Surgical Management of Vascular Trauma

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KEYWORDS

• Vascular trauma • Trauma care • Hemorrhage

KEY POINTS

- Vascular injuries remain among the most challenging entities encountered in the setting of trauma care.
- Improvements in diagnostic capabilities, resuscitation approaches, vascular techniques, and prosthetic device options have afforded considerable advancement in the care of these patients.
- This evolution in care capabilities continues — most recently in the form of endovascular treatment modalities.
- Despite advances, however, uncontrolled hemorrhage due to major vascular injury remains one of the most common causes of death after trauma.
- Successful management of vascular injury requires the timely diagnosis and control of bleeding sources; to facilitate this task, trauma providers must appreciate the capabilities and limitations of diagnostic imaging modalities.
- Above all else, trauma providers must understand when and how to most effectively apply these strategies.

INTRODUCTION AND GENERAL CONSIDERATIONS

Vascular injuries remain among the most challenging entities encountered in the setting of trauma care. Although described since the earliest eras of surgical history, it has only been in the latter half of the twentieth century that significant progress has been made in the management of these injuries. Improvements in diagnostic capabilities, resuscitation approaches, vascular techniques, and prosthetic device options

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have afforded considerable advancement in the care of these patients. This evolution in care capabilities continues — most recently in the form of endovascular treatment modalities. Despite these advances, however, uncontrolled hemorrhage due to major vascular injury remains one of the most common causes of death after trauma.

Successful management of vascular injury requires the timely diagnosis and control of bleeding sources. To facilitate this task, trauma providers must appreciate the capabilities and limitations of diagnostic imaging modalities. They must also prove facile in the effective emergent control of these injuries and understand the appropriate role of both initial and definitive management strategies. Above all else, they must understand when and how to most effectively apply these strategies.

Entire textbooks have been dedicated to the topic of vascular trauma. The limited context of this article strives to emphasize key topics pertinent to the contemporary care of vascular injuries. Key principles are reviewed, with additional comment on injuries at specific locations and injury in unique populations.

INITIAL EVALUATION

Patient presentation is an important consideration in the choice of diagnostic strategies that might be used in the evaluation of suspected vascular injuries. For patients presenting with active hemorrhage, the diagnosis is straightforward and no additional evaluation is required. As a general principle, the presence of a hard sign of vascular injury (**Table 1**) warrants immediate operation for exploration and earliest possible control of vascular hemorrhage. Patients who present with soft signs (see **Table 1**) suggestive of occult vascular injury, however, benefit from additional diagnostic imaging. A variety of imaging options are available, each with important capabilities and limitations to consider.

Duplex Ultrasonography

Duplex ultrasonography can be performed at the bedside. This imaging modality does, however, require effective training for utilization and likely has limited applicability in most acute trauma settings. Images may be obscured by the presence of associated hematoma, soft tissue injury, and bony injuries. When adequate images are attainable, however, color flow duplex and spectral waveform analysis combine to provide invaluable information (**Fig. 1**). This tool is also useful for follow-up of injuries treated nonoperatively and for postoperative evaluation of vascular injury repairs.

Computed Tomographic Angiography

Modern Computed Tomographic angiography (CTA) has emerged as the modality of choice for the diagnosis of vascular injury for the majority of stable trauma patients with vascular injuries — even at peripheral arterial injury locations.[1–3] This modality

Table 1
Signs of vascular injury

Hard Signs	Soft Signs
Active pulsatile bleeding	Diminished pulses distal to the injury site
Absent pulses distal to the injury site	Stable, small hematoma
Expanding or pulsatile hematoma	Proximity to major vessels
Bruit or thrill at the injury site	Peripheral nerve deficit
Unexplained shock	History of hemorrhage at scene
	Suspicious pattern of fracture or dislocation

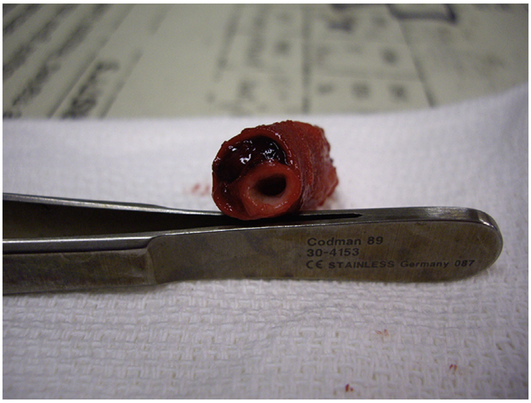

Fig. 1. Gross back-table photo of a dissection of the superficial femoral artery detected by duplex ultrasound evaluation.

is generally more rapid than traditional angiography to obtain at most centers, is widely available, and yields high-resolution imaging that can be used for management planning. It is important to consider, however, that optimal imaging requires a contrast load — which may be detrimental to patients with impaired renal function at presentation. Additionally, although rapidly obtained, CTA images require time to obtain that may not be afforded in patient who has aggressive hemorrhage and instability. Despite these concerns, CTA has emerged as the modality of choice for vascular imaging after trauma at most centers.

Traditional Angiography

Once the mainstay of vascular imaging, traditional digital subtraction angiography has now largely been replaced by CTA. In specific instances, however, this modality remains an integral tool of evaluation — particularly when foreign metal objects in proximity to vascular structures result in scatter artifacts that obscure CTA images. One classic scenario where this may occur is that of a shotgun blast injury at relatively close range — resulting in focused metallic burden that defies optimal CTA imaging of nearby vascular structures. In addition, the resources and expertise that must be mustered for optimal employment of traditional angiography may take considerably more time than modern CT-based imaging.

Intravascular Ultrasound

Although not used aggressively in a majority of centers, intravascular ultrasound (IVUS) bears mention as an emerging technology for the imaging of large vessel injuries.[4] This technology has already demonstrated potential in the effective characterization of blunt thoracic aortic injuries and can serve to provide key information regarding optimal sizing of endovascular covered stent grafts for these injuries. Although additional study is required, IVUS demonstrates some promise in select applications of this kind after vascular injuries.

EMERGENT MANAGEMENT — DAMAGE CONTROL SURGERY

Although definitive surgical treatment of vascular trauma remains the ultimate objective of care for patients requiring surgery, there are important caveats to consider. Vascular repairs can prove technically demanding and time-consuming affairs. Patients with physiologic depletion due to hemorrhage may require the employment of abbreviated damage control approaches that permit stabilization of the patient. In this fashion, a second intervention can be undertaken in a more controlled setting and under circumstances that permit an optimal definitive repair. Similarly, damage control approaches may be optimal in situations that demand expedient conduct of more critical procedures. For example, a shunt can be used to restore temporary perfusion to a distal limb so that a craniectomy can be conducted to prevent herniation in the setting of severe traumatic brain injury.

A variety of vascular damage control adjuncts have been described. Each has utility in specific situations but also potential pitfalls. An exhaustive discussion of the application of these adjuncts is not permissible here, but each warrant mention as a potential tool of emergent vascular trauma care.

Ligation

As a general rule, all major named arteries should be repaired or reconstructed if at all possible. In the setting of damage control, however, ligation may be considered for specific vessels if the conduct of repair will compromise the ability of the patient to survive operation. It must be recognized, for example, that the principle of “life over limb” applies in specific settings. Specific anatomic redundancies of the vascular system and collateral pathways for distal perfusion may also afford ligation as a simple answer for the patient in extremis. Applicable situations of this type include ligation of the radial artery in an upper extremity that has dominant ulnar perfusion to the palmar arch or ligation of the peroneal artery in the setting of an intact tibial artery outflow to the plantar arch.

In more drastic situations, ligation of the carotid artery has been described without residual ischemic sequela — provided the patient has an intact circle of Willis. Ligation of the subclavian artery has also been described, with preservation of upper extremity perfusion. Although ligation in these more extreme situations has been espoused an effective means of salvaging life, modern experience has suggested that the liberal use of temporary arterial vascular shunts may prove a more appropriate damage control intervention for injuries to these vessels.

A majority of venous injuries should be ligated in the setting of damage control, whereas in stable patients formal repair of simple injuries is advisable. The decision to repair venous injuries that require an interposition graft should be made on a case-by-case basis and should be considered advisable in larger venous structures. As with arterial injury, temporary vascular shunts can be used for larger venous injuries as a temporizing measure.

Temporary Vascular Shunts

Endoluminal temporary shunts should be used in damage control situations that involve injuries to moderate-sized arteries (ie, popliteal and visceral) but can be effectively used in a variety of venous and arterial vessels of varying sizes.[5] Commercially available shunts used in elective vascular surgery are ideally suited for this purpose. Careful insertion of the shunt is required to prevent additional vessel trauma and distal dissection. Prior to insertion, the injured vessel should be débrided and all thrombus removed both proximally and distally. A Rummel tourniquet using either umbilical tapes or silastic vessel loops can be used to secure the shunts and prevent dislodgment during patient movement (**Fig. 2**).

Temporary Balloon Occlusion

Growing experience with the utilization of endovascular technologies in the trauma setting has demonstrated that balloon occlusion for proximal vascular control can

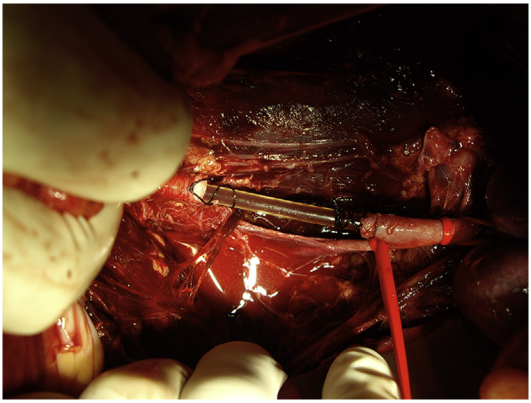

Fig. 2. Vascular shunt of the superficial femoral artery used in damage control setting.

prove useful in a variety of settings. Endovascular balloon positioning and inflation can be used either as a bridge to definitive endovascular repair of traumatic injuries or in a hybrid approach to facilitate open exposure and surgical repair. The use of endovascular balloon occlusion in a hybrid fashion may prove particularly useful when vascular injuries occur at anatomic sites that represent challenging surgical exposures, including axillosubclavian and iliac artery injuries occurring in the junctional region between the torso and the extremities.

Recent evidence also suggest that there may be a role for early Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) for patients who present to the trauma center with significant hemorrhage at noncompressible sites.[6] Although additional study is required on the topic, early evidence suggests that REBOA is a feasible alternative to traditional aortic occlusion via resuscitative thoracotomy for patients in extremis due to bleeding from these sources.[7]

DEFINITIVE REPAIR

Definitive vascular repair may take place after stabilization of a patient after damage control utilization or as initial treatment in patients who are stable enough to tolerate the time required for repair at the first operation. The modern era of care affords a variety of potential definitive solutions to most vascular injury problems. The choice of repair must be made with careful consideration of the potential role of each approach.

Primary Repair

Primary repair of both venous and arterial injuries can be considered for clean lacerations of vessels. It may also be entertained when, after appropriate débridement, the gap between the proximal and distal ends of the vessel can be mobilized to come together in a tension-free fashion. Traditional dogma has often espoused 2 cm as the maximal gap that can be bridged to achieve this goal. In practice, however, even a smaller gap between anastomotic ends can prove problematic at select anatomic locations. A safe principle for utilization is to strongly consider an interposition graft when any tension is anticipated with attempted primary repair.

Specific suture size and repair technique are dictated by vessel size and location. Repair with interrupted suture may prove the least likely to result in an anastomotic stricture when addressing smaller arteries. The adjunctive utilization of vascular pledgets may prove useful in specific large vessel repairs, particularly when conducting tenuous repairs of large, thin-walled venous structures.

Autogenous versus Prosthetic Conduit

Interposition repair using autogenous reversed saphenous vein grafts remains a standard of vascular injury repair for appropriately sized vessels (**Fig. 3**). These native vessels are considered a lower risk for potential infection and are familiar to the majority of trauma and vascular surgeons. Size mismatch, however, frequently makes this option an impossibility in the trauma setting. In addition, adequate vein may not be available for a variety of reasons, and there is a concern of possible delayed aneurysmal conversion of these grafts. Finally, saphenous vein harvest can take additional time to perform.

Prosthetic Conduits

Prosthetic grafts are an effective and durable alternative when used in surgical fields that are not compromised by gross contamination. For vessels greater than 4 mm to 6 mm in diameter, a prosthetic graft is also an advisable solution to avoid the size mismatch that can be problematic with saphenous vein utilization. Prosthetic utilization also obviates time that is required for vein harvest. When prosthetic is selected as the interposition conduit after vascular injury, expanded polytetrafluoroethylene (ePTFE) is preferred due to its higher resistance to infection.[8]

Endovascular Stent Grafts

For stable patients, emerging endovascular capabilities have demonstrated considerable promise a specific anatomic locations of vascular injury. The treatment of blunt thoracic vascular injury with thoracic endovascular aortic repair (TEVAR) has, for example, proved superior to traditional open repair techniques.[9,10] The potential of endovascular repair at other anatomically challenging locations, such as the axillosubclavian region, has also been recently demonstrated.[11,12] Although additional study is required to determine the optimal role of endovascular stent grafts in the treatment of vascular injuries at other locations, early incorporation of providers with endovascular skillsets may prove useful in determining the repair options for these injuries.

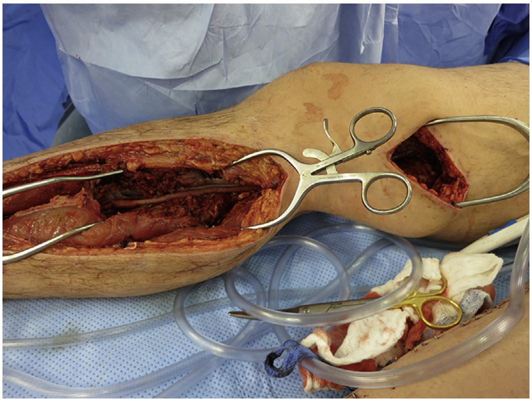

Fig. 3. Saphenous vein interposition graft repair of a popliteal artery injury.

Intraoperative Anticoagulation

The use of systemic heparinization is ubiquitous to elective vascular surgery and may be beneficial for the operative management of vascular injuries after vascular control and during reconstruction. The use of this adjunct has been shown to improve outcomes in select vascular injuries, including carotid and popliteal artery injuries.[12,13] The decision to use systemic heparinization does, however, require careful consideration and multidisciplinary discussion with the trauma team. Appropriate use requires patient stability, the absence of traumatic brain injury, or neurologic deficit and minimal associated blood loss from concomitant solid organ and musculoskeletal injuries. When heparin is contraindicated, the authors recommend liberal instillation of heparinized saline into the proximal and distal segments of the injured vessel at regular intervals during repair.

Postoperative Evaluation

After any vascular intervention or repair, restoration of perfusion should be confirmed appropriately. For patients with return of bounding distal pulses, physical examination may suffice. A multiphasic hand-held Doppler signal is a reassuring finding that should be sought when palpable pulses are not clearly appreciated or there is a discrepancy between sides for repairs of extremity vessels. Any discrepancy should likely be investigated with an intraoperative formal duplex examination or angiogram to confirm patency of repair and the absence of a missed additional injury. Even among patients who have clear demonstration of patency at the time of initial operation, significant vigilance must be maintained with serial examinations/Doppler utilization in a monitored setting postoperatively to guard against early loss of patency.

An additional question postoperatively remains the optimal role of postintervention anticoagulation or antiplatelet therapy. Although data to definitively guide management are currently lacking, the routine use of aspirin for most repairs should be considered long term, particularly in the setting of stent utilization or synthetic conduit repairs. More advanced antiplatelet medications should also be considered strongly in these 2 settings. The role of heparin, direct-thrombin inhibitors, or other agents has not been defined — but may be of use for repairs/interventions considered at high risk for thrombosis. In every instance the risk of antiplatelet or anticoagulation induced bleeding must be carefully weighed against the benefit of use — which requires careful consideration of individual risk for each patient. It is the authors' hope that additional data will accumulate in coming years to better guide these choices.

SPECIFIC INJURIES

Head and Neck/Cerebrovascular Injuries

The neck is classically divided into 3 distinct anatomic: zone I extends from the clavicles to the cricoid cartilage, zone II from the cricoid cartilage to the angle of the mandible, and zone III from the angle of the mandible to the base of the skull. Injuries in zone II are the most accessible for direct surgical exposure, which is performed through an anterolateral cervical exploration. Exposure of injuries in zone I usually requires median sternotomy for proximal control. Surgical exposure of injuries in zone III is challenging, which makes these lesions best treated with an endovascular approach.

Carotid arteries

Differently from blunt cerebrovascular injuries, which are in general treated with anticoagulation or antiplatelet therapy (**Fig. 4**), penetrating cerebrovascular injuries

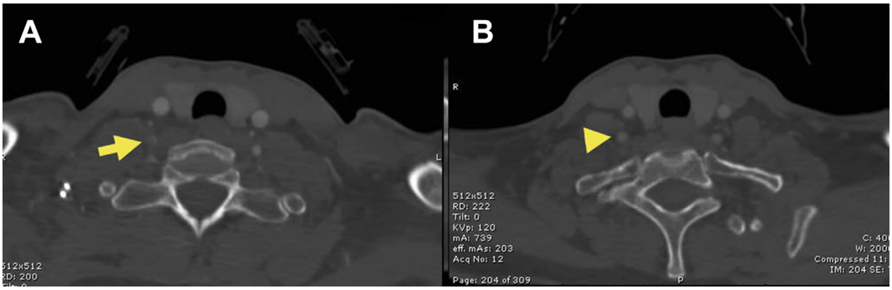

Fig. 4. CT scan demonstrating blunt injury of the right vertebral artery (*A*) Injury denoted by arrow, with complete resolution after 6 weeks on antiplatelet therapy. (*B*) Former location of injury indicated by arrowhead.

generally require surgical intervention. Unless hard signs of cerebrovascular injury are present, mandating surgical exploration, CT angiogram is imaging modality of choice for diagnosis.

Injuries to the external carotid artery with active bleeding are, in general, best managed by ligation or embolization (Fig. 5). Penetrating injuries to the internal and common carotid arteries are best managed by direct repair or reconstruction.[13,14] For those cases in which the tissue destruction is minimal, usually resulting from a stab wound, direct repair or patch may be applicable. In most instances, however, particularly with firearm injuries, arterial reconstruction is necessary.

The carotid sheath is exposed through an anterolateral neck incision. There is usually a significant hematoma that distorts the anatomy and may increase the risk of cranial nerve damage. After the carotid is exposed, proximal and distal control is obtained and the injury is carefully evaluated. All nonviable tissue should be débrided and a decision is made regarding the need to use an interposition graft. A reverse greater

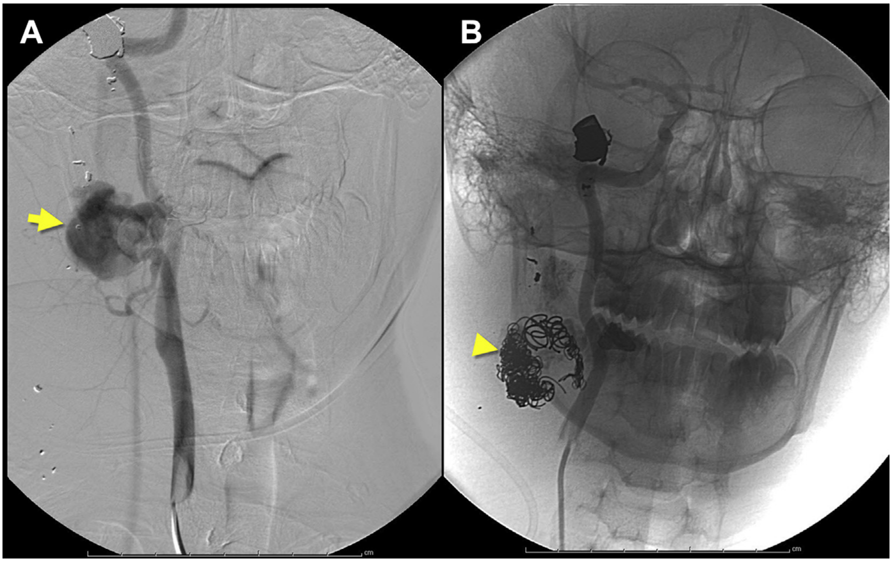

Fig. 5. Angiography demonstrating active extravasation from a gunshot wound to the right external carotid artery (*A*) indicated by arrow and after successful coil embolization (*B*) indicated by arrow head.

saphenous vein graft is the preferred conduit for carotid reconstruction Fig. 6; however, the repair can be done with ePTFE if time is of the essence or if no suitable autogenous conduit is available.

Perioperative shunting is usually not necessary for injuries of the common carotid artery particularly if there is adequate back bleeding from the distal stump.

For internal carotid injuries, the use of a temporary shunt, although not definitively supported by data, may have a role not only in decreasing the risk of cerebral ischemia during the reconstruction but also in maintaining cerebral perfusion while an autogenous conduit is harvested or while other associated life-threatening injuries are addressed.

Vertebral artery

Because of its trajectory through the vertebral foramen from the sixth to the first cervical vertebrae, exposure to the vertebral artery is exceedingly challenging and repair is not feasible in most situations. If exposure of the vertebral artery, however, becomes necessary to control active bleeding, it can be achieved by unroofing the vertebral transverse process foramen using a rongeur or pituitary forceps. Ligation of the proximal segment, before the artery becomes surrounded by the bony structures, can be performed and it is an acceptable approach. Angioembolization techniques are also attractive therapeutic modalities for injuries of the vertebral artery.

Internal jugular vein

Isolated penetrating injuries of the jugular vein can be safely managed nonoperatively[15]; however, neck exploration is usually necessary to address associated injuries. Unilateral internal jugular injuries are best managed with ligation if significant stenosis of the vein would result from an attempt to repair. In the rare occasion of bilateral internal jugular vein injuries, at least one of the veins must be repaired because bilateral ligation invariably results in cerebral venous congestion with high mortality, this being the only indication for extensive internal jugular vein reconstruction with patch or interposition graft.

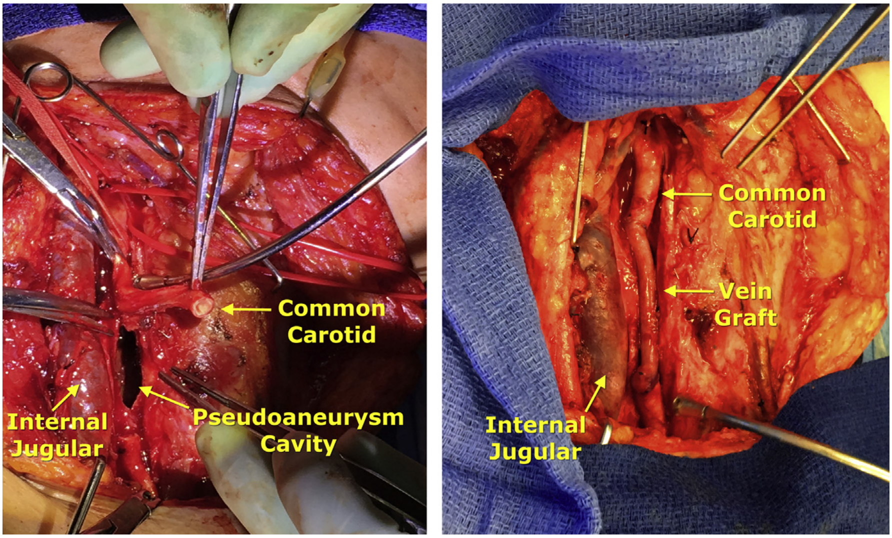

Fig. 6. Pseudoaneurysm of the right common carotid artery before and after repair with interposition graft using reverse greater saphenous vein.

Thoracic

Penetrating thoracic injuries

Penetrating thoracic vascular injuries are highly lethal and often present with exsanguination resulting in hemodynamic instability requiring immediate surgical exploration for resuscitation and hemostasis. Patients with thoracic penetrating wounds are managed according to the Advanced Trauma Life Support guidelines, usually involving a chest tube placement early during the primary survey and resuscitation phase. Hemodynamic instability and high-volume output from the chest tube are both indicators for thoracotomy. The decision regarding what incision to perform depends on the estimated injury trajectory and suspected vascular injury, side of high chest tube output, and need for open cardiac massage. It is also important to consider that not uncommonly more than one cavity may need to be explored, particularly if a transmediastinal or thoracoabdominal injury trajectory is suspected.

Injuries to the aortic arch branches are usually approached through a median sternotomy. This incision can also be extended through an anterolateral neck incision when additional exposure to the thoracic outlet is necessary (Fig. 7). Proximal left subclavian injuries may be challenging to control through a median sternotomy due to a more posterior location of this vessel. A left high thoracotomy through the second or third intercostal space provides optimal access and allows control of the proximal left subclavian artery. After proximal and distal control of the aortic arch, branch is obtained and hemostasis achieved, the next decision is how to best repair the vascular injury. Options include primary repair, patch, or reconstruction with an interposition graft. For the aortic arch branches, reconstruction with prosthetic grafts

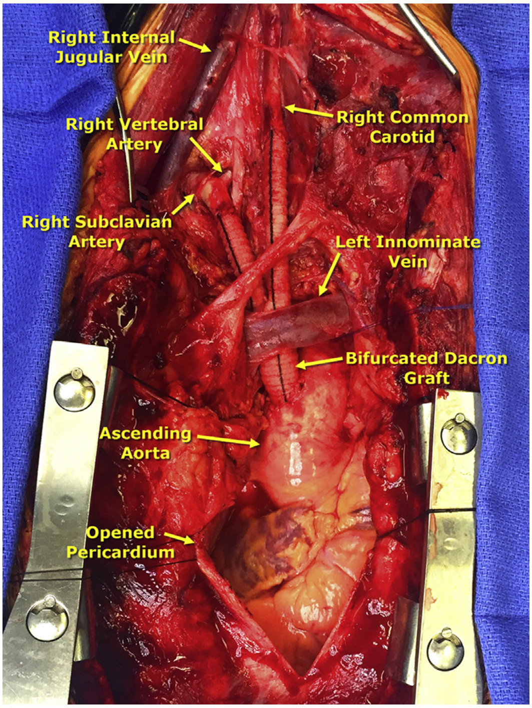

Fig. 7. Innominate artery injury repaired with an ascending aortic to right subclavian artery and right common carotid artery bypass using bifurcated Dacron graft.

(8–10 mm ePTFE or Dacron) is usually adequate due to the high patency rates of prosthetic grafts in these high-flow arterial beds.

All superior vena cava injuries should be repaired either primarily or using a venous or prosthetic patch. In those instances of destructive injuries to the superior vena cava requiring reconstruction with an interposition graft, large diameter (18–20 mm) ringed ePTFE grafts are the alternative of choice. These injuries, however, carry an exceedingly high mortality.

Penetrating injuries to the aortic arch are rarely survivable injuries. For those patients in whom repair is attempted, femoral cannulation and cardiopulmonary bypass may be necessary.

Blunt descending thoracic aortic injury

Thoracic aortic injury remains a major cause of mortality for victims of blunt trauma, with a majority of deaths occurring at the scene of the accident. For the select group of patients in whom exsanguination does not happen at the scene, significant changes have occurred in the way this injury is diagnosed and managed. CT scan has become the diagnostic imaging modality of choice and strict blood pressure control has significantly reduced the risk of rupture. This injury can, therefore, be addressed in a delayed fashion, after abnormal physiology is corrected and other immediately life-threatening injuries are treated. Ongoing progress in endovascular techniques have resulted in significant survival improvement and aortic stenting has now replaced open surgery as the preferred treatment modality.[16]

Currently, all patients with a diagnosis of blunt thoracic aortic injury should be considered candidates for endovascular repair. After strict blood pressure control is instituted in the ICU and associated life-threatening associated injuries are treated, endovascular aortic repair is performed using an endograft selected based on the initial chest CT scan (Fig. 8). IVUS can be used to confirm the location of the pseudoaneurysm and its distance from the aortic arch branches and to determine aortic diameters (Fig. 9). After deployment of the thoracic aortic endograft, completion angiogram is obtained to confirm complete exclusion of the pseudoaneurysm (Fig. 10). Coverage of the left subclavian artery by the endostent may be necessary to obtain adequate proximal seal (Fig. 11), which is usually well tolerated in trauma patients.[10,17,18] Stroke and spinal ischemia are the most important potential acute complications of left subclavian artery coverage. Myocardial infarction can also occur in patients with a history of left internal mammary coronary bypass. Subclavian steal syndrome and left arm claudication are both possible long-term sequelae of left subclavian artery ostial

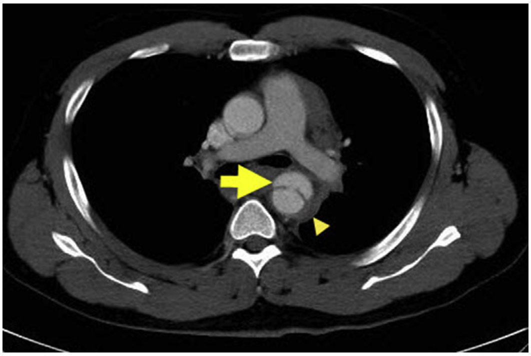

Fig. 8. Chest CT scan demonstrating descending thoracic aortic pseudoaneurysm (*arrow*) and mediastinal hematoma (*arrowhead*).

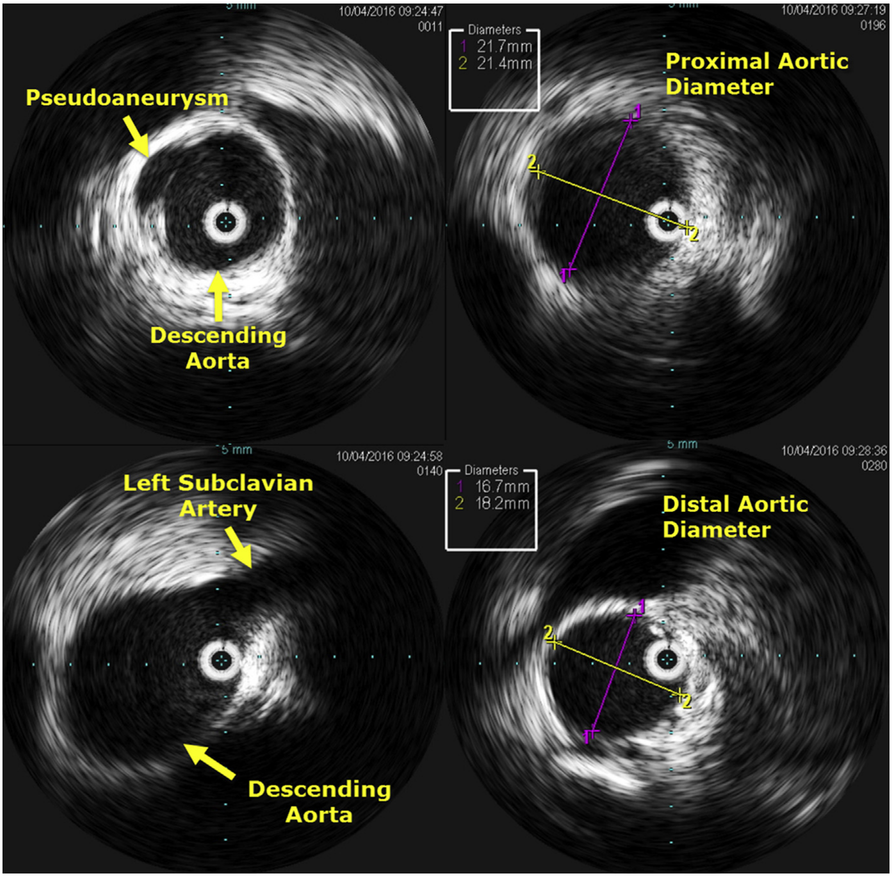

Fig. 9. IVUS during TEVAR, demonstrating pseudoaneurysm (*top left*), position of left subclavian artery (*bottom left*), and measurement of aortic diameters (*right top and right bottom*).

occlusion by the stent graft. If subclavian revascularization is needed, both carotid-subclavian bypass (Fig. 12) and subclavian-carotid transposition (Fig. 13) are acceptable surgical options.

A more expanded understanding of the natural history of blunt thoracic aortic injuries is evolving. Several groups have demonstrated that most Society for Vascular Surgery grade I and 2 injuries can likely be managed without repair and will not progress to aneurysm or rupture. Anticoagulation or antiplatelet use in these settings is under investigation, with the routine use of long-term aspirin used preferentially in some centers. When nonoperative management is selected, it is advisable that these injuries be referred after discharge to a vascular surgeon for long-term follow-up.

Lumbar drain is not used routinely but should be promptly placed in patients who develop symptoms of spinal ischemia, which is unusual in this setting.

Abdominal

Patients with penetrating abdominal vascular injuries are generally hemodynamic unstable on presentation and require immediate surgical exploration for hemostasis. Bleeding from retroperitoneal vascular injuries may remain contained and high level

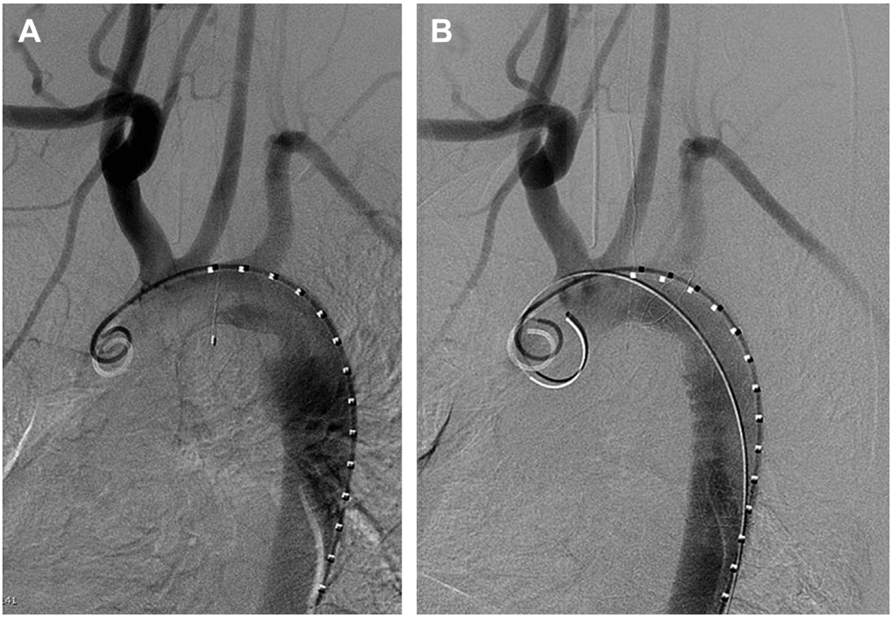

Fig. 10. Blunt descending thoracic aortic injury (*A*) before and (*B*) after endovascular repair.

of suspicion is necessary to identify those injuries in patients who arrive hemodynamically stable or who respond to initial volume resuscitation. The presence of peritonitis not only points to the presence of associated hollow viscus injury but also suggests the possibility of intra-abdominal vascular injury.[19]

Surgical exposure of the abdominal aorta and its visceral branches is challenging and major blood loss usually happens before hemostasis is achieved. The presence

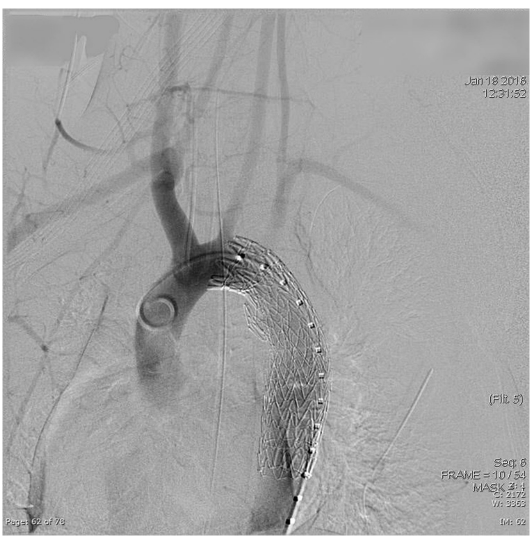

Fig. 11. Coverage of the left subclavian artery during endovascular repair of blunt descending thoracic aortic injury.

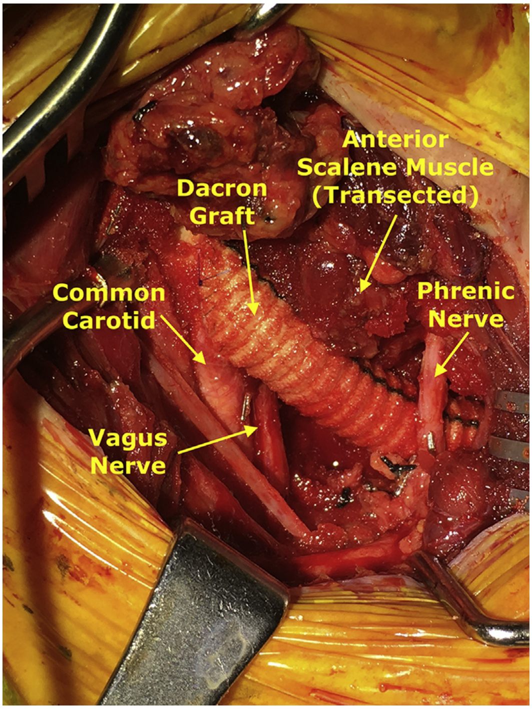

Fig. 12. Left common carotid artery to left subclavian artery bypass.

of associated intra-abdominal injuries aggravates this complex scenario. Successful treatment of patients with abdominal vascular injuries is not possible without strict adherence to damage control principles and keen knowledge of surgical anatomy. Early blood product resuscitation with balanced ratios and protocolized massive transfusion strategies are also important contributors to improve the outcomes for this patient population. In contrast to peripheral vascular injuries, abdominal vascular injuries cannot be temporarily controlled by external pressure. Immediate abdominal exploration with expedited assessment of the injury burden is paramount. This

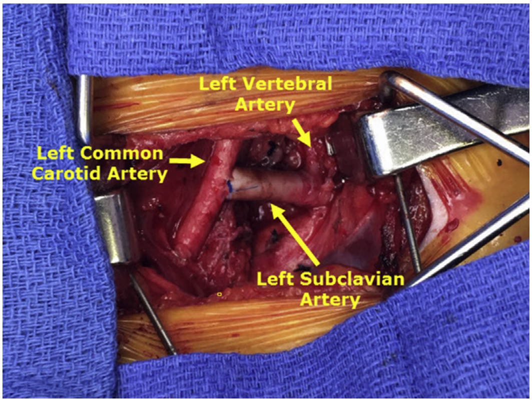

Fig. 13. Left subclavian artery to left common carotid artery transposition.

information should be promptly used in conjunction with the patient's hemodynamic and physiologic condition to decide if damage control operation should be performed. This decision must be made as early as possible. Abdominal vascular injuries are usually associated with additional intra-abdominal injuries. Associated injuries not only increase the complexity of the procedure but may also result in enteric contamination of the vascular repairs. Autologous conduits are preferable for intra-abdominal vascular reconstructions, notably in the presence of enteric contamination. Adherence to the basic principles of nonviable tissue débridement and gentle balloon catheter thromboembolectomy of both inflow and outflow prior to vascular repair is important.

The retroperitoneum is systematically compartmentalized into 4 anatomic zones (a single zone 1, paired lateral zone 2s, and a distal zone 3), with implications for the surgical approach to abdominal vascular injuries:

- Zone I: central area of the retroperitoneum, from the aortic hiatus to the sacral promontory. The aorta with its major branches (celiac artery, superior mesenteric artery [SMA], renal arteries, and inferior mesenteric artery), the inferior vena cava (IVC), and the superior mesenteric vein (SMV).
- Zone II: located laterally, it includes the kidneys and hilar renal vessels.
- Zone III: located in the space of the pelvic retroperitoneum and contains the iliac arteries and veins.

Zone I

Exploration is indicated for all hematomas encountered in zone I to rule out the possibility of major vascular injuries, regardless of the injury mechanism. Prior to entering the hematoma, proximal aortic control is essential. This can be accomplished through 1 of 3 maneuvers:

1. Left anterolateral thoracotomy and control of distal thoracic aorta in the chest (thoracic aorta cross-clamp). This maneuver is appropriate for patients who progress to cardiac arrest prior to laparotomy. In this situation the left anterolateral thoracotomy is used both for resuscitative purposes as well as for placement of an aortic cross-clamp. The left thoracotomy may also be necessary when a massive zone I hematoma extends proximally into the aortic hiatus. If an aortic injury is suspected at the level of the aortic hiatus, a thoracophrenolaparotomy can be quickly performed by extending the laparotomy into a low left thoracotomy at the level of the eighth or ninth intercostal space and dividing the diaphragm toward the hiatus. This maneuver is rarely performed in the trauma setting but provides adequate exposure for proximal control and definitive repair of an aortic injury at the thoracoabdominal transition.
2. Control the distal thoracic aorta through the esophageal hiatus (supraceliac aortic control). Placement of a vascular clamp across the supraceliac aorta may be challenging due to the dense connective and neurovascular tissue surrounding the aorta at this level. Direct compression of the proximal abdominal aorta against the spine at the level of the hiatus using an aortic compression device is a better alternative if an additional surgical assistant is available to hold pressure until definitive hemostasis is obtained. Another alternative is to cross-clamp the distal thoracic aorta, which is accessible through the esophageal hiatus, a location where the artery is relatively free from the aforementioned dense periaortic tissue, facilitating the exposure and placement of a vascular clamp. The gastrohepatic ligament is divided and the hepatic left lateral segment is mobilized to the patient's right. The esophagus is circumferentially mobilized and retracted to the left with a Penrose drain. The right diaphragmatic crus is divided at the 2-o'clock position

and the aorta is bluntly dissected on each side, allowing placement of a DeBakey or Cooley aortic aneurysm clamp.

3. Left medial visceral rotation. This maneuver allows exposure of the proximal abdominal aorta and visceral branches. First, the white line of Toldt on the left is divided and the left colon is mobilized away from the lateral abdominal wall. The dissection plane at the retroperitoneum is carried out anteriorly to the Gerota fascia leaving the left kidney in place. The dissection is extended in a cephalad direction. The splenophrenic ligament is divided and an en bloc medial rotation of the spleen, pancreas, colon, and small bowel is performed. This exposes the proximal abdominal aorta as it travels across the aortic hiatus. Exposure of the celiac axis, SMA, and left renal artery is achieved. If an injury to the posterior aspect of the aorta is suspected, the same maneuver (described previously) is performed, but instead of staying anterior to the left kidney, the plane of dissection extends posterior to the left kidney, which is included in the en bloc medial visceral rotation.

Visceral branches

Celiac Artery The celiac artery emerges anteriorly from the aorta and trifurcates into left gastric, common hepatic, and splenic arteries. In addition to the medial visceral rotation, described previously, the celiac trunk and its branches can also be approached through the lesser sac. This exposure, however, requires division of the median arcuate ligament and the celiac ganglion, which may not be straightforward in the trauma setting. If properly performed however, excellent exposure of the supraceliac aorta and celiac trunk is accomplished.

A rich network of collaterals makes ligation of the celiac trunk the treatment of choice when an injury is encountered in this location. Ligation of the celiac branches, including the common hepatic artery, can also be performed with negligible risk of visceral ischemia. Injuries to the proper hepatic artery that is distal to the gastroduodenal artery should be repaired.

Superior Mesenteric Artery, Superior Mesenteric Vein, and Portal Vein Surgical approach to the SMA is determined by the segment of the artery requiring exposure. As described previously, a left visceral rotation maneuver provides adequate exposure to the retropancreatic SMA segment. The SMA segment caudal to the inferior pancreatic border is best exposed through the root of the mesentery by retracting the transverse colon cephalad, dividing the ligament of Treitz and mobilizing the duodenum to the right. Transection of the pancreas is a well described maneuver to obtain expedited exposure to the retropancreatic segment of the mesenteric vessels. This maneuver, however, must be used very parsimoniously because the possibility of a pancreatic leak at the area of vascular reconstruction has significant morbidity implications.

Unless irreversible bowel necrosis has already occurred, injuries to the SMA generally require repair or reconstruction. Ligation of this artery invariably results in bowel ischemia, more significant if the ligation is performed proximal to the middle colic artery, which usually results in extensive ischemia to the entire small bowel and right colon. Autogenous conduits are preferable for SMA reconstructions, but prosthetic grafts can be used if enteric contamination is not present. Most cases of SMA reconstruction in should be managed with a temporary abdominal closure and planned second look to confirm graft patency and bowel viability.

For unstable patients, the use of a damage control temporary SMA shunt should be considered because complex prolonged reconstructions may result in further deterioration of the patient physiologic condition.

Injuries to the SMA and portal vein are highly lethal. Although ligation is a viable strategy, mortality associated with this maneuver is exceedingly high[20] and, unless the hemodynamic condition of the patient is prohibitive, these injuries should be repaired. If primary repair is expected to result in significant stenosis, the vein should be reconstructed either with a venous patch or an interposition graft. The internal jugular vein remains the best conduit for an interposition graft at the SMV/portal vein location.

Inferior Vena Cava Injuries to the IVC are usually associated with significant blood loss and are highly lethal. Quick exposure to the IVC is achieved with a Cattell-Braasch maneuver extended with kocherization of the duodenum and full mobilization of the duodenopancreatic complex. This exposes the entire extent of the IVC from the common iliac veins confluence to where the cava becomes retrohepatic. Direct sponge-stick compression above and below the IVC injury is effective for temporary bleeding control, which allows assessment of the extension of the injury and definitive repair. Immediate control is also important to avoid air embolism. Primary repair without significant stenosis can be accomplished in a majority of cases. If greater than 50% stenosis is expected with primary repair, ligation should be performed and is generally well tolerated in the infrarenal segment. Complex infrarenal IVC reconstructions have limited indication, only for patients with isolated IVC injury and normal hemodynamic condition. Repair of juxtarenal IVC injuries can be facilitated by division of the left renal vein adjacent to the IVC, which is safe because the venous outflow from the left kidney is maintained through the left renal vein tributaries (lumbar, gonadal, and adrenal veins). Ligation of the right renal vein results in hemorrhagic infarct of the right kidney.

Ligation of the suprarenal IVC is associated with high risk of renal failure. IVC injuries at this level should be repaired primarily or using a patch. If reconstruction is necessary, a large diameter (18–20 mm) externally supported polytetrafluoroethylene graft is the graft with best patency rates.[21,22]

Zones I and II

Proximal renal artery exposure is achieved by division of the ligament of Treitz and mobilization of the duodenum to the right. The left renal vein is identified and usually needs to be mobilized to allow exposure of the aortic segment where the renal arteries originate.

The management of renovascular injuries is determined by the duration of warm ischemia, hemodynamic status of the patient, and condition of the contralateral kidney. Active bleeding from a renal hilum is best managed by nephrectomy in a hemodynamically unstable patient, but renovascular reconstruction should be considered for a hemodynamically stable patient with less than 6 hours of warm renal ischemia.

Zone III

Hematomas from penetrating trauma in zone III should be explored to rule out injuries to the iliac vessels. Proximal control prior to hematoma exploration is obtained at the distal aorta level or at the common iliac level in cases of smaller unilateral hematomas. For injuries at the level of the external iliac arteries, distal control may need to be performed at the thigh and division of the inguinal ligament may be necessary. Iliac arterial reconstruction is routinely performed with prosthetic grafts. If a patient's hemodynamic condition allows, an endovascular repair with covered stent can be attempted in those institutions equipped with a hybrid operating room. If enteric contamination is present, the cavity should be extensively irrigated and an omental flap should be used to cover the area of arterial reconstruction.

Injuries to the iliac veins are managed with ligation if simple primary repair without stenosis is not possible.

Zone III hematomas secondary to blunt trauma are not explored unless they are expanding in the operating room. Angioembolization is the modality of choice for management of ongoing pelvic bleeding from blunt trauma. For those patients, however, who require exploration of a pelvic hematoma to control massive hemorrhage, the utility of internal iliac artery ligation and pelvic packing has been described.[23]

Peripheral Vascular Injuries

Peripheral vascular injuries occur due to blunt and penetrating mechanisms at equal frequencies, although the mortality rate associated with blunt injury is typically higher and mortality is increased with more proximal injuries.[24,25] In the upper extremity, the forearm vessels are the most commonly injured. In the lower extremity, the popliteal artery is the most commonly injured after blunt mechanisms, whereas the superficial femoral is the most common penetrating location of vascular injury. Amputation rates after vascular injury tend to be higher after blunt trauma and are more common at the level of the forearm for the upper extremity and the popliteal level for lower extremity.[25]

Although patients with hard signs require immediate surgical intervention, patients with soft signs concerning for vascular trauma should undergo a wrist to ankle brachial index of the injured extremity. An index of less than 0.9 is suggestive of a vascular injury and warrants additional investigation.[26] CTA has emerged as the preferred imaging modality in most trauma centers. Patients with documented arterial injuries consisting of small intimal tears, downstream intimal flaps, pseudoaneurysm (<5 mm), and small arteriovenous fistulas can be safely observed.[27] Formal angiography may prove useful as an adjunct of intervention in the operating room — as such, patients with vascular injury should be placed on an operative table capable of accommodating fluoroscopic imaging intraoperatively.

There are several general rules that should be applied to the operative treatment of all peripheral vascular injuries. Preparation of the effected extremity should be circumferential, with consideration of preparing for potential saphenous vein harvest from the contralateral extremity. The applicability of tourniquets, temporary balloon occlusion, and rapid proximal open exposure and vessel control should be considered early.

Once vascular control has been obtained, the decision to use damage control principles, as discussed previously, should be evaluated. Liberal utilization of temporary vascular shunts, in particular, is invaluable for the purpose in extremity vascular injury. For definitive repair, the saphenous vein is generally the conduit of choice for interposition repairs in extremity vascular trauma. If this choice is not available, ePTFE is preferred although there is a greater risk for infection. Wide débridement of wound contamination and nonviable tissue should be undertaken, with special attention paid to the coverage of a vascular repair with viable soft tissue.

For stable patients with few associated injuries, the decision to repair major venous injuries is predicated on the extent of injury. Primary or patch repair should be performed ideally. If a more complex venous repair at this location is required, ligation is likely indicated. A majority of venous ligations are well tolerated in the extremities with postoperative elevation and cautious compression.

A low threshold should exist for performance of prophylactic fasciotomies — particularly in the lower extremities and with prolonged ischemia, significant resuscitation needs, or associated musculoskeletal injury. In every instance, all 4 compartments of the lower extremity should be liberally decompressed.

Specific Peripheral Vascular Injuries

Subclavian/axillary

Among the most challenging of peripheral exposures, it is useful to appreciate the routes to proximal control of subclavian and axillary injuries. Proximal control of subclavian injuries medial to the anterior scalene may require a high anterior thoracotomy. Proximal control of axillary arteries medial to the pectoralis minor muscle may require supraclavicular exposure and control of the subclavian artery.

Selected subclavian/axillary injuries can be managed by endovascular covered stents in stable patients (Fig. 14). When an open interposition repair is required, an 8-mm ePTFE graft is a useful conduit in most patients. Brachial plexus injuries are not uncommon with injuries at these locations.

Brachial artery

During exposure of the brachial artery, care must be taken to avoid injury to the median nerve as it runs medial in the brachial sheath. If distal exposure of the brachial artery distal to the flexure of the elbow is required, an S-shaped incision can be carried across the antecubital fossa and onto the forearm. The brachial artery lends itself to mobilization with dissection and exposure, facilitating an end-to-end anastomosis in a majority of instances. For the remainder, autogenous vein interposition is recommended.

Ulnar/radial arteries

In the setting of an isolated occlusive vessel injury to either the ulnar or radial arteries, assessment for a patent palmar arch by an Allen test should be performed. If the palmar arch is patent, surgical repair is not necessary. Isolated arteriovenous fistula and pseudoaneurysms can be treated by endovascular embolization or ligation, provided palmar arch patency is preserved. Injuries to both vessels require repair of the ulnar artery at a minimum, because it is most commonly the dominant source of palmar arch arterial supply. Selected patients may require radial repair as well — all predicated on palmar arch anatomy.

Femoral arteries

Exposure of the femoral arteries is obtained through a slightly oblique incision extended longitudinally. The inguinal ligament can be divided if additional proximal exposure is required. The common femoral artery is commonly repaired with a short segment interposition of ePTFE graft or via vein patch. All profunda femoris artery

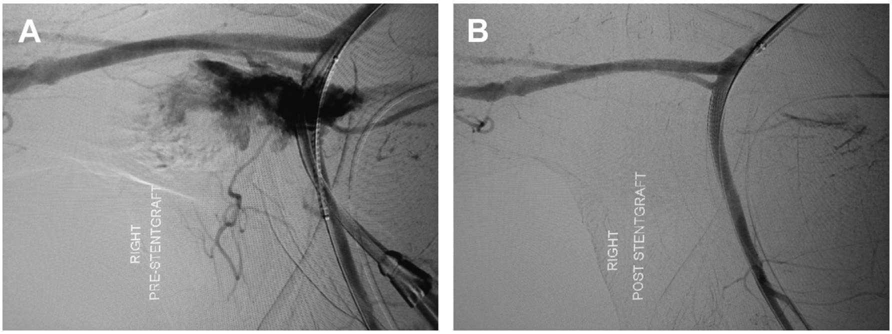

Fig. 14. (*A*) Before and (*B*) after arteriogram images of a penetrating injury to the left subclavian artery repaired with an endovascular stent graft.

injuries should be optimally repaired. Ligation of this vessel is only acceptable in the extremes of damage control for unstable patients with multiple injuries. The superficial femoral artery is best repaired with interposition saphenous vein graft (Fig. 15). These injuries are rarely amenable to end-to-end or patch repair.

Popliteal artery

Blunt popliteal arteries are commonly associated with tibial plateau fractures and posterior knee dislocations (Fig. 16). Missed injuries and injuries not promptly repaired have high rates of amputation. Medial exposure of the retrogeniculate popliteal is accomplished with separate incisions above and below the knee, preserving the musculotendinous attachments of the semimembranosis and semitendinosis tendons whenever possible. Select short segment popliteal injuries in the retrogeniculate location may be repaired through a posterior approach.

A majority of popliteal artery injuries can be repaired with either an end-to-end repair or a saphenous vein interposition. Associated venous injuries should be performed if primary or patch repair is possible. Prophylactic, 4-compartment lower extremity fasciotomy should be strongly considered for occlusive popliteal injuries with prolonged warm ischemic time (4–6 hours).

Tibial/peroneal

Surgical repair of an isolated single-vessel tibial artery injury is not indicated. For patients with multiple injuries, at least one tibial (anterior or posterior) should be repaired. Interposition or bypass repairs using saphenous vein are usually required.

Special Population — Pediatric Patients

In young children, supracondylar humerus fractures are associated with high risk for brachial artery injury. If a radial pulse or strong Doppler signal is not restored after reduction of these fractures, brachial artery exploration should be performed.

The vessels of young children are small and prone to vasospasm during the manipulation required for repair. Topical or intra-arterial nitroglycerine or papaverine may prove helpful for treatment of this arterial vasospasm.

For extremity arterial injuries, a limb with normal neurologic function and distal arterial Doppler signals can be managed nonoperatively. Long-term follow-up is required,

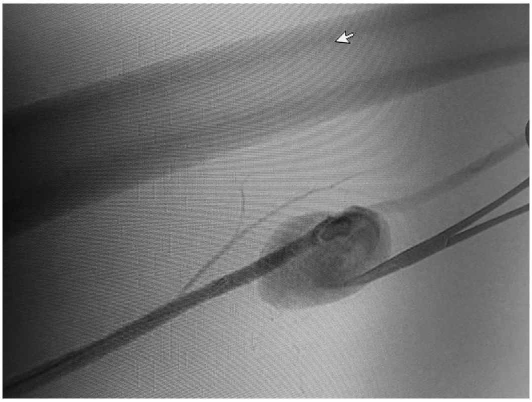

Fig. 15. Pseudoaneurysm of the superficial femoral artery after a stab wound. This injury was repaired with a reversed saphenous vein interposition graft.

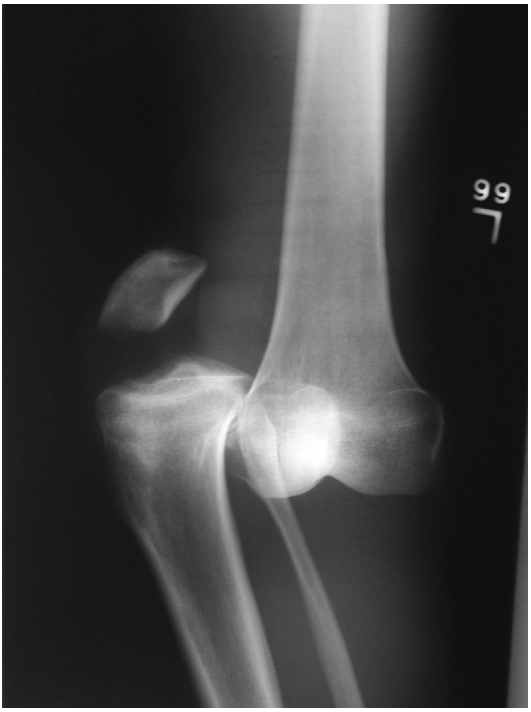

Fig. 16. Plain radiograph of a posterior knee dislocation.

however, due to the risk of stunted limb growth with age. When required, pediatric arterial repairs should be performed with interrupted anastomotic sutures.

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