusion.⁷

The diameter of the innominate artery presents a challenge for embolic occlusion: it is simply too large for safe treatment with most coils, which would have a high likelihood of slipping through the target area and causing distal occlusion. Among currently available agents, the most appropriate for innominate artery embolization is the Amplatzer plug.

CAROTID ARTERY

The carotid artery is the important conduit to the eye and brain; however, the presence of the circle of Willis does afford an opportunity for the rare necessary carotid sacrifice. This may be life saving following penetrating injury, gunshot wounds, and carotid blowout from post-radiation state, large aneurysms, or carotid cavernous fistulas. The standard practice is to perform a diagnostic angiogram of the bilateral carotid arteries and the dominant vertebral artery to document presence or absence of anterior and posterior communicating arteries. Cerebral angiography with manual compression of the contralateral carotid artery will demonstrate the potential cross flow through the anterior communicating artery. An Alcock's maneuver, which involves carotid compression during vertebral angiography, can show the posterior communicating artery and potential collateral flow.

In a planned carotid occlusion, it is advisable to use transcranial Doppler monitoring of the ipsilateral middle cerebral artery during a pre-embolization balloon test occlusion. A 30% drop in velocities with the balloon inflated indicates only borderline collateralization, and a 40% decrease indicates that the degree of collateral flow is probably inadequate to support cerebral perfusion.

Carotid occlusion can be performed with various devices including detachable balloons, coils, and Amplatzer plugs. Liquid agents or particulates are to be avoided to prevent catastrophic downstream embolization to the brain. To avoid the "stump phenomenon," in which thrombus formed in the carotid remnant embolizes to the brain through an external carotid artery to the ophthalmic artery circuit, the patient is advised to take a daily aspirin for life.

EXTERNAL CAROTID ARTERY

The external carotid artery (ECA) and its branches are generally tolerant of embolization by proximal and distal coil placement. The extensive collaterals between the ipsilateral and contralateral ECA branches generally ensure continued flow. Hemorrhage from distal branch injuries or neoplasms may be treated with flow-directed

particulates. External carotid-to-intracranial communications, although uncommon, are quite variable, and the inadvertent passage of embolic material through these pathways is potentially devastating. For example, the ophthalmic artery may in some cases arise from the middle meningeal artery, and facial artery continuation into the ophthalmic has been reported.⁸ Specific angiographic evaluation for such communications is required before a particulate or flow-directed embolization. Furthermore, flow slows during embolization and hemodynamic changes may increase flow to the intracranial collaterals, thus creating flow through collaterals that might not have been demonstrable initially. Therefore, repeat diagnostic angiograms at intervals during the procedure are necessary to avoid nontarget embolization. To further protect against nontarget cerebral embolization through very small anastomoses that are difficult to visualize, it is recommended that embolic particles be $> 350 \mu\text{m}$. Having $> 2 \text{ cm}$ of catheter purchase prevents catheter wedging and also helps avoid reflux of embolic agents into the internal carotid circulation via collaterals.

There are several individual branches of the ECA that warrant special consideration. The ascending pharyngeal artery supplies the lower cranial nerves through its neuromeningeal trunk. Damage to this branch could cause severe laryngeal and pharyngeal dysfunction. When occlusion of this branch is necessary, it must be performed at a proximal level with coils or the use of particles $> 350 \mu\text{m}$ to prevent distal infarction. Under no circumstances should glue or Onyx (Micro Therapeutics, Irvine, CA) be used. The occipital artery has a robust anastomosis with the vertebral artery at level of C1 via its muscular branch. Therefore, proximal occlusion of the occipital should be performed with coils. Distal branches may be safely embolized with particles or liquid agents, with some exceptions. For example, there are dural branches from the proximal portion of the occipital artery and these may communicate with the neuromeningeal trunk. Embolization here risks cranial nerve injury. Similarly, posterior auricular artery branches may communicate with the ascending pharyngeal artery branches. The middle meningeal artery often has communication with the ophthalmic artery, and this should be identified before embolization. The petrosal branch of the middle meningeal artery also supplies the facial nerve as do branches of the facial artery near the parotid gland. Liquid embolization or small particles in these locations can cause facial palsy.

VERTEBRAL ARTERIES

Vertebral artery injuries, including hemodynamically significant stenoses, false aneurysms, and AVFs may be treated with transcatheter coil occlusion if endovascular stent graft repair is not feasible^{3,9,10} (Fig. 2). If the vertebrobasilar anatomy is normal and the contralateral

Figure 2 (A, B) Arch aortography in the right anterior oblique (RAO) and left anterior oblique (LAO) projections reveals vigorous bleeding from the left vertebral artery. The proximal segment of the dominant right vertebral artery is seen. (C) Final arch aortogram after coil embolization.

vertebral is intact, coil embolization presents little risk of ischemic compromise. However, visualization of the contralateral vertebral artery from its origin to the basilar artery is mandatory (Fig. 3) to ensure continuity. In one uncommon anatomical variant, a vertebral artery will terminate at the posterior inferior cerebellar branch, and would not provide adequate intracranial collateral flow. Another issue with vertebral artery embolization is backbleeding. Free retrograde flow from the contralateral vertebral artery can readily supply the vasculature distal to the area of embolization, so one must pay particular attention to obtaining control both distally and proximally to the lesion being treated.

THYROCERVICAL/COSTOCERVICAL TRUNKS

The thyrocervical trunk and its branches can be safely embolized. However, because thyrocervical trunk branches may contribute to the cervical spinal artery distally, liquid agents or small particulate embolization should be avoided unless spinal artery contribution has been excluded. Careful attention should be paid during particulate embolization, as the origins of these trunks are in close proximity to the vertebral artery. The deep cervical arteries communicate with the vertebral arteries so adequate purchase with a microcatheter and small volume injections are necessary to maintain control. Coil embolization to occlude an injured segment of these

Figure 3 (A) Lateral right vertebral artery shows a large pseudoaneurysm with traumatic arteriovenous fistula. (B) Selective left vertebral artery demonstrates an intact vertebrobasilar system and no backbleeding. (C) Final angiogram following proximal and distal right vertebral artery coil embolization.

trunks or their branches can safely be performed if adequate purchase can be achieved, although rich collateralization requires distal as well as proximal occlusion to prevent backbleeding from collaterals.

INTERNAL MAMMARY ARTERY

The internal mammary arteries can be empirically embolized in nearly all cases. Important exceptions are: (1) patients with a history of coronary bypass using this vessel, and (2) patients with severe aortoiliac occlusive disease in whom the internal mammary artery is the proximal portion of an epigastric artery collateral pathway to the femoral artery. Internal mammary branches are commonly embolized using particles or Gelfoam (Upjohn, Kalamazoo, MI) in cases of hemorrhage from chest trauma or as collateral supply to bleeding bronchial vessels. Proximal coil embolization is usually ineffective due to backbleeding from superior epigastric and intercostal collaterals.

PERIPHERAL UPPER EXTREMITY ARTERIES

The axillary artery is a conduit artery to the hand and generally cannot be safely embolized without revascularization. However, attempts at brachial artery embolization can be made in some unusual circumstances, such as mycotic aneurysms that result from intravenous drug abuse, and revascularization options are limited by the absence of suitable vein or an infected surgical field. A detailed vascular examination using continuous wave Doppler is required before and after embolization to

ensure a viable extremity. Some distal collateral flow is expected from the profunda brachial artery. Segments of the ulnar and radial arteries can usually be coil embolized safely after confirmation of an intact palmar arch. This can be done with a simple Allen test but should be confirmed angiographically at the time of embolization. Muscular arterial branches in the arm can be safely occluded due to the extensive collateral supply. However, particulate or liquid embolization in the upper extremity is potentially hazardous due to the risk of digital ischemia and necrosis if nontarget distal embolization occurs.

SUBCLAVIAN

The subclavian artery is not usually considered expendable. However, if the vertebrobasilar circulation is intact, the segment proximal to the vertebral artery origin can be occluded, with distal perfusion thereafter arising from reversed flow in the vertebral artery (Fig. 4). The thoracic endograft repair literature offers extensive experience with occlusion of the left subclavian origin.¹¹ Acute cerebral or limb ischemia is rare, although delayed upper extremity claudication may require a bypass.^{12,13} Embolization of the left subclavian artery distal to the vertebral artery is generally ill-advised, as it is an important conduit to the upper extremity. In the case of hemodynamic instability and frank hemorrhage, coil, plug, or temporary balloon occlusion may be performed as a temporizing maneuver before surgical repair.⁵ Often costocervical and thyrocervical communications with the circumflex humeral arteries at the shoulder will maintain perfusion such that a bypass may be semi-elective.

Figure 4 Elderly patient with a complex 8-cm thoracic aneurysm. Complex hybrid repair required carotid-to-subclavian bypass and occlusion of the proximal subclavian artery to prevent a large type II leak. The size of the aneurysm and distortion of the great vessel origins would have required thoracotomy for safe surgical ligation of the subclavian artery, so embolization was performed. (A) Left subclavian angiogram demonstrates the short segment before the vertebral artery origin. (B, C) Angiograms following deployment of 12-mm Amplatzer Vascular Plug.

THORACIC AND LUMBAR SPINAL ARTERIES

The spinal cord is supplied by one anterior spinal artery and paired posterior spinal arteries. The anterior spinal artery is continuous over the anterior portion of the cord and usually derive supply from one or both vertebral arteries in the cervical spine and a large thoracic segmental vessel commonly known as the artery of Adamkiewicz. The latter has a variable origin from the lower intercostal arteries. The posterior spinal arteries (also known as radiculospinal) have numerous origins all along the cervical thoracic and lumbar spine. These branches must be excluded from the field before embolization, and, when in doubt, proximal coils or large Gelfoam torpedoes are preferred for accomplishing this. Large particles ($> 350 \mu\text{m}$) can otherwise be used in intercostal and lumbar embolization.

INTERCOSTAL ARTERIES

The intercostal arteries can be safely embolized if a shared origin with the artery of Adamkiewicz has been excluded. In cases where the artery of Adamkiewicz arises from the target intercostal artery, embolization of the intercostal artery distal to the Adamkiewicz origin can be performed if the utmost care is taken to prevent reflux of the embolic material into the distribution of this anterior spinal artery.¹⁴⁻¹⁶ Catheter position at least 2 cm beyond the artery origin and particles with a $> 250\text{-}\mu\text{m}$ diameter minimize the risk of errant spinal emboli. Proximal embolization of peripheral lesions can permit collateral bleeding from the adjacent intercostals or anterior intercostals branching from the internal mammary arteries.

BRONCHIAL ARTERIES

Hemoptysis from bronchial arterial bleeding is a common sequela of chronic inflammatory diseases of the lung, the most common of which are tuberculosis and cystic fibrosis. Fortunately, the bronchial arteries are quite readily expendable: the entire bronchial distribution can be safely embolized in a single setting in the treatment of hemoptysis.¹⁷ As with intercostal or spinal embolization, care must be taken to exclude a shared origin with the artery of Adamkiewicz, and similar precautions must be taken. Small anastomoses have been described connecting the bronchial arteries to the pulmonary arteries, measuring up to $325 \mu\text{m}$.¹⁸ Particle sizes larger than $300 \mu\text{m}$ should therefore be the first choice to limit errant pulmonary artery emboli. Generally, the bronchial arteries should not be embolized proximally with coils in the treatment of hemoptysis, as this may limit repeat access to the future bleeding sites that are expected with disease

progression; for most etiologies (infectious, inflammatory, and neoplastic), recurrence is the rule rather than the exception. Cases of diaphragmatic paralysis have been reported following bronchial artery embolization due to embolization of the left pericardiophrenic artery and subsequent impairment of the phrenic nerve.¹⁹

PULMONARY ARTERIES

Pulmonary arteries may contribute to hemoptysis because of traumatic injury, bronchial artery-to-pulmonary artery fistulas, direct vascular erosion by tumor, pulmonary artery, or pulmonary artery pseudoaneurysm. In addition, pulmonary arteriovenous malformations (PAVMs) can allow venous emboli to enter the systemic circulation, with resultant injury to the brain and other arterial territories. Pulmonary arteriovenous malformations and pseudoaneurysms should be embolized from a pulmonary artery approach and as distally as possible. The high-flow nature of PAVMs requires a careful choice of coil or plug size: a coil that is too large will push the delivery catheter out of place, whereas a coil that is too small might pass through the AVM and embolize to the systemic circulation. The initial coils or plugs should be matched to the feeding pulmonary artery branch rather than the draining vein. Initial coils should be oversized, 1 to 2 mm, and Amplatzer plugs should be oversized by 20 to 40%. In large-diameter or short-length feeding arteries, where concern for paradoxical embolization of the initial coil is particularly high, some authors have advocated coiling through the lumen of an occlusion balloon, which is used to stop blood flow while a stable coil nest is being created. Others have suggested partial deployment of the initial coil into a side branch to anchor the coil.²⁰ Our initial experience with Amplatzer plug occluders has been very favorable, and both their size range and their ability to be recaptured have made them our agent of choice for PAVM.

PHRENIC ARTERIES

Inferior phrenic arteries usually arise from the celiac trunk or directly from the aorta. The right phrenic is the most common extrahepatic collateral vessel to supply hepatic tumors and may also communicate with the gastric artery and, through transpleural systemic to pulmonary arterial anastomoses, the pulmonary circulation.²¹ These anastomotic and collateral pathways must be occluded with large particles or coils before transarterial chemoembolization (TACE) or radioembolization of the liver to prevent nontarget injury by the therapeutic agent. Although proximal phrenic embolization with coils or large particles is generally well tolerated, diaphragmatic impairment has been described following this procedure in up to 40% of patients.²² Phrenic artery

embolization should therefore be approached cautiously in patients with limited pulmonary reserve. Phrenic arteries also contribute collateral flow to the bronchial artery territory, and these branches should be considered for embolization in the setting of hemoptysis.

CELIAC ARTERY

The celiac trunk is a candidate for embolization in the setting of a celiac aneurysm²³ or pseudoaneurysm. Celiac origin exclusion and/or embolization have also been described as maneuvers to extend the inferior “seal zone” during endovascular repair of thoracic aneurysms.^{24,25} In either scenario, blood supply to the liver is usually maintained by collateral flow from the superior mesenteric artery (SMA) through the pancreaticoduodenal arcade and gastroduodenal artery (GDA). Pancreaticoduodenal artery supply to the pancreatic and gastroepiploic arteries provides additional collateral blood flow to the celiac distribution, supplying short gastric and splenic arteries. If there is concern regarding the adequacy of collateral supply to the celiac territory, it can be evaluated before definitive embolization by performing SMA arteriography during balloon occlusion of the celiac trunk.²⁵

COMMON HEPATIC ARTERY

The common hepatic artery is (in the case of a widely patent celiac trunk) a conduit vessel that provides important arterial supply to the liver and gallbladder. In the case of patent celiac and superior mesenteric arteries and a well-developed GDA, the common hepatic artery segment itself may be safely embolized with coils or a

vascular plug device. Clinical scenarios where this would be effective would be limited to true or false aneurysms involving only this segment, which is unusual. It is important to recognize that in cases of celiac occlusion, the common hepatic arterial flow may reverse and serve as a conduit for splenic arterial supply.

PROPER HEPATIC ARTERY

The proper hepatic artery is a conduit vessel for hepatic perfusion; embolization of the proper hepatic artery leaves the liver parenchyma entirely dependent on the portal vein for oxygenation.

RIGHT AND LEFT HEPATIC ARTERIES

The left or right hepatic arteries can be selectively embolized in the setting of trauma or therapeutically for hepatic malignancy if the portal vein is patent and there is adequate hepatic reserve. In the treatment of lobar hemorrhage, the degree of intrahepatic collateralization should not be underestimated. Proximal coil embolization of the right or left hepatic arteries can permit persistent bleeding in the periphery from reconstituted vessels via the opposite main trunk branch (Fig. 5). Therefore, if distal catheterization—with placement of coils both proximal and distal to the injury—is not technically possible, flow-directed occlusion of the branch peripheral to the injury with Gelfoam or other particulate agents is necessary to prevent collateral bleeding.

The main right and left hepatic arteries are commonly treated in separate sessions during catheter-directed treatment of unresectable hepatic malignancy. The agents used include an array of materials from

Figure 5 (A) Celiac angiogram shows a large right hepatic artery pseudoaneurysm following iatrogenic injury from retrograde cholangiopancreatography (ERCP). (B) Right hepatic angiogram following coil embolization distal and proximal to the pseudoaneurysm demonstrates filling of distal branches through hepatic collaterals. This illustrates the potential for hepatic backbleeding from proximal embolization alone.

Gelfoam to radioactive beads and resins to chemotherapeutic agents mixed with ethiodized oil. Combinations of these agents are often used in the same setting. Coil embolization is generally not recommended for this purpose because permanent proximal occlusion may compromise subsequent access for additional palliative procedures.

GASTRODUODENAL ARTERY

The GDA can be empirically embolized in the treatment of upper gastrointestinal (GI) bleeding localized to the proximal duodenum. The proximal GDA is also empirically embolized to widen the safety margin of hepatic radioembolization.²⁶ Discrete pseudoaneurysms of the GDA can also be embolized safely. However, GDA embolization should be approached with caution in cases of concurrent occlusion of the celiac or SMA origins. In such cases, the GDA may serve as an important conduit vessel providing perfusion to the liver or bowel, respectively. In treating the GDA, coil embolization is usually preferred over particulate embolization because the latter has a high likelihood of nontarget occlusion of branches to the pancreatic head. In cases of GDA pseudoaneurysm, embolization both distal and proximal to the lesion is essential to prevent backbleeding.

PANCREATICODUODENAL ARCADE

All branches (superior, inferior, anterior, and posterior) of the pancreaticoduodenal arcade can be safely embolized in the setting of GI bleeding or pseudoaneurysm. Due to the rich collateralization in this region, control of bleeding often requires wider embolization than is suggested initially even by superselective angiography. Completion angiography after embolization of individual branches often reveals additional feeding vessels. This often complicates simple coil embolization. Wider embolization with Gelfoam slurry or large particles to block collaterals may be necessary and is generally safe due to regional contribution from the dorsal pancreatic and transverse pancreatic branches.

RIGHT GASTRIC ARTERY

The right gastric artery can safely be embolized in almost all cases, although care should be taken in patients who have undergone previous gastric surgery, which may have disrupted normal gastric collateral pathways. This branch is commonly embolized electively before radioembolization of the liver.

LEFT GASTRIC ARTERY

The left gastric artery can be embolized empirically in the case of bleeding in the gastric fundus or distal

esophagus. This is a very well-tolerated procedure, although caution must be observed when there is a history of previous gastric surgery that may have disrupted the normal collateral pathways, which protect against gastric ischemia. It is important that the operator be aware of two relatively common anatomic variants: (1) the left hepatic artery arises entirely from the left gastric artery in 3 to 10% of patients, and (2) accessory left hepatic arteries arise from the left gastric in an additional 10% of cases.²⁷ Care should be taken to embolize the gastric artery distal to variant hepatic arteries, for two reasons. First, particles introduced proximally to these branches will flow into the liver and, especially in cases of portal vein occlusion, could cause hepatic parenchymal infarction. Second, coils placed proximally to these branches could allow persistent perfusion of a distal gastric artery lesion through retrograde flow from the hepatic collaterals.

SPLENIC ARTERY

Splenic artery embolization in the setting of trauma is commonly performed and accepted. In cases of severe splenic injury, successful control of hemorrhage is more important than maintaining organ function. However, in general, most splenic trauma can be managed with preservation of the spleen. For discrete injury to distal branches, selective embolization is safe and well tolerated, although it may be technically difficult given the usual tortuosity of the splenic artery. Because they are truly end-arteries, splenic branch or intraparenchymal vessels can be effectively treated by proximal embolization alone. Unlike other branches discussed in this article, splenic branches do not generally require embolization distal and proximal to the sites of injury. Multiple distal branch injuries may be treated by selective proximal branch embolization, but often bleeding sites are quite numerous and the required embolization would result in little viable remaining splenic tissue. The accepted approach for multiple sites of intrasplenic extravasation is proximal splenic artery embolization.^{28,29} This interrupts the usual direct, high-pressure pathway to the splenic parenchyma while preserving lower pressure collateral flow via three pathways: (1) gastroduodenal to right and then left gastroepiploic arteries, (2) transverse pancreatic to pancreatic magna to splenic arteries, and (3) left gastric to short gastric arteries. These collaterals maintain splenic perfusion and function while the decrease in arterial pressure allows bleeding sites to tamponade and ultimately to heal.³⁰

Partial embolization of the spleen is an effective mechanism for controlling hypersplenism of various etiologies. The technique is to "prune" splenic artery branches with the proximal delivery of flow-directed emboli, including polyvinyl alcohol (PVA), Gelfoam, and deliberately undersized coils.³¹⁻³⁴ At sequential

sessions, embolization of a third of the remaining parenchyma is performed until thrombocytopenia is reduced. To reduce the likelihood of abscess formation, some authors have advocated using Gelfoam soaked in antibiotics as the agent of choice.³⁵

SUPERIOR MESENTERIC ARTERY AND BRANCHES

Although there are communications between the mesenteric vessels and the mesenteric arcades that ensure local collateral arterial supply, mesenteric ischemia or bowel infarction is a risk whenever embolizing in the bowel. Although the segment of the SMA proximal to the first branch may theoretically be occluded if the celiac and inferior mesenteric artery (IMA) are patent and the normal collateral pathways are present, the initial choice to treat a focal injury from an endovascular approach would be stent graft repair. Beyond the origin of the intestinal arcades, the communication between the remainder of the branches permits treatment of focal aneurysms or arteriovenous lesions with proximal and distal coil occlusion. If adequacy of the arcade collaterals is questionable, an injection with an occluding balloon in place is useful. Because of the extensive collateral arcades, treatment of small- or large-bowel hemorrhage requires subselective catheterization to the most distal arcade or terminal branch. Proximal and distal embolization that isolates an arcade risks bowel infarction, whereas proximal embolization allows continued bleeding from collateral supply to the lesion. Ideally, the bleeding terminal branch is selected and embolized. In the case of life-threatening GI bleeding, wider embolization may be undertaken with Gelfoam if the patient is not a surgical candidate, coagulation factors have been normalized, subselective catheterization has failed, and the patient has failed or is not a candidate for vasopressin infusion. Although the bowel is very sensitive to infarction, a late postembolic ischemic stricture may be a better solution than ongoing hemorrhage or a major abdominal surgery.

ADRENAL ARTERIES

Adrenal arteries can be a source of significant retroperitoneal hemorrhage. Bleeding can occur following trauma, rupture of an aneurysm, erosion by tumor, or spontaneously as the result of stress-related conditions such as sepsis or burns.^{36–38} The adrenal glands are well vascularized—by branches from the inferior phrenic artery, the aorta, and the renal artery—and are richly collateralized within the gland. Subselective arteriography and embolization is recommended to preserve adrenal gland viability and function. Acute adrenal insufficiency has been reported in up to half of patients following bilateral adrenal hemorrhage.³⁹ If the functional capacity of the contralateral adrenal gland is

unknown, care should be taken when the embolization required to control bleeding may infarct an entire gland.^{40,41}

RENAL ARTERIES

The renal arteries are true end arteries; parenchyma distal to the level of occlusion usually infarcts. Therefore, the more subselectively one can embolize, the more renal parenchyma may be preserved. Although the main renal artery trunk can be quickly and efficiently embolized in the setting of massive hemorrhage from a main renal artery injury, preservation of renal blood flow by endovascular stent grafting (if technically feasible) or open surgical repair is preferred. In cases of hemodynamic instability, an occlusion balloon in the renal origin may temporize while a stent graft is prepared or while the patient is transported for operative repair. Because they are truly end arteries, renal branch or intraparenchymal arteries can be effectively treated for injury by proximal embolization alone.

Extensive renal embolization is commonly performed before resection of large renal tumors, as a palliative technique in patients who are not resection candidates, or to destroy nonmalignant but nonetheless pathological renal tissue nonsurgically. When performed as an adjunct to surgical resection, one usually embolizes with a combination of particle agents and coils or plugs. Close coordination with the surgeon performing the resection is crucial to correctly time the procedure, and the placement of coils or plugs at or near the renal artery origin should be avoided to prevent displacement of these devices into the aorta during surgical clamping. When performed as a definitive procedure, renal embolization should be with coils or Amplatzer plugs, preceded by small particles or alcohol to more effectively destroy the target tissues. Alcohol is delivered with an occluding balloon in place and must be aspirated before the balloon is deflated to avoid the release of accumulated alcohol into the systemic arterial or venous systems. Such release can have a devastating outcome.

GONADAL ARTERIES

Gonadal arteries can be embolized in the setting of severe or life-threatening bleeding associated with pelvic trauma or postpartum hemorrhage. Prominent ovarian arteries are also embolized during uterine artery embolization (UAE) procedures where there is significant ovarian artery supply to the uterus. However, one must assume an increased risk of subsequent ovarian insufficiency and amenorrhea, especially if bilateral ovarian artery embolization is performed. To prevent ovarian insufficiency, stepwise embolization of the ovarian arteries in separate sessions can be performed if conventional UAE fails to control fibroid symptoms.⁴² Ideally, one advances the

Figure 6 (A) Left femoral angiogram shows inflamed mycotic pseudoaneurysm. Note occlusion of the superficial femoral and profunda femoral trunks. (B) Computed tomography after surgical excision shows multiple broken needles in the surgical field.

catheter beyond the ovary to embolize only the fibroid tissue, but this is often technically impossible.

COMMON AND EXTERNAL ILIAC ARTERIES

The common and external iliac arteries are conduit vessels required for lower extremity perfusion. These vessels generally cannot be embolized safely and should be repaired with a stent graft or by open surgery. Acute occlusion of these vessels results in ischemia that can present immediate limb threat or long-term claudication. In cases of catastrophic bleeding, proximal temporizing balloon occlusion should be attempted from a contralateral groin approach. An injury that involves the aortic bifurcation may require infrarenal aortic balloon occlusion.

In cases of mycotic femoral pseudoaneurysms resulting from illicit drug use, obtaining control of the proximal common femoral artery with open surgery can be technically difficult, especially if—as is common—the surgical field is littered with broken needles. In these unusual cases, coil or Amplatzer plug embolization of the distal external iliac artery may offer a rapid and appealing alternative. Limiting the superior extent of the required dissection may help to limit occupational hazards associated with open resection and ligation of the common femoral artery in patients with infected aneurysms resulting from extensive intravenous (IV) drug abuse. (Fig. 6)

INTERNAL ILIAC ARTERIES

Proximal and distal coil embolization may be used to treat focal injury to the internal iliac artery or the more proximal aspects of its branches. In addition, both internal iliac arteries can generally be safely embolized nonselectively with Gelfoam slurry or

pledgets in the setting of pelvic trauma. These branches are well collateralized from lumbar, contralateral internal iliac, and profunda branches.⁴³ There have been reports of gluteal ischemia with nonselective bilateral embolization using Gelfoam,⁴⁴ but this risk appears to be associated with concomitant local soft tissue injury.⁴⁵ The greater risk is from inadequate embolization leading to unchecked pelvic arterial bleeding.⁴⁶

UTERINE ARTERIES

The uterine arteries can be embolized in patients with life-threatening postpartum bleeding. Gelfoam slurry is the embolic agent of choice. Bilateral uterine arteries are also safely and commonly embolized in the treatment of uterine leiomyoma. Gelfoam, PVA, and calibrated microspheres have all been employed effectively for this procedure. Coils provide a proximal occlusion, rather than occlusion of branches within the leiomyomata, and should be avoided.

INTERNAL PUDENDAL

The internal pudendal arteries can be embolized safely in the setting of hemorrhage from pelvic trauma. Because there is a high rate of neurogenic impotence following pelvic fractures severe enough to cause pudendal artery injury, the impact of pudendal embolization on male erectile function cannot be independently evaluated. One retrospective study found no increased incidence in erectile dysfunction in trauma patients with pelvic fractures who underwent Gelfoam embolization compared with matched controls.⁴⁷

Figure 7 Left internal pudendal angiogram reveals a traumatic pseudoaneurysm causing high-flow priapism after a hockey injury. The left penile artery was selectively embolized with a single Gelfoam pledget.

Figure 8 (A) Angiogram of the right thigh following gunshot wound. Note profunda branch bleed (arrow). (B) Selective angiogram of the profunda femoral trunk shows the bleeding culprit profunda branch. (C) Following coil embolization, bleeding is controlled.

Penile branches of the internal pudendal may be embolized in the setting of high flow priapism. (Fig. 7) In such cases, the goal is to occlude flow long enough for priapism to resolve, but without permanent compromise of erectile function. Thus, the agent of choice is Gelfoam or, historically, autologous clot. Due to concerns of future erectile function/dysfunction, bilateral embolization should be avoided if technically possible.

COMMON FEMORAL ARTERY

The common femoral artery is a conduit vessel required for lower extremity perfusion. This vessel generally cannot be embolized safely and should be repaired surgically. In cases of catastrophic bleeding, proximal temporizing balloon occlusion should be attempted from a contralateral groin approach; however, external manual compression can often achieve the same results. As described previously, when common femoral artery lesions derive from illicit drug use, one must exercise great caution in performing manual compression because broken needles may be present in the soft tissues.

EXTERNAL PUDENDAL

Superficial and deep external pudendal arteries can be embolized as needed in the treatment of traumatic bleeding. However, at least one study has shown that the external pudendal branches contribute to erectile function in up to 7% of men, with several cases of erectile dysfunction following isolated external pudendal artery injuries associated with surgery.⁴⁸

INFERIOR EPIGASTRIC ARTERY

The inferior epigastric artery can be embolized safely in most instances. In cases of aortic or ipsilateral iliac artery occlusion, the inferior epigastric artery may aid in lower extremity collateral perfusion via internal mammary to superior epigastric collaterals, forming a natural axillary to femoral arterial route. In such cases, branch embolization while maintaining the main trunk would be preferred.

PROFUNDA FEMORAL ARTERY

The profunda femoral artery is arguably the most important vessel for preserving lower limb perfusion. Small muscular branches can be embolized safely in the setting of bleeding; however, the main trunk must be preserved if at all possible (Fig. 8). In the case of catastrophic bleeding in the thigh, Gelfoam embolization of profunda artery injuries may be performed only if the superficial femoral artery is patent.

PERIPHERAL LOWER EXTREMITY ARTERIES

The superficial femoral and popliteal arteries are conduit vessels for lower extremity perfusion and should not be embolized. In cases of catastrophic bleeding, proximal temporizing balloon occlusion can be attempted (Fig. 9), although a simple tourniquet may be equally effective and more expeditious. Individual muscular branches are expendable and may be embolized in the case of trauma, but this generally entails coaxial and potentially time-consuming microcatheter techniques.

Figure 9 (A) Right superficial femoral angiogram after gunshot wound demonstrates a gushing bleed despite blood pressure cuff placed at the thigh to act as a tourniquet. (B) Spot image shows placement of a temporizing occlusion balloon to aid surgical repair.

Although maintenance of at least one trifurcation vessel is mandatory for preservation of the foot, these are difficult vessels to repair surgically and any one of the three can be considered expendable if the others are patent. The surgical treatment of active arterial bleeding from these vessels is often ligation. If an injury is identified at angiography, embolization can be expeditious and equally

Figure 10 (A) Angiogram right below the knee demonstrates an irregular pseudoaneurysm in the posterior tibial artery. The anterior tibial artery and peroneal artery are intact. The posterior tibial vessel was not felt to be salvageable. (B) Angiogram following Onyx embolization, which provided proximal as well as distal control.

effective (Fig. 10). Due to the rich distal collateralization between tibial-peroneal arteries, retrograde flow distal to the target is expected, and both proximal and distal occlusion should be performed. If the limb is not viable from a vascular or orthopedic standpoint, embolization has little role, as placement of a tourniquet can be performed readily and with far less expense.

CONCLUSION

Embolization can be performed safely in most, but not all, vascular territories. Some high-risk vessels should only be embolized when not acting puts the patient at even greater risk of permanent organ dysfunction or death, and there are no viable medical or surgical options. Having a detailed knowledge of the relevant collateral anatomy is essential when embolizing high-risk vessels. In richly collateralized areas, consideration of all other potential sources of arterial flow is essential for successful embolization.

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