67 CHAPTER

Vascular Trauma

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CHALLENGE OF VASCULAR TRAUMA

Injuries to blood vessels are some of the most dramatic challenges facing trauma surgeons because the repair is often urgent, the surgeon has to decide between several management options (open or endovascular), and gaining control of and reconstructing a major arterial injury can be technically demanding. Furthermore, in an era of increasing subspecialization and markedly reduced exposure to vascular surgery in the general surgery training curriculum, increasing numbers of surgeons taking trauma call are now less comfortable dealing with these injuries. Yet major vascular trauma remains a crucial element of trauma surgery, and every general surgeon must be prepared to deal with them either definitively or using so-called bail-out vascular damage control tactics. A phone call to bring in a vascular surgeon from home is not a valid solution for the exsanguinating patient with an iliac vein injury.

The effective management of vascular injuries hinges on successfully merging the principles of modern trauma care with the current approach to vascular therapy as outlined in the previous chapters of this section. The fundamental difference between elective vascular surgery and vascular trauma is the physiology of the wounded patient. A lacerated major vessel is typically only one component of the multitrauma complex that includes injuries to other organs and systems. These patients are often critically ill and rapidly approaching a point of physiologic irreversibility.[1] In these dramatic clinical circumstances, the key to a favorable outcome is maintaining correct priorities.

The surgeon must keep in mind that although major hemorrhage (typical of truncal vascular injuries) is an immediate threat to the patient's life, ischemia (commonly from peripheral arterial injury) is a threat to limb viability, a much lower priority. Furthermore, although control of hemorrhage is usually mandatory and lifesaving, the reconstruction of an injured vessel may be neither. As the injured patient is approaching the boundaries of his or her physiologic envelope, a simpler, sometimes temporary technical solution is often a safer option than a complex and time-consuming reconstruction.[2] In the severely traumatized patient, the best technically feasible definitive solution is not always in the patient's best interest.

The first part of this chapter focuses on fundamental principles in the diagnosis and management of vascular trauma. The second part deals with injuries to named vessels in specific anatomic locations. Both parts emphasize the modern convergence of innovative surgical strategies with cutting-edge imaging and endovascular technology, a convergence that offers the trauma surgeon an expanded and improved array of options for the management of injuries to major vessels.

GENERAL APPROACH TO VASCULAR TRAUMA

Injury Patterns

Vascular trauma occurs in a limited number of patterns, which are determined primarily by the mechanism of

injury.[3] Penetrating trauma typically results in varying degrees of laceration or transection of the vessel. The severed ends of a completely transected artery often retract and undergo spasm with subsequent thrombosis. Therefore, a lacerated or incompletely transected vessel typically bleeds more profusely than a completely transected one.

Blunt trauma results in disruption of the arterial wall, ranging in severity from small intimal flaps to extensive transmural damage with either extravasation or thrombosis. Deceleration injury causes deformation of the arterial wall. In a small vessel (e.g., the renal artery), this leads to intimal disruption and subsequent thrombosis, whereas in a larger vessel, the result will be full-thickness injury with only a thin layer of adventitia temporarily bridging the gap, as typically occurs in the descending thoracic aorta.

Bleeding from a lacerated vessel can be free or contained, the latter leading to pseudoaneurysm formation. An arteriovenous fistula is the result of a traumatic communication between an injured artery and vein.

Limb loss is more likely to result from blunt trauma and high-velocity gunshot injuries, mainly because of the greater damage to bone and soft tissue of the injured extremity. Low-velocity gunshot injuries and stab wounds rarely lead to limb loss.

The rapidly increasing use of invasive diagnostic, monitoring, and therapeutic modalities in many fields of medicine has brought with it a corresponding dramatic increase in iatrogenic vascular trauma. Every cardiac catheterization or arterial line insertion is, in fact, a form of vascular injury, where the physician relies on the patient's hemostatic mechanism to plug the hole and repair the damage. Iatrogenic injury may occur either at the target site of the intervention (e.g., a coronary artery) or at the access site (e.g., the common femoral artery). The latter is more common and may require surgical repair.

Concept of Minimal Vascular Injury

Not all arterial injuries require operative management. During the past 2 decades, a series of studies have convincingly demonstrated that nonocclusive intimal flaps, segmental arterial narrowing, small false aneurysms, and small arteriovenous fistulas have a benign natural history and are very likely to either heal or improve without intervention. These asymptomatic angiographic findings that are neither occluding nor extravasating have been named minimal arterial injuries. Contrary to previous belief, only about 10% of minimal injuries progress to require a surgical or endovascular repair.[4] Nonoperative management with careful follow-up is therefore a safe and cost-effective course of action for these patients. However, currently there are no objective criteria to precisely define what constitutes a minimal lesion. The size of the angiographic defect, the patient's overall trauma burden, and most importantly, the patient's availability for follow-up are factors to consider in making a decision to treat a minimal lesion conservatively. In rare instances, when a nonocclusive minimal injury increases in size and eventually requires operative or endovascular repair, morbidity is not increased by the delay.

Endovascular Management

With the rapid progress in endovascular therapy of arterial disease, it is not surprising that endovascular management options are gaining in popularity as alternatives to open repair in selected arterial injuries. In the hemodynamically stable patient with a nonbleeding traumatic arterial lesion, percutaneous placement of an endovascular stent-graft across a defect in the arterial wall is a low-morbidity solution to a problem that may otherwise require a technically challenging surgical procedure in a patient with a severely compromised physiology. In fact, endovascular therapy has revolutionized the management of delayed complications of trauma such as arteriovenous fistulas and pseudoaneurysms, especially in inaccessible sites.[5]

For some arterial injuries, the endovascular option is proving to be the preferred approach. The technical difficulties of gaining access to the vertebral artery inside the bony canal or obtaining distal control of a distal injury to the internal carotid artery make angiographic occlusion of the injured artery a very attractive alternative. In nonocclusive blunt injuries to the renal artery, endovascular stenting offers great expediency as compared with an open repair, albeit at the risk of yet unknown long-term patency. Similarly, blunt subclavian artery injury is often part of an injury complex involving multiple organ systems, and an endovascular stent-graft may well be the quickest and least hazardous solution for the patient.

The endovascular approach to blunt injuries to the descending thoracic aorta is rapidly gaining in popularity.[6-10] The clinical experience with endovascular stent-grafting of the aorta is showing promise, mainly because it is associated with low morbidity, and paraplegia, the dreaded complication of an open repair, has not been reported in endovascular repairs. The procedure is especially applicable in patients with multiple associated injuries who are poor candidates for a major aortic reconstruction. The major barriers to the adoption of endovascular repair as the procedure of choice for blunt aortic injury are technical problems with currently available devices[6,7] and the lack of prospective randomized studies.

OPERATIVE PRINCIPLES

Access, Exposure, and Control

Initial control of hemorrhage is achieved by direct pressure over the bleeding site using digital or manual compression. Blind clamping of a bleeding vessel is usually ineffective and may damage adjacent structures in the neurovascular bundle. The surgeon then chooses a definitive hemostatic technique from a wide array of available hemostatic options. These include, among others, hemostatic suture, ligation, reconstruction, and temporary shunt insertion.[11-13] Balloon catheter tamponade using a

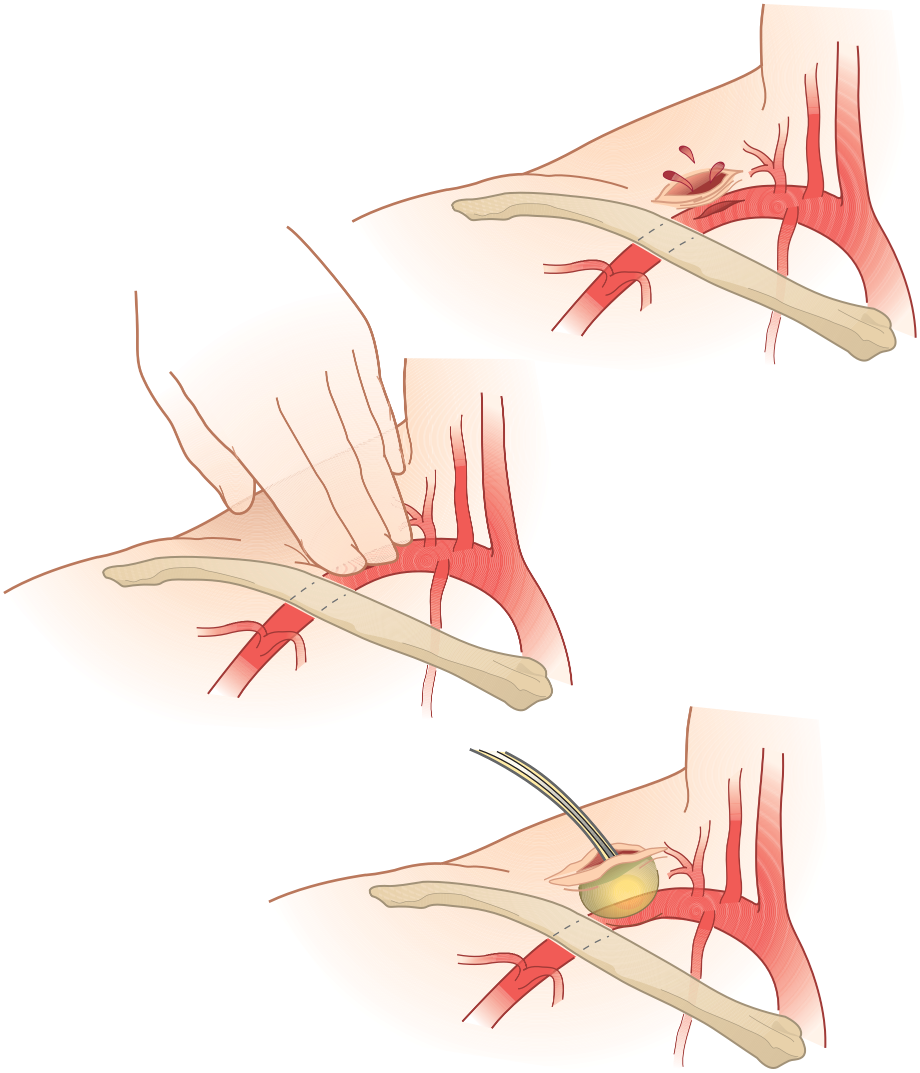

Figure 67-1 **Use of a balloon tamponade for temporary hemostasis of subclavian artery injury.** (Illustration by Jan Redden. © Kenneth L. Mattox, MD.)

Foley catheter inserted into the missile tract is a useful technique for obtaining rapid temporary control of torrential bleeding from a penetrating injury to an inaccessible vessel, such as high in the neck or deep in the pelvis (Fig. 67-1).

A cardinal operative principle in managing major vascular trauma is to first obtain proximal (and, if possible, also distal) control of the injured vessel before entering the hematoma. In the extremities and in the neck, control is achieved using standard extensile vascular exposure techniques.[13,14] In the chest, control of a vascular injury hinges on correct selection of a thoracotomy incision because each incision provides access to a different thoracic visceral compartment. In the abdomen, the major vessels are located in the retroperitoneum, and therefore exposure is based on operative maneuvers that rotate the intraperitoneal viscera off the underlying retroperitoneal structures.[15]

Assessing the Injury and the Patient

The anatomic extent of injury is revealed only when the traumatized vessel is carefully explored and opened. External inspection often does not reflect the full extent of intimal damage, especially in blunt trauma. The entire length of the injured segment must be precisely delineated at operation because leaving proximal or distal intimal damage will result in early failure of the reconstruction.

An important principle in the operative management of vascular trauma is that selection of the repair technique is heavily influenced not only by the anatomic situation but also by the patient's physiologic condition, associated injuries, and overall clinical trajectory. The massively bleeding patient incurs a rapidly increasing burden of physiologic insults. The marker of an irreversible (and lethal) physiology is a self-propagating triad of

hypothermia, coagulopathy, and acidosis. From the vascular perspective, coagulopathy means that a suture line will continue to bleed after completion, and diffuse oozing will persist all over the operative field regardless of the technical success of the reconstruction. The hypothermia-coagulopathy-acidosis syndrome effectively marks the boundaries of the patient's physiologic envelope beyond which there is irreversible shock. The operative management of a vascular injury must therefore focus not only on restoration of anatomic integrity but also, more importantly, on the patient's physiologic envelope. The complexity and duration of the planned repair must be inversely proportional to the physiologic insult that the patient has already sustained.

Vascular Damage Control

These considerations have led to the introduction of so-called damage control surgery in trauma. The damage control approach replaces definitive and complex operation with a staged repair. The introduction of damage control was the most important innovation in trauma surgery in the last quarter of the 20th century. The damage control sequence begins with a rapid procedure in which simple temporary bail-out tactics are used to arrest hemorrhage, maintain distal perfusion, and control spillage. The patient is transferred to the surgical intensive care unit for resuscitation, rewarming, and reconstitution of the physiologic envelope. Definitive repair of the injuries is undertaken 24 to 48 hours later, during a planned reoperation.

The damage control approach has been applied to vascular injuries as well. Hemorrhage is controlled by ligation or balloon tamponade. Distal perfusion in an injured artery is maintained by means of a temporary intra-arterial shunt instead of a formal reconstruction.

Ligation of an injured vessel in a critically injured patient is a marker of good surgical judgment rather than an admission of defeat. All peripheral veins and most truncal veins can be ligated with impunity. The external carotid, celiac axis, and internal iliac arteries are examples of arteries that can be ligated with no adverse effects. The risk for amputation after ligation of the femoral vessels was 81% for the common femoral and 55% for the superficial femoral artery during World War II (before the advent of fasciotomy). The upper extremity is even more tolerant to ligation of the subclavian artery.

A temporary intraluminal shunt maintains distal perfusion through an injured artery.[16] Blood flow through the shunt is about half of the normal flow, enough to maintain limb viability. There are reports of temporary shunts remaining patent for more than 24 hours after insertion. A commercially available carotid shunt, endotracheal suction catheter, or sterile intravenous (IV) tubing trimmed to the appropriate length is inserted into both ends of a disrupted vessel and held in place with vessel loops or ligatures (Fig. 67-2). An intraluminal shunt can be used in three clinical situations:

1. As a damage control technique in a critically injured patient who is unlikely to survive a complex repair because physiologic reserves have been exhausted

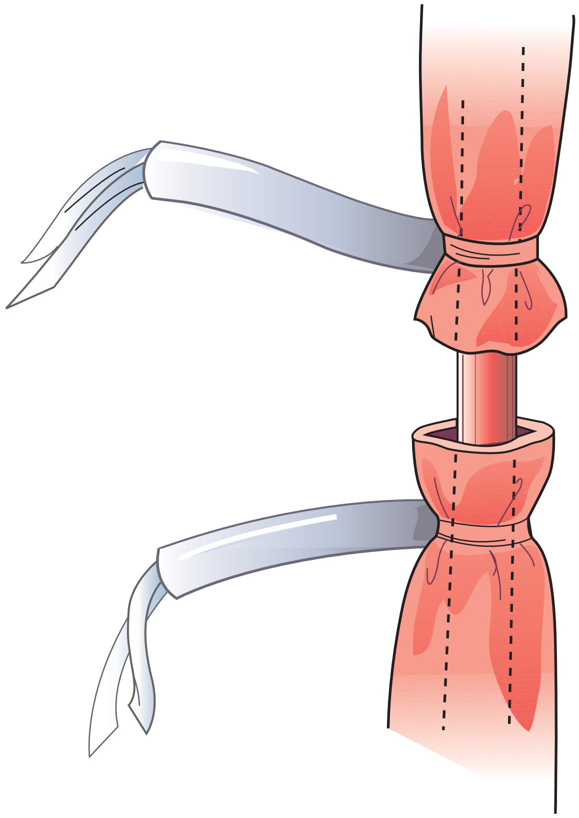

Figure 67-2 **Temporary intravascular shunt.** (Illustration by Jan Redden. © Kenneth L. Mattox, MD.)

2. Transfer of a patient with peripheral arterial injury from the field (or from a remote facility) for vascular reconstruction at a trauma center
3. Repair of combined vascular and orthopedic extremity injuries, when skeletal alignment is accomplished before vascular repair in an ischemic limb

NECK INJURIES

The anatomy of the neck consists of two large neurovascular bundles within the carotid sheaths, which are closely adherent to midline aerodigestive structures in a very compact arrangement. It is therefore not surprising that injuries to major cervical vessels are frequently associated with trauma to adjacent structures. An expanding cervical hematoma presents an immediate threat to the patient's airway. Major vascular injury occurs in one of every four patients with penetrating cervical trauma.[13] The most commonly injured vascular structure is the internal jugular vein, which is amenable to simple lateral repair or ligation.

Clinical Presentation and Immediate Concerns

Major cervical vascular injury may present as vigorous external bleeding, an expanding or stable cervical hematoma, or a hemispheric neurologic deficit. However, a

major arterial injury may also remain asymptomatic, so physical examination alone cannot reliably exclude it. Blunt carotid artery injury is an uncommon but potentially devastating injury.[17-20] The only initial clinical clue may be a gross hemispheric neurologic deficit without computed tomographic (CT) evidence of cerebral trauma.

Two immediate concerns are the focus of clinical attention during the initial evaluation. The first is a rapidly expanding hematoma that requires immediate endotracheal intubation before the upper airway is shifted and compressed, making an orotracheal intubation difficult or impossible. The second immediate concern is severe external hemorrhage, which may lead to exsanguination. Vigorous external bleeding requires temporary control by manual pressure or balloon tamponade using a Foley catheter until proximal control is obtained in the operating room.

Diagnostic Studies

The actively bleeding unstable patient with a penetrating neck injury is taken immediately to the operating room for neck exploration. Management of the hemodynamically stable patient with a suspected vascular injury depends on the zone of cervical penetration. Asymptomatic patients with penetrating injuries to the base of the neck (zone 1) require four-vessel arch angiography either to exclude major arterial injury or to plan the operative approach if an injury is present. The same applies to penetrating injuries above the angle of the mandible (zone 3), where both exploration and distal control are technically difficult; therefore, an endovascular solution, if feasible, may be the safest option.

Patients with asymptomatic midcervical injuries (zone 2) may undergo either neck exploration (a straightforward procedure associated with very low morbidity) or a combination of four-vessel angiography, esophagoscopy, and barium swallow to rule out significant arterial and esophageal injury. Both pathways are acceptable alternatives, and thus choice between operative exploration and a sequence of diagnostic procedures reflects individual preferences or institutional policies.

Duplex ultrasonography is an excellent imaging modality for major cervical arterial trauma. However, lack of immediate availability around the clock in the trauma resuscitation area prevents it from becoming a practical substitute for angiography in most emergency centers.

Operative Management

Safe exploration of an anatomically hostile neck distorted by an expanding hematoma hinges on systematic progress from one key structure to the next using a so-called trail of safety. The standard cervical incision is along the anterior border of the sternocleidomastoid muscle. After division of the platysma, dissection proceeds to identify the first key structure: the anterior border of the sternocleidomastoid muscle. Dissection then progresses to identify the next key structure: the internal jugular vein. Dissection along the anterior border of this large vein identifies the facial vein, the gatekeeper structure of the

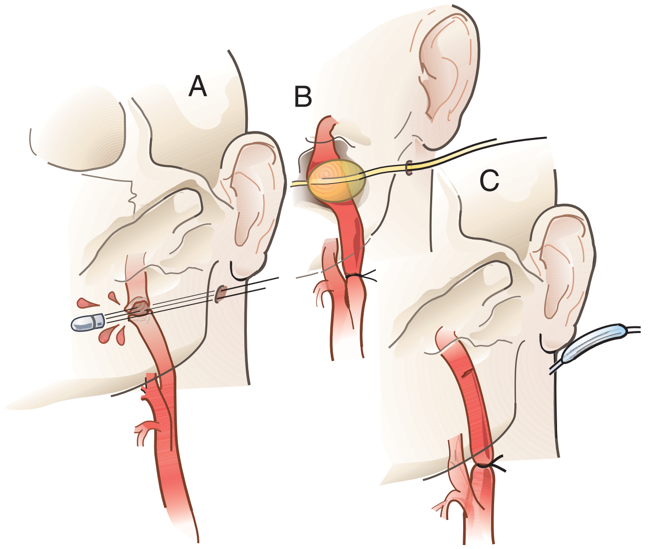

Figure 67-3 **A** to **C, Balloon tamponade of inaccessible internal carotid artery injury**. (© Baylor College of Medicine, 1980.)

carotid bifurcation. The facial vein is divided between ligatures to gain access to the carotid bifurcation.

The traumatized carotid arteries are reconstructed using standard vascular techniques. There are no good data to support preference for vein or synthetic interposition grafts in reconstructing the common or internal carotid artery, nor is there strong evidence to support routine shunting. A synthetic graft has the advantage of immediate availability, and a shunt can be threaded through the graft and then inserted into the internal and common carotids to facilitate construction of the anastomotic suture lines with the shunt in place. Control of the distal stump of an injured internal carotid artery at the base of the neck may be impossible even with adjunctive measures such as dividing the posterior belly of the digastric muscle, and an interventional angiographic solution is by far the best. Balloon catheter tamponade through the missile tract followed by ligation and division of the internal carotid artery at the carotid bifurcation, with removal of the balloon 3 days later, affords a simple solution to a difficult technical problem (Fig. 67-3). Another option is to insert an intraluminal Fogarty balloon catheter into the distal stump of the internal carotid, then clip and trim the catheter and leave the balloon inside the artery.

The need to reconstruct the carotid artery of a patient with a clear preoperative hemispheric neurologic deficit has long been a subject of controversy. Current evidence supports revascularization regardless of the patient's neurologic status, accepting that prognosis is poor in the presence of a profound neurologic deficit (i.e., coma) with or without revascularization.

Most vertebral artery injuries are diagnosed angiographically and are best managed by angiographic means. Rarely, it is encountered in the operative field as vigorous bleeding emanating from a hole between the transverse processes of the cervical vertebrae, posterolateral to the carotid sheath.[21-23] Although several elaborate techniques

have been described for operative exposure of the extracranial vertebral artery, none is a practical option in the acute situation of severe hemorrhage. The artery is best controlled by simple means, such as tightly filling the bleeding hole in the transverse process with bone wax. If extravasation from the vertebral artery is encountered during arteriography, angiographic control of this inaccessible vessel is clearly the preferred course of action.

Blunt Cerebrovascular Trauma

The estimated incidence of clinically important blunt injury to the carotid and vertebral arteries is 1 to 3 patients per 1000 admitted to major trauma centers.[17-19,24] However, with increased awareness and a targeted screening protocol for asymptomatic patients, it is possible to identify these injuries in up to 1% of blunt trauma admissions. The typical mechanism is either hyperextension with contralateral rotation of the neck or a direct blow to the neck, but in some patients, no such mechanism can be elicited. The key pathophysiologic event is an intimal tear that can remain asymptomatic or progress to local thrombosis, embolization, distal dissection, and pseudoaneurysm formation.

The clinical hallmark of blunt carotid artery injury is a hemispheric neurologic deficit that is incompatible with CT findings. A salient clinical feature of this injury is that in about half of the patients, there is a latent period of hours or days before the neurologic deficit appears. Maintaining a high index of suspicion in patients with severe maxillofacial trauma, a mechanism of cervical hyperextension, and evidence of direct trauma to the neck or fractures of the skull base or cervical spine in proximity to the relevant vessels generally enables early diagnosis of these lesions. The standard diagnostic modality is angiography because duplex scanning is not sensitive enough. The sensitivity of CT angiography as a screening test for blunt cerebrovascular trauma is under investigation.

The treatment of blunt carotid and vertebral artery injury remains controversial and primarily nonoperative. Most patients are treated with systemic anticoagulation (if not prohibited by associated injuries), although the benefits of IV heparin are less clear in low-grade nonobstructing luminal irregularities. Hemodynamically significant dissection or inaccessible pseudoaneurysms are amenable to endovascular therapy, but there are several recent disturbing reports of high complication rates with endovascular therapy of blunt carotid artery injuries, so the role of endovascular therapy in these injuries is not well defined.

THORACIC VASCULAR INJURIES

Penetrating Thoracic Vascular Trauma

The patient with a major penetrating thoracic vascular injury typically presents in shock, with either a massive hemothorax or an expanding hematoma at the thoracic inlet. The need for urgent operation is usually obvious. Less commonly, the patient may be hemodynamically stable and a nonbleeding injury (e.g., a pseudoaneurysm, an arteriovenous fistula, or an occluded artery) is suspected on clinical grounds and then delineated angiographically.

Choice of Incision

The choice of thoracotomy incision is a central consideration in the management of thoracic vascular trauma because an incorrectly placed incision will often convert a straightforward procedure into a difficult one. In stable patients, the choice of incision is dictated by the angiographic findings. In the actively bleeding, hemodynamically unstable patient, the surgeon must base the incision on the presumed location of the vascular injury. As a general rule, an anterolateral thoracotomy on the injured side is the incision of choice for patients with ongoing bleeding into the pleural cavity. This incision, performed immediately below the nipple in men or below the manually retracted breast in women, does not require special patient positioning, nor does it limit access to the contralateral hemithorax or to the abdomen. The only exception is a penetrating injury to the right lower chest (below the nipple) where bleeding will most commonly emanate from an injured liver, so the operative approach begins with a midline laparotomy. An anterolateral thoracotomy can be rapidly extended across the sternum to provide access to the mediastinal great vessels and the contralateral hemithorax, albeit at the cost of additional morbidity associated with transecting the sternum.

Penetrating injuries to the base of the neck (thoracic outlet) present special access problems. Right-sided injuries to the base of the neck are approached through a median sternotomy, which provides access to the innominate artery and the proximal right carotid and subclavian arteries. The proximal part of the left subclavian artery is intrapleural and posterior, so the most expeditious way to obtain proximal control is through a separate left anterolateral thoracotomy incision through the third intercostal space (above the nipple).

A supraclavicular incision is used to gain access to the more distal parts of the subclavian artery. The incision entails careful division of two muscle layers: the sternocleidomastoid and the anterior scalene muscle behind it. The phrenic nerve, which crosses the latter muscle, is the key to the dissection and must be identified and preserved. In the actively bleeding patient with a grossly swollen upper chest, exposure of the subclavian vessels can be expedited by subperiosteal resection of the medial half of the clavicle.

Management of Specific Injuries

Penetrating injuries to the innominate vessels and proximal carotid arteries present intraoperatively as a mediastinal hematoma. Much like any other types of hematoma resulting from a major vascular injury, plunging into it without proximal control is a recipe for disaster. Proximal control can be obtained from within the pericardium where the anatomy is not obscured by the hematoma. Exposure is enhanced by division of the innominate vein.

The bypass exclusion technique for innominate artery injuries is described later.

In patients who are massively bleeding from pulmonary hilar injuries, the mortality rate is in excess of 70%. In practice, these injuries usually involve more than one element of the pulmonary hilum. Instead of attempting vascular repair of the pulmonary artery or vein in these exsanguinating patients, a rapid pneumonectomy using a linear stapler may prove lifesaving.

For injuries of the subclavian arteries, the exposure required is almost always more extensive than initially anticipated, and the incision can be extended laterally to expose the proximal axillary artery. Special care must be taken to avoid injury to the phrenic nerve and brachial plexus. Most subclavian artery injuries are repaired using a synthetic interposition graft. Subclavian vein injuries are repaired with lateral venorrhaphy or ligation of the vein. Penetrating injuries to the intrapericardial great vessels and to the vena cava are very rare, and repair requires cardiopulmonary bypass. In practice, these injuries are almost invariably fatal.

Blunt Thoracic Vascular Trauma

Aorta

Aortic injury is the great nemesis of blunt trauma, having caused or contributed to 10% to 15% of motor vehicle crash–related deaths for nearly 30 years.[25] It is a potentially lethal injury that provides the surgeon with a window of opportunity for effective intervention. This window may be missed because the injury remains asymptomatic until catastrophic bleeding suddenly occurs. Despite recent advances in diagnosis and management, mortality rates as high as 11% to 40% persist.[3-5,26] Paraplegia, the most dreaded complication of this injury, has been reported in roughly 13% of open repairs, but results vary considerably between institutions and individual surgeons.

In autopsy studies, injury location was reported at the proximal descending thoracic aorta in only 36% to 54% of cases; however, in surgical cases, this location is reportedly injured in 84% to 100%. Only 3% to 10% are reported to occur in the ascending aorta, arch, or distal descending thoracic aorta. Associated trauma to other cavities and organ systems is very common. In a multicenter report, 51% of patients with aortic injury had concomitant head injury, 46% had rib fractures, and 38% sustained lung contusions. Twenty to 35% of the patients had orthopedic injury, and abdominal injury was common. These multiple associated injuries often complicate or prohibit an urgent aortic repair, and the use of systemic heparin carries the potential for increased neurologic and hemorrhagic complications.

The dominant pathophysiologic event in blunt aortic injury is sudden deceleration with creation of a shear force between a relatively mobile part of the thoracic aorta and an adjacent fixed segment. The classic mechanism of blunt aortic injury is sudden deceleration during a frontal impact motor vehicle collision or a fall from height. However, recent data show a considerable number of cases secondary to other mechanisms, such as side-impact collisions, vehicular-pedestrian accidents, and crush and blast injuries. Certainly, the possibility of blunt aortic injury needs to be considered in all victims of motor vehicle collision, regardless of the point of impact.

It is important to keep in mind that a contained blunt aortic injury does not explain hemodynamic instability in the injured patient. If the patient with a suspected or proven blunt aortic injury is hemodynamically unstable, the explanation almost always lies in other associated injuries, typically in the abdomen. This source of active bleeding is an immediate threat to the patient's life and needs to be addressed before the aortic injury. Very rarely, the aortic disruption itself may present as an ongoing nonexsanguinating hemorrhage causing hemodynamic instability. The window of opportunity to salvage these patients is extremely narrow, and the surgeon is often forced to operate without an angiographic definition of the injury. The mortality rate in these patients is 90%.

Physical examination of the patient with blunt aortic injury is rarely helpful because the classically described signs such as upper extremity hypertension, diminished femoral pulses (called *pseudo-coarctation*), and an intrascapular murmur are distinctly uncommon. The most important aspect of the physical examination is to identify associated injuries that may have either priority over the aortic injury or a major impact on the operative risk.

Several radiographic findings on a supine chest radiograph suggest the diagnosis of blunt aortic injury. The most significant findings are a widened mediastinum (>8 cm), an obscured or indistinct aortic knob, deviation of the left main-stem bronchus, an off-midline position of a nasogastric tube, and obliteration of the aortopulmonary window. The diagnosis of blunt aortic injury remains notoriously elusive. In 5% of patients, the mechanism of injury is, in fact, the only clue to the diagnosis. In others, radiographic signs may be so subtle that even an experienced interpreter will not discern them.

The role of CT in the diagnosis of blunt aortic injury continues to be the focus of debate. Spiral or helical scan of the chest has a high negative predictive value and is a useful screening modality for aortic injury.[24,27-30] However, demonstration of a mediastinal hematoma does not obviate the need for subsequent aortography to clearly define the site and extent of injury. At least 10 aortic arch anomalies exist that are not demonstrated by CT, and the surgeon is best advised to know of these anomalies.

Helical CT angiography is rapidly becoming an imaging modality that rivals aortography as being more expedient and noninvasive. Three-dimensional reconstructions of the aorta provide accurate anatomic detail that obviates the need for a subsequent aortography. However, these reconstructions are time consuming and use massive computing resources. As this technology matures, it may replace aortography as the imaging modality of choice.

The correct and timely identification of blunt aortic injury hinges on a low threshold for aortography when the mechanism of injury, relevant physical findings, or an abnormal chest radiograph suggests the diagnosis. Aortography remains the gold standard imaging modality

to which all other modalities are compared. It provides valuable information, not only about precise location and extent of the injury, but also about other details that may affect the operative plan. Two classic pitfalls in interpretation of aortograms are ductus diverticulum and vascular ring remnant.

The traditional management of blunt aortic injury is prompt repair of the injured aortic segment. However, in some patients, a purposeful delay or even nonoperative management may be indicated.[25,31,32] Patients with severe head injury or complex multisystem injury and those about to breach their physiologic envelope are bad candidates for an aortic reconstruction. The estimated risk for free rupture of 1% per hour pales into insignificance when compared with the risk of aortic surgery under these circumstances. Patients with severe comorbid factors are also poor candidates for aortic reconstruction. Evidence is now accumulating that in stable patients, purposeful delay of surgery combined with pharmacologic control of the blood pressure and afterload reduction (aiming for blood pressure values below preinjury levels) and careful monitoring of the mediastinal hematoma may be an acceptable course of action. This purposeful delay allows the surgeon to assess the total injury burden of the patient, select the optimal timing for intervention, and construct a tailor-made endograft when necessary. The concept that early blood pressure control and afterload reduction (typically using an IV β-blocker) converts these cases from urgent to delayed cases that can be repaired the next morning or even several days later is a paradigm shift that simplifies the management of these injuries and allows transfer of the patient to a center of excellence. In addition, minimal blunt aortic injuries, such as a small intimal flap or a small pseudoaneurysm, are probably amenable to nonoperative management. However, the long-term behavior of these minimal lesions is still not well defined, so careful follow-up by serial imaging is mandatory whenever nonoperative management is selected.

The use of endovascular stent-grafts to treat blunt aortic injury is rapidly gaining in popularity despite the conspicuous absence of data from randomized trials, long-term follow-up, and some serious technical problems with the endograft devices. Initially, such endografts were used in chronic transections. During the past 10 years, however, small series reporting use in acute aortic injury have been published.[6-9,25-28] At least 24 different custom and manufactured endografts and off-label use of components of abdominal aortic endografts have been used in the thoracic aorta.[6] Some radiologists and surgeons currently consider thoracic endografting to be as much a standard of care as open aortic reconstruction following trauma, despite the lack of controlled trials and long-term follow-up. This enthusiasm stems from the fact that although the reported mean mortality rate for posttraumatic open thoracic aortic repair is 13% (range, 0%-55%), and the paraplegia rates average 10% (range, 0%-20%), the mortality and paraplegia rates for selected blunt aortic injuries treated endovascularly is 3.8%, and only 1 out of 239 reported cases developed paraplegia. The endovascular option is particularly attractive for patients with multiple associated injuries who cannot tolerate the single-lung ventilation required for an open repair or in whom systemic heparin is contraindicated because of associated injuries.

Several technical obstacles are still preventing endovascular repair from becoming the standard approach to blunt aortic injuries. One of the major obstacles is the issue of graft and aorta size discrepancy. The average diameter of a young patient's descending thoracic aorta is 19.3 mm. Commercially available endografts, originally designed for elderly patients with chronic aortic disease, are significantly larger. The smallest thoracic endograft approved in the United States is 26 mm in diameter. Inserting a larger endograft into a smaller aorta may lead to enfolding of the graft. This problem has led to the use of custom devices or off-label use of iliac endograft limbs, cuff extenders, and abdominal aortic endografts.

Other technical problems with currently available endografts are angulation at the junction of the aortic arch and the descending thoracic aorta (i.e., around the proximal fixation point of the endograft), which predisposes the endograft to endoleaks, and lack of a sufficient proximal neck to safely anchor the endograft proximal to the aortic tear. In addition, iatrogenic trauma at the insertion site and to the femoral and iliac arteries that must be traversed to insert the endograft adds to the morbidity of the procedure. Technologic advances and technical refinements will address most of these issues in the near future, enhancing the attractiveness of the endovascular repair over open reconstruction.

Open repair of the descending thoracic aorta is performed through a left posterolateral thoracotomy in the fourth intercostal space. The standard operative repair of aortic injuries uses clamp and direct reconstruction and can be achieved by using one of three adjuncts: pharmacologic control of central hypertension, a temporary passive shunt, or a pump-assisted atriofemoral bypass. The latter can be achieved either by a traditional pump bypass (which requires full heparinization) or by using a centrifugal pump without heparin.[26]

The use of temporary shunts or pump bypass is more complex than direct reconstruction with pharmacologic control. However, it has gained in popularity in recent years because of the perception among surgeons (unsupported by controlled clinical trials) that using a shunt or partial bypass may improve outcome and reduce the incidence of paraplegia.

Proximal control of the injury is obtained by encircling the subclavian artery and the aortic arch (between the carotid and left subclavian arteries). The latter is the most difficult part of the dissection. The pleura between the vagus and phrenic nerves is incised, and using a combination of blunt and sharp dissection, a plane is developed between the pulmonary artery and the inferior aspect of the aortic arch. A large curved vascular clamp can then be carefully brought around the aorta, making just enough space for an aortic clamp. The distal descending aorta is encircled after opening the mediastinal pleura, taking care not to injure an intercostal vessel. Clamps are placed on the isolated vessels, and extreme blood pressure fluctuations are avoided by careful pharmacologic control.

After clamping, the hematoma is entered, and the extent and configuration of the tear are assessed through a longitudinal aortotomy. Direct primary repair is possible in only 15% of patients, whereas the rest require an interposition graft.

The reported operative mortality following an open repair is 5%% to 25% and is related not only to the procedure itself but also to the presence of associated injuries and their late sequelae. The most dreaded complication is paraplegia or paraparesis, which occurs in about 8% of patients. The incidence of spinal cord damage is affected neither by choice of operative technique nor by the method chosen to deal with central hypertension and distal ischemia. There is also no direct proven correlation between aortic cross-clamp time and the incidence of spinal cord damage. As noted earlier, one of the most remarkable aspects of the endovascular repair option is that this dreaded complication does not occur.

Innominate Artery

The second most common blunt thoracic vascular injury is a tear at the origin of the innominate artery. The artery is either sheared off the aortic arch, as with blunt aortic injury, or pinched between the sternum and the spine during frontal impact. Blunt innominate artery injury is akin to a side hole in the thoracic aorta because operative repair requires obtaining control at the aortic arch.

The clinical presentation is similar to that of blunt aortic injury in that most patients are hemodynamically stable and asymptomatic. Radiologic evidence of mediastinal widening at the aortic outlet and leftward deviation of the trachea suggest the diagnosis, but angiography is the definitive diagnostic modality.

The operative repair of blunt innominate artery injury is based on the bypass and exclusion principle, eliminating the need for cardiopulmonary bypass, shunts, or the use of heparin.[20,25] After median sternotomy, the ascending aorta is exposed inside the pericardium while deliberately avoiding the traumatized segment. Using a partially occluding clamp on a segment of normal aorta, a graft is sewn to it in an end-to-side configuration, away from the injury. The distal innominate artery is then exposed and clamped, and the distal anastomosis is constructed (Fig. 67-4). Only then is the injured segment of the aortic arch addressed and repaired.

ABDOMINAL VASCULAR INJURIES

Most abdominal vascular injuries result from penetrating trauma and are associated with other abdominal injuries.[3] Vascular injuries are much more common after abdominal gunshot wounds (25% of patients) as compared with stab wounds (10%). Major abdominal vascular trauma presents clinically either as free intraperitoneal hemorrhage or as a contained retroperitoneal hematoma.[33,34] Most patients with major abdominal vascular trauma present with a contained or at least partially contained retroperitoneal hematoma because free bleeding from a major intra-abdominal artery usually results in death at the scene.

Occasionally there are clinical hints to the presence of an abdominal vascular injury. Examples are a bullet trajectory across the abdominal midline in a hypotensive patient or an absent femoral pulse. In most patients, the indication for urgent celiotomy is obvious and the diagnosis is made at operation. Time must not be wasted on unnecessary diagnostic tests or on futile attempts to stabilize the patient because volume loading before achieving surgical control of the bleeding vessel may augment bleeding and adversely affect the outcome.

Immediate Concerns

The typical situation encountered at celiotomy is vigorous bleeding or an expanding hematoma at a relatively inaccessible site, combined with other abdominal visceral injuries. Rapid temporary control of hemorrhage is the obvious first priority and is achieved by direct manual or digital pressure, whereas formal proximal and distal control is obtained later. After bleeding has been temporarily controlled, the surgeon needs to stop and organize the operative attack on the injury. The natural urge to immediately proceed with definitive repair is the worst possible mistake at this point. Instead, the time interval needs to be used to transfuse and resuscitate the patient, to obtain additional instruments and an autotransfusion device, to optimize exposure, and to organize the operating room team. Only then does the definitive repair begin.

Once the total injury burden of the patient is determined, the surgeon has to choose between the traditional operative profile of definitive repair and a damage control profile. The latter consists of a rapid initial operation wherein only temporary bail-out measures to control hemorrhage and spillage are employed. The patient is then transferred to the surgical intensive care unit for rewarming and stabilization, with definitive repair performed at a planned reoperation after 24 to 48 hours. This operative strategy is particularly suitable for the patient with major abdominal vascular injury in conjunction with hollow or solid abdominal visceral trauma, in whom formal repair of all injuries will not be tolerated by the patient's fragile physiology. In these circumstances, the surgeon may decide to address the vascular injury using only bail-out techniques such as ligation or temporary shunt placement. Another option is to perform a definitive repair of the vascular injury and use bail-out techniques for hollow visceral damage.

Aortic Clamping

Aortic cross-clamping is both an adjunct to resuscitation and a means of obtaining global proximal control to reduce torrential hemorrhage in the abdomen. The supraceliac aorta is most expediently clamped at the diaphragmatic hiatus. Rapid blunt creation of an opening in the lesser omentum allows the surgeon to approach the left diaphragmatic crus and open it longitudinally in the direction of its fibers. This is done by finger dissection, and the purpose is to create just enough space on both sides of the aorta to accommodate an aortic clamp. The

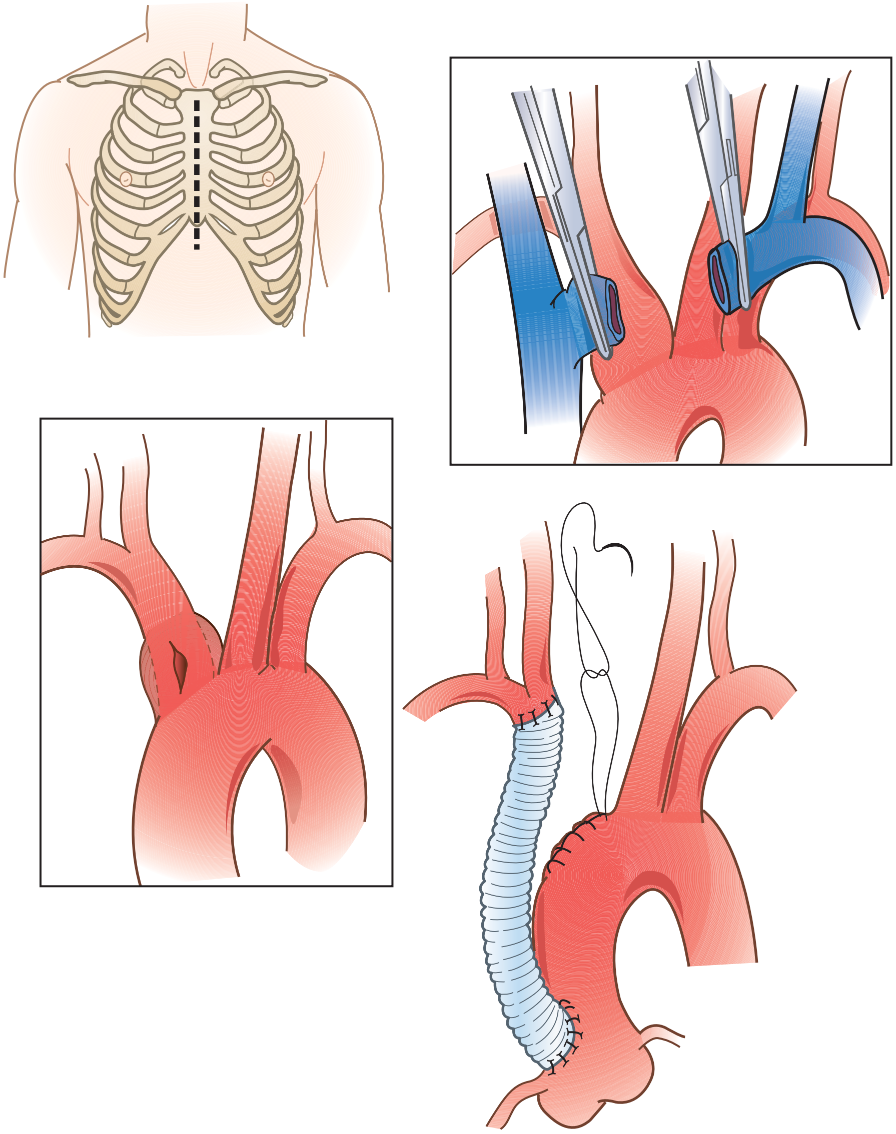

Figure 67-4 **The "bypass and exclusion" technique for repair of innominate artery injuries.** (Illustration by Jan Redden. © Kenneth L. Mattox, MD.)

transcrural route avoids the dense periaortic tissue of the suprarenal abdominal aorta. Clamping the aorta through the lesser sac is typically performed blindly in a pool of blood, and the dissection required is often far from simple, especially for the inexperienced. It is therefore much safer to compress the aorta manually at the hiatus than to risk iatrogenic damage to the celiac axis, esophagus, or even the aorta itself by a blindly and incorrectly placed clamp.

Aortic clamping has profound physiologic consequences. Although the maneuver elevates the patient's blood pressure, it also causes sudden afterload augmentation and visceral and peripheral ischemia, all of which are detrimental to the patient's borderline physiology. Thus, aortic clamping, although at times a lifesaving maneuver in a crashing patient, must be used judiciously and performed carefully.

Maneuvers for Retroperitoneal Exposure

The major abdominal vessels are retroperitoneal structures that lie posterior to the content of the peritoneal sac and close to the midline. Rapid exposure of these relatively inaccessible structures hinges on two mobilization maneuvers that rotate the abdominal visceral content off the midline retroperitoneal structures.

Left-sided medial visceral rotation (Mattox maneuver) exposes the entire length of the abdominal aorta and its branches (except the right renal artery).[15] The correct plane is entered by incising the lateral peritoneal attachment of the sigmoid and left colon. The hand is then swept upward lateral to the left colon, kidney, and spleen (Fig. 67-5). The presence of a retroperitoneal hematoma greatly facilitates the dissection. The plane of dissection is developed bluntly in front of the left common iliac

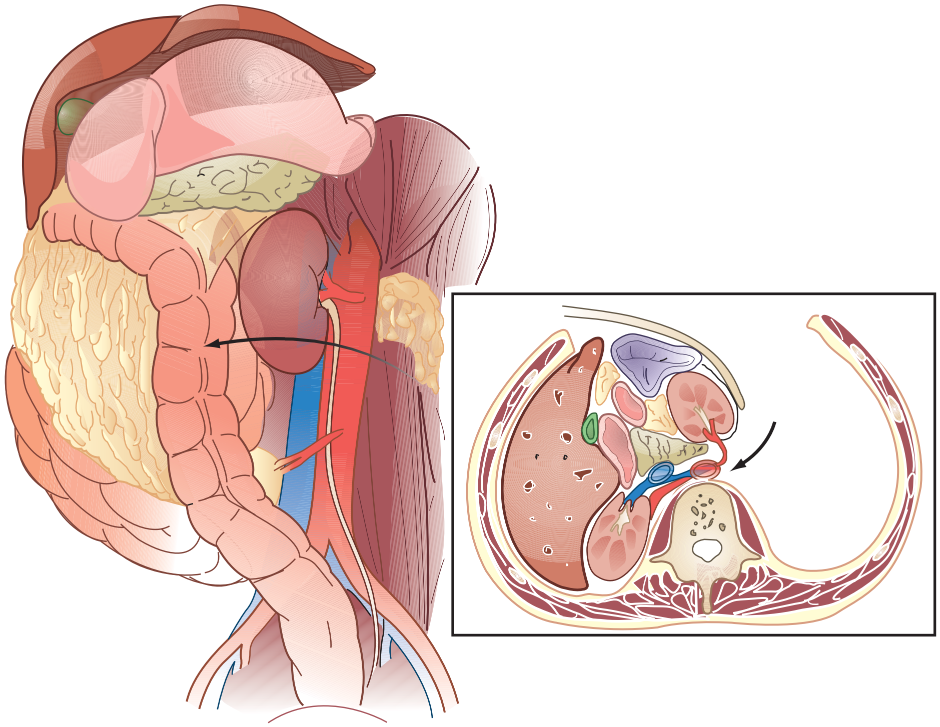

Figure 67-5 **Left-sided medial visceral rotation (Mattox maneuver).** (Illustration by Jan Redden after Jim Schmidt. © Kenneth L. Mattox, MD.)

vessels and behind the kidney, with the back of the dissecting hand sliding on the posterior abdominal wall muscles. The left-sided viscera (left colon, kidney, spleen, and pancreas) are brought to the midline, and the entire length of the abdominal aorta is thus exposed.

Right-sided medial visceral rotation (extended Kocher maneuver) consists of medial reflection of the right colon and duodenum by incising their lateral peritoneal attachments (Fig. 67-6). This exposure can be extended medially by detaching the posterior attachments of the small bowel mesentery toward the duodenojejunal ligament (Cattell-Braasch maneuver) (Fig. 67-7). The small bowel and the colon are reflected onto the lower chest, thus providing the widest possible exposure of the retroperitoneum, including the aorta, inferior vena cava, and iliac and renal vessels.

Approach to Retroperitoneal Hematoma

The location of a retroperitoneal hematoma and mechanism of injury guide the decision to explore the hematoma. The retroperitoneum is divided into three anatomic zones: the midline retroperitoneum (zone 1) (Fig. 67-8), the perinephric space (zone 2), and the pelvic retroperitoneum (zone 3).

Any hematoma in zone 1 mandates exploration for both penetrating and blunt injury because of the high likelihood and unforgiving nature of major vascular injury in this area. The transverse mesocolon is the dividing line between the supramesocolic and inframesocolic compartments. A central supramesocolic hematoma presents behind the lesser omentum, pushing the stomach forward, whereas an inframesocolic hematoma develops behind the root of the small bowel mesentery, pushing it forward in a configuration similar to that of a ruptured abdominal aortic aneurysm.[2,35]

This distinction between supramesocolic and inframesocolic hematoma has critical implications for proximal control and exposure. A supramesocolic hematoma is the result of injury to the suprarenal aorta, celiac axis, proximal superior mesenteric artery, or proximal part of a renal artery. Proximal control is obtained by clamping (or compressing) the aorta at the diaphragmatic hiatus, and the injured vessel is exposed by left-sided medial visceral rotation. A central inframesocolic hematoma is the result of injury to the infrarenal aorta or inferior vena cava. Proximal control is achieved at the supraceliac aorta, and exposure is provided by opening the posterior peritoneum in the midline, in much the same way as for an infrarenal aortic aneurysm.

A hematoma in zone 2 is the result of injury to the renal vessels or parenchyma and mandates exploration for penetrating trauma to assess the damage and repair the injuries. A nonexpanding stable hematoma resulting from a blunt trauma mechanism is better left unexplored because opening Gerota's fascia is very likely to result in further damage to the traumatized renal parenchyma and subsequent loss of the kidney. In the severely injured patient with a stable hematoma from a penetrating injury, it is advisable not to explore the injured kidney because the patient may not have the physiologic reserves to tolerate an elaborate and time-consuming repair.

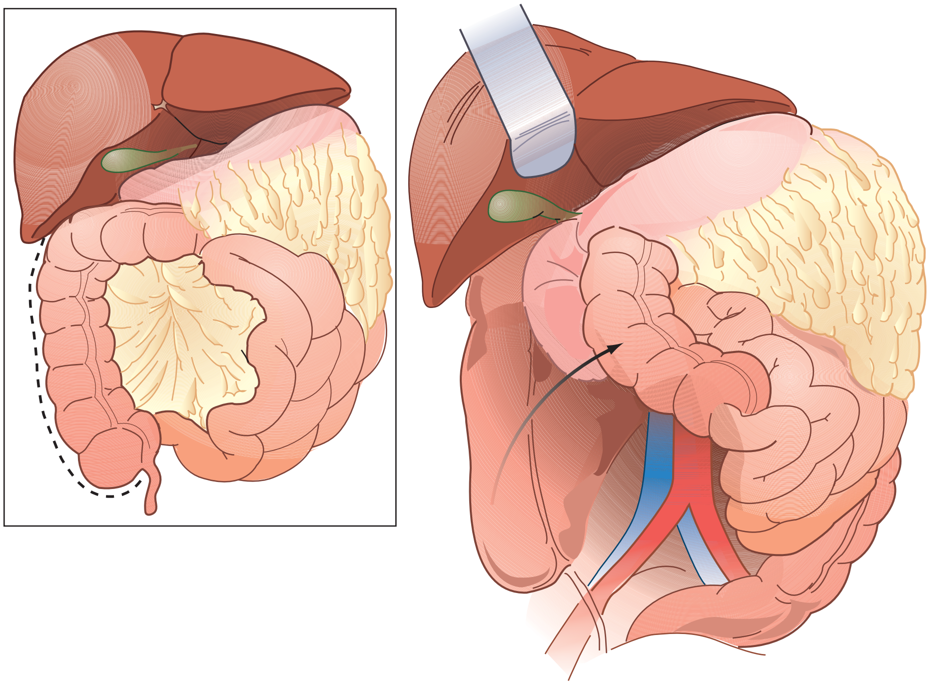

Figure 67-6 **Right-sided medial visceral rotation (extended Kocher maneuver).** (Illustration by Jan Redden. © Kenneth L. Mattox, MD.)

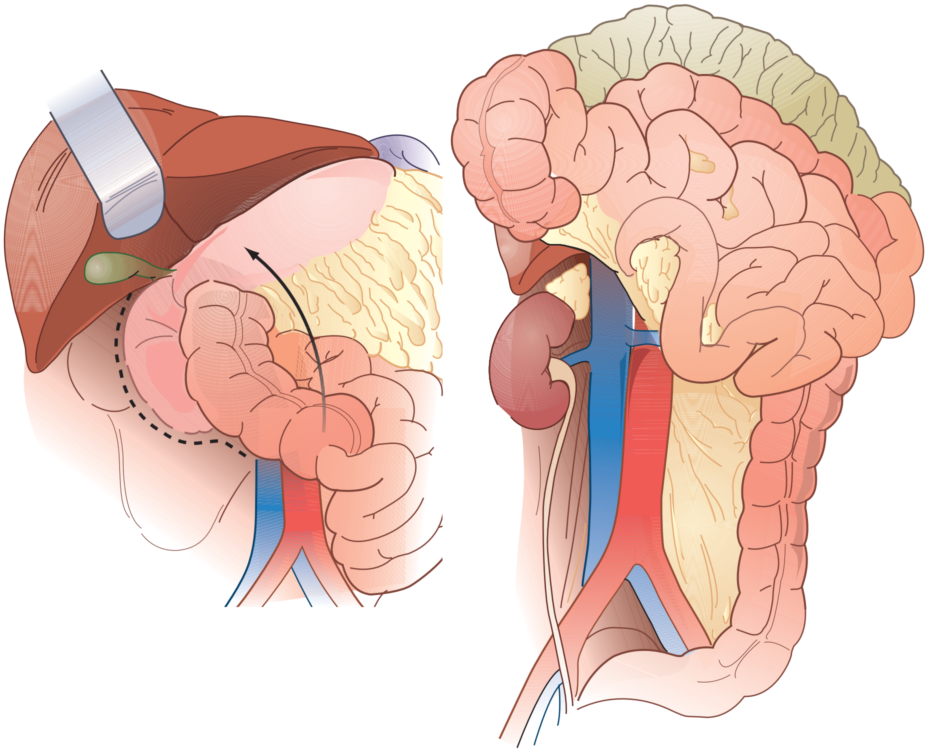

Figure 67-7 **Extensive retroperitoneal exposure by the Cattell-Braasch maneuver.** (Illustration by Jan Redden. © Kenneth L. Mattox, MD.)

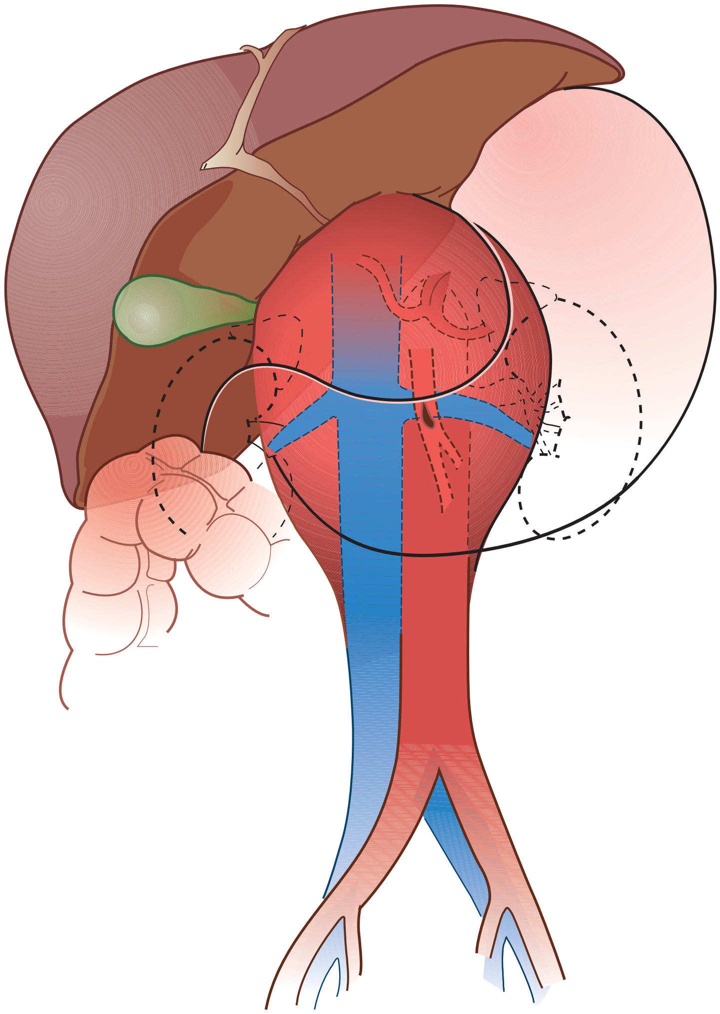

Figure 67-8 **Retroperitoneal hematoma, zone 1.** (Illustration by Jan Redden after Jim Schmidt. © Kenneth L. Mattox, MD.)

Traditional teaching advocates proximal control of a perinephric hematoma by midline looping of the ipsilateral artery and vein at the midline. However, this dissection is time-consuming and often unnecessary. In the presence of active hemorrhage, the injured kidney can be rapidly mobilized by incising the posterior peritoneum and Gerota's fascia lateral to it, lifting the injured kidney up and medially, and then clamping the entire renal hilum.

A pelvic retroperitoneal hematoma (zone 3) secondary to penetrating trauma mandates exploration because of the likelihood of iliac vessel injury. However, zone 3 hematomas resulting from blunt trauma are usually associated with pelvic fractures and are not explored because the effective management of this type of bleeding is based not on operative control (which rarely proves effective) but on external fixation or angiographic embolization of the bleeding vessels. The only exception is a rapidly expanding hematoma in which the surgeon suspects a major iliac vascular injury that requires operative repair.

Specific Abdominal Vascular Injuries

A high-grade penetrating injury to the abdominal aorta with near transection is rarely seen in the operating room because it usually results in immediate exsanguination and death. The mortality rates for abdominal aortic injuries range from 50% to 90%, with injuries to the perirenal aortic segment being the most lethal (>80% mortality), followed by suprarenal (50%-70%) and infrarenal injuries (50%-60%).[25] Clean lacerations of the aorta can sometimes be primarily repaired by transverse approximation of the lumen, but more often destruction of the aortic wall mandates prosthetic graft interposition. Despite theoretical concerns that spillage of intestinal content may cause synthetic graft infection, a synthetic graft is the only practical option, and graft infections after placement for penetrating trauma to the aorta have not been reported.

Blunt trauma to the abdominal aorta is very rare, usually the result of motor vehicle collision with impingement of the steering wheel or a seat belt. The most

common location is the origin of the inferior mesenteric artery, and the clinical presentation is that of acute aortic thrombosis secondary to intimal disruption. The diagnosis is made at angiography, and operative repair usually requires a synthetic interposition graft.

Penetrating injuries to the iliac vessels carry high mortality rates (25%-40%) because exposure and control can be difficult, and associated injuries to adjacent abdominal organs are the rule rather than the exception.[36-38] Proximal control is initially obtained away from the injury, on the inframesocolic aorta and vena cava, and distal control is achieved on the external iliac vessels at the inguinal ligament by "towing in" with a large retractor to compress the iliac vessels against the edge of the bony pelvis. Reflection of the colon from its lateral peritoneal attachment on the relevant side unroofs the pelvic hematoma. Vascular control is then optimized by gradually advancing the clamps closer and closer to the injury as the dissection proceeds.

The iliac vessels are amenable to bail-out tactics such as temporary shunt insertion, balloon tamponade of a venous injury, or even arterial ligation with a delayed extra-anatomic reconstruction. Occasionally, the only way to gain access to an injured iliac vein is to divide the overlying common iliac artery and then reconstruct it after the venous repair has been completed.

The use of a synthetic graft for iliac artery reconstruction in the presence of peritoneal contamination is a cause for concern.[39] In the presence of limited spillage of small bowel content, use of a synthetic graft (after the bowel injury has been repaired and the field irrigated) is an acceptable option. However, with gross fecal contamination, ligation of the injured iliac artery and a subsequent femorofemoral bypass is the safe course of action.

A low threshold for fasciotomy is maintained after iliac vessel injuries because leg edema is common (particularly after iliac vein ligation) and repair of an iliac artery injury may be time-consuming and associated with prolonged ischemia. The hypotensive critically injured patient is particularly susceptible to the devastating effects of elevated compartment pressures.

Injuries to the superior mesenteric vessels present either as exsanguinating hemorrhage from the root of the mesentery, a supramesocolic central retroperitoneal hematoma, or ischemic bowel. The proximal segment of the superior mesenteric artery is exposed by left-sided medial visceral rotation, whereas the infrapancreatic segment is accessed by pulling the small bowel down and to the left and incising the peritoneum of the root of the mesentery. Another good option for exposure of the infrapancreatic segment is the Cattell-Braasch maneuver. The close proximity of the mesenteric vessels to the pancreatoduodenal complex, inferior vena cava, and the right renal pedicle means that severe associated injuries are the rule, opportunities for reconstruction are rare, and mortality is very high. The successful use of a temporary shunt in the superior mesenteric artery as a damage control technique has been reported. If graft interposition is required to reconstruct the superior mesenteric artery, a takeoff from the distal aorta above the bifurcation keeps

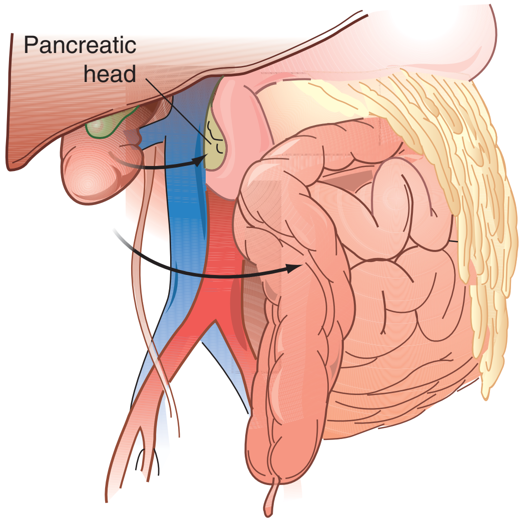

Figure 67-9 **Right-sided medial rotation of the viscera to expose the inferior vena cava.** (© Baylor College of Medicine, 1981.)

the suture line away from an injured pancreas. A second-look exploratory laparotomy is mandatory to assess the viability of the bowel. The injured superior mesenteric vein is repaired by lateral venorrhaphy when possible. Often the only technical option is ligation, which requires aggressive postoperative fluid resuscitation to compensate for ensuing massive splanchnic sequestration and may lead to venous gangrene of the bowel. A second-look laparotomy is mandatory.

Penetrating injuries to the renal arteries typically result in nephrectomy because associated injuries make complex vascular reconstruction of the renal artery an unattractive option. Blunt renovascular deceleration trauma is usually asymptomatic and is discovered when a kidney fails to opacify on CT. Arteriography is required for diagnosis and may document a spectrum of injuries ranging from intimal tear to complete renal artery thrombosis. Because blunt renovascular trauma is often associated with more life-threatening injuries, a significant diagnostic delay is common, and attempted renal salvage by major vascular reconstruction is usually not a practical option. For possible suitable operative candidates, the time limit that precludes a successful revascularization remains controversial. If 4 to 6 hours have elapsed since the injury and the renal artery is occluded, repair is not undertaken.

Injuries to the inferior vena cava (IVC) remain highly lethal, with mortality rates consistently in excess of 50%, particularly for the least accessible segments of the vein (iliac bifurcation, suprarenal and retrohepatic IVC).[2,40-44] The IVC is exposed by a right-sided medial visceral rotation (Fig. 67-9), and initial control is achieved by direct pressure above and below the injury (Fig. 67-10). The technical options for the infrarenal IVC are lateral repair or ligation.

Retrohepatic IVC injuries are especially unforgiving and difficult to access and control.[45] The typical operative findings are massive venous bleeding either through a deep hepatic wound or from the posterior aspect of a

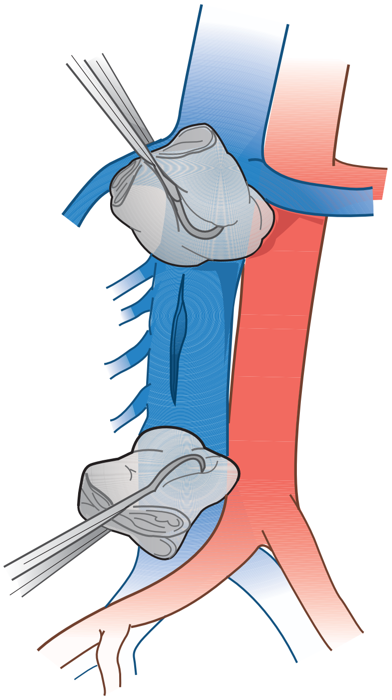

Figure 67-10 Compressing the inferior vena cava above and below the injury.

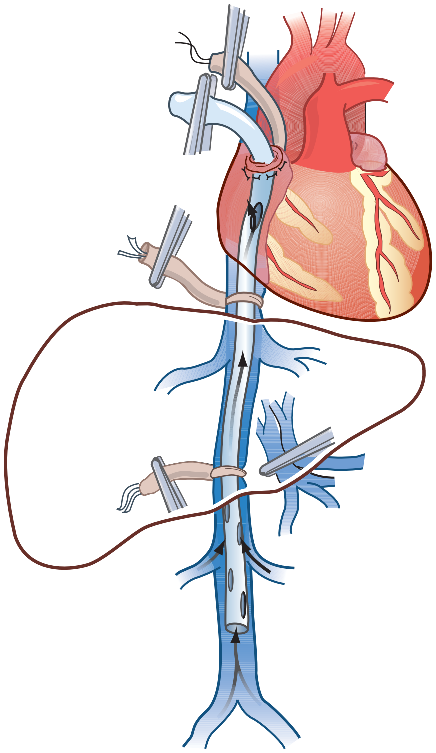

Figure 67-11 The atriocaval shunt. (© Baylor College of Medicine, 1984.)

severely injured liver. The bleeding is unaffected by a Pringle maneuver. Usually by the time the injury is recognized, the patient has already sustained massive blood loss and is in profound shock. Direct repair options for the retrohepatic IVC are complex and have dismal results. The most widely known technique is the atriocaval shunt first described by Schrock in 1968.[40,44,45] The atriocaval shunt uses either a chest tube or an endotracheal tube inserted through the right atrium to exclude the injured segment without compromising cardiac preload (Fig. 67-11). This technically demanding procedure requires familiarity with cardiac cannulation and is usually performed by two teams working simultaneously in the chest and abdomen. It is therefore not surprising that this elaborate technical maneuver, usually employed in dire circumstances, carries a reported mortality rate in excess of 80%. There is no optimal solution for the technical challenge of retrohepatic IVC trauma. Several authors have reported successful packing of these injuries, and this simple solution, if performed early and effectively, may prove the most practical solution for these inaccessible venous injuries.

PERIPHERAL VASCULAR TRAUMA

General Principles

Initial Assessment

Initial assessment and care of the patient with peripheral vascular trauma focuses on control of external hemorrhage and diagnosis of limb ischemia. In an ischemic extremity, assessing the severity of ischemia and identifying the arterial segment involved are the key considerations. It is extremely important to document the neurologic status of the injured extremity and to assess it for compartment syndrome. In the hemodynamically unstable trauma patient, a diminished arterial pulse or a cold and pale extremity is difficult to assess, so the diagnosis of ischemia often depends on comparison to the contralateral extremity.[24]

Although it is stated that restoration of arterial perfusion in less than 6 hours improves limb salvage rates, the window of opportunity for salvage is never a fixed interval but rather a flexible time frame that is heavily influenced by the site and nature of injury, the presence of efficient collaterals, and the patient's age and hemodynamic status. Of all the symptoms and signs of acute limb ischemia, a neurologic deficit conveys the greatest urgency because it signifies the imminent threat of an irreversible ischemic insult.

Noninvasive Vascular Diagnosis

The hand-held Doppler flow detector provides limited but useful qualitative information, especially in the hemodynamically unstable, cold, and vasoconstricted patient in whom diagnosis of limb ischemia is often difficult. The hand-held Doppler is a reliable screening tool for significant arterial obstruction after both blunt and penetrating trauma, and arteriography is indicated for any significant difference (>10 mm Hg) in ankle pressures between extremities. The hand-held Doppler is also useful in

assessing severity of ischemia by determining the presence of an arterial and venous Doppler signal. Absence of the latter signifies grave ischemia.

Duplex scanning has an overall accuracy rate of about 98% in detecting clinically significant injuries. It can also detect minimal arterial injuries such as intimal flaps and small pseudoaneurysms. However, the routine use of Duplex ultrasonography in the acute admission area of many trauma centers is limited by logistical constraints. It remains a valuable tool for follow-up in patients with suspected or minimal vascular injuries, postoperative patients, and those with late complications of vascular trauma such as pseudoaneurysm and arteriovenous fistula.

Role of Arteriography

Arteriography is the definitive modality for diagnosing extremity arterial injuries in hemodynamically stable patients. It is indicated when the information gained can alter or facilitate the operative approach. In patients with multiple penetrations in an ischemic extremity and in those with blunt trauma (especially if several fractures are present), preoperative arteriography eliminates the need for extensive exposure and tedious exploration of the neurovascular bundle by precisely pinpointing the site of injury. In the actively bleeding patient, immediate surgical exploration without angiography is the correct course of action.

The use of arteriography to exclude arterial trauma in asymptomatic patients with penetrating wounds in proximity to the neurovascular bundle has changed in the past decade. Although previously considered a standard practice, it has been conclusively shown that physical examination accurately detects arterial injuries that require operative repair. If exclusion arteriography is routinely performed for proximity injuries, about 10% of patients will have an angiographic abnormality, but these lesions are minimal injuries that do not require operative repair and have a benign natural history. Based on these considerations, there is now conclusive evidence supporting a selective policy that avoids routine arteriography in asymptomatic patients with proximity injuries.

The Mangled Extremity

The decision to immediately amputate a severely wounded extremity (rather than attempt salvage) is difficult and emotionally charged, especially because vascular reconstruction is usually technically feasible, being one of the less problematic aspects of the injury. The *mangled extremity* is defined as injury that involves at least three of the four major tissue systems of a limb, consisting of bone, soft tissue, vessels, and nerves. Several scoring systems have been proposed to predict the ultimate fate of the limb based on the severity of injury and the patient's associated injuries and comorbid factors. However, in practice, the decision to proceed with amputation hinges on surgical judgment and the patient's specific circumstances. It is a team decision and is made only after careful examination and consideration. The decision is usually made in the operating room, where the mangled extremity can be meticulously examined under optimal conditions. This is the only reliable way to assess the full extent of the damage, especially to nerve continuity, a critical factor in the decision process. Although the vascular injury itself is usually a less critical component than the neural damage or the ability to cover the vascular reconstruction with viable soft tissue, the total ischemia time is a major consideration in the decision to amputate. As a general rule, a totally interrupted distal innervation, extensive soft tissue destruction, and bone loss exceeding 6 cm in length all portend a grave prognosis for the limb.

Operative Technique

Although control of active hemorrhage is always a top priority, reconstruction of injured vessels must be carefully orchestrated with the management of bone and soft tissue injuries. It is preferable to achieve bone alignment before vascular reconstruction because orthopedic manipulation and reconstruction takes time and may disrupt the vascular repair. Thus, if the limb is not grossly ischemic, reduction and fixation of fractures is performed first. If the limb is ischemic, a temporary intraluminal shunt is inserted to maintain distal perfusion during the orthopedic procedure.

As in any type of vascular trauma, a key technical principle is to achieve proximal and distal control outside the hematoma and away from the area of active bleeding, using extensile exposure that can be carried proximally and distally as necessary.

The next step is to define the full extent of the injury and plan the necessary repair. In a contused vessel that remains in continuity, the key factor is integrity of the intima. An overlooked segment of injured intima can easily frustrate an otherwise meticulous arterial repair. The injury is carefully débrided and a reconstruction technique chosen depending on the specific circumstances in the operative field.

Because of the relatively small diameter of limb arteries, lateral repair is feasible only in a minority of patients: those with iatrogenic lacerations or a simple stab wound. Most injuries require end-to-end anastomosis or an interposition graft. The completely transected artery of a young patient typically retracts a surprising distance, making interposition graft the only practical option.

Before beginning the repair, a Fogarty thrombectomy is performed on both ends of the injured vessel to remove intraluminal clot and ascertain the presence of good inflow and backflow. The vessel ends are then irrigated with heparinized saline. Full systemic anticoagulation is often contraindicated in the patient with multiple injuries. If there is any uncertainty about the integrity or adequacy of the outflow tract, an intraoperative angiogram is performed before the reconstruction.

The small diameter of arteries in the arm and below the knee prohibits the use of synthetic material, making a segment of greater saphenous vein the ideal conduit in these locations. A synthetic graft is the preferred conduit in the thoracic outlet and above the groin. There is some controversy surrounding graft interposition of the femoral artery.[39] The traditional view that autogenous

vein grafts have a better outcome in contaminated traumatic wounds is supported neither by clinical nor experimental data. Considerable evidence has accumulated to support the use of polytetrafluoroethylene (PTFE) grafts in a contaminated operative field because the material is resistant to dissolution by bacterial collagenase and fares better than a vein graft if soft tissue cover is lost. Use of a synthetic graft also expedites the operative procedure, an important consideration in severely injured patients.

Graft protection by adequate soft tissue cover is a fundamental principle in vascular surgery that is especially relevant in trauma. The graft must be routed through a noncontaminated field and must also be adequately covered with viable soft tissue. An exposed graft, even if patent, represents a serious threat, not only to the viability of the limb but also to the patient's life. Therefore, consideration of graft protection may dictate the use of a longer extra-anatomic route rather than a shorter but contaminated route and may also affect the operative sequence.

Vein Injuries

The need to repair injured peripheral veins and the long-term consequences of vein ligation in trauma patients remain the focus of active debate. The available evidence supports the repair of venous injuries encountered during exploration for an associated arterial trauma, but only if the patient is hemodynamically stable and the repair will not jeopardize or delay management of other significant injuries. Long-term patency rates of complex venous repairs (including interposition grafts using either saphenous vein or synthetic material) are poor. The best results are achieved by simple lateral repair that does not narrow the lumen or by end-to-end anastomosis. Contrary to previously held views, peripheral veins (including the popliteal vein) can be ligated without compromising adjacent arterial repairs or affecting limb salvage rates. The risk for long-term leg edema or chronic venous insufficiency is also very low.

Fasciotomy

Multiple factors contribute to the rapid dynamics of elevated compartment pressures in the patient with peripheral vascular injury: direct muscular trauma, hypotension, reperfusion of the ischemic extremity, and ligation of injured veins.[46,47] Compartment syndrome is common in these patients but is also notoriously difficult to diagnose early. Generalized edema, swelling of the injured extremity, and lack of communication with the patient all combine to deprive the surgeon of vital early clues. Arbitrary definitions of ischemic times are poor guidelines to the need for fasciotomy. Pressure measurement using a hand-held transducer is problematic in the hemodynamically labile patient, where the compartment pressure that compromises capillary perfusion may be significantly lower than in the stable patient. Therefore, the safest course of action is to maintain a low threshold for fasciotomy. Combined arterial and venous trauma, long delay between injury and revascularization, and extensive bone and soft tissue destruction are examples of clinical circumstances in which early fasciotomy is in the patient's best interest.

In lower extremity fasciotomy, the four compartments of the leg are all decompressed. This is most commonly achieved through two longitudinal incisions (Fig. 67-12). A longitudinal incision is made about 2 fingerbreadths lateral to the tibial crest, beginning immediately below the tibial tuberosity and extending to the ankle. Dividing the fascia along the line of incision decompresses the muscles of the anterior compartment, with special care

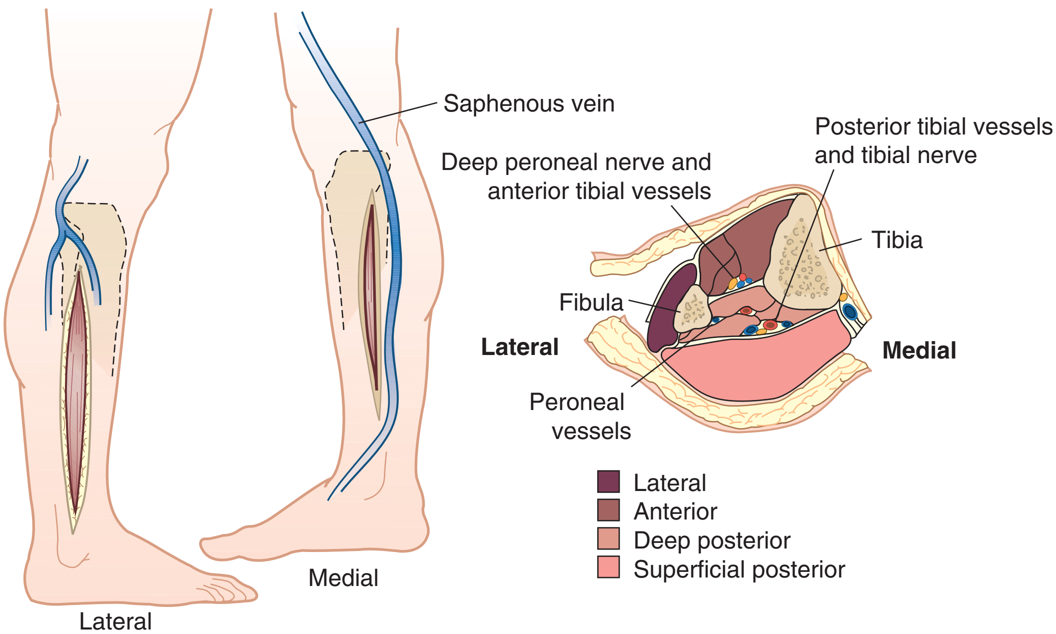

Figure 67-12 Fasciotomy.

being taken to divide the superior extensor retinaculum above the ankle. The surgeon then identifies the crural fascia between the anterior and lateral compartments and divides it along the entire length of the incision, taking care to avoid injury to the lateral peroneal nerve in the superior aspect of the incision, the most common iatrogenic injury during an anterior fasciotomy. The posterior compartments are decompressed through a separate medial incision placed immediately posterior to the posterior edge of the tibia, carefully avoiding injury to the long saphenous vein. The superficial posterior compartment is decompressed by incising the deep fascia. Detaching the soleus muscle from the posterior aspect of the tibia using the electrocautery opens the deep posterior compartment and completes the procedure.

Iatrogenic Trauma

Iatrogenic trauma to the femoral vessels in the groin can serve as a model of similar iatrogenic injuries in other anatomic locations. Bleeding from a groin puncture wound is often the result of inadequate groin compression after catheter removal. Ongoing hemorrhage into the subcutaneous tissue presents as an expanding hematoma, where the major concern is not massive blood loss but rather pressure necrosis of the overlying skin and compression of the cutaneous branches of the femoral nerve with a resulting painful neuralgia. The management is by operative decompression of the hematoma and repair of the injured femoral artery through a longitudinal groin incision. Proximal control can usually be obtained at or immediately above the inguinal ligament, and a simple hemostatic suture is all that is required.

An inadvertently high cannulation of the external iliac artery is difficult to compress effectively and may result in a large retroperitoneal hematoma. The patient typically presents with flank or groin pain and clinical signs of ongoing blood loss without a groin hematoma. Abdominal CT scan demonstrates the hematoma, and bleeding is usually self-limited. Rarely, hemodynamic deterioration leads to urgent operative repair of the injured external iliac artery.

Despite effective compression, a pseudoaneurysm may still develop at the puncture site. The typical presentation is groin pain and hematoma that may appear hours and even days after the arterial cannulation. With a large pseudoaneurysm, a pulsatile hematoma may be noted. Diagnosis of a pseudoaneurysm is made by color-flow Doppler ultrasound, and the initial treatment is by ultrasound-guided manual compression with the aim of inducing thrombosis of the pseudoaneurysm. The reported success rate of ultrasound-guided compression is 80% to 90% for small acute pseudoaneurysms but significantly lower for large ones and in anticoagulated patients. Thus, 20% to 30% of patients with iatrogenic femoral pseudoaneurysms still require operative repair.

Iatrogenic arteriovenous fistula is typically the result of a low groin puncture that perforates the superficial or deep femoral artery together with an adjacent vein. The resulting arteriovenous fistula is often asymptomatic and is incidentally discovered during color Doppler evaluation of a groin hematoma. A larger fistula may be associated with a continuous murmur and a palpable thrill. Small incidentally discovered fistulas usually have a benign natural history. They either close spontaneously or remain asymptomatic and do not require treatment. A large or symptomatic fistula may require surgical repair.

Arterial thrombosis is another frequently encountered type of iatrogenic injury. It is more common with large-bore cannulations in patients with atherosclerosis of the common femoral artery. The underlying mechanism is an intimal flap or fracture of a small segment of the arterial wall that leads to thrombosis. Understanding this mechanism of injury is the key to an effective repair because simple thrombectomy will not suffice. The underlying intimal injury must be identified and repaired, sometimes by means of a patch angioplasty.

Management of Specific Injuries

Most injuries to the common or superficial femoral arteries are penetrating. Proximal control for a high thigh or groin wound is usually obtained through a longitudinal groin incision using the inguinal ligament as a guide to dissection. The inguinal ligament limits the upward extension of a groin hematoma. Therefore, by carrying the dissection through the inguinal ligament and into the preperitoneal fat behind and above it, the surgeon can rapidly identify and control the distal external iliac artery before addressing the hematoma itself. Alternatively, the external iliac artery can be exposed through a separate oblique incision above and parallel to the inguinal ligament, using a retroperitoneal approach. Dissection can then proceed inside the femoral triangle to expose the injured vessels. The deep femoral artery needs to be identified and preserved during reconstruction of an injured common femoral artery.

The superficial femoral artery in Hunter's canal is exposed through a medial longitudinal thigh incision. The sartorius muscle is mobilized and retracted, exposing the roof of Hunter's canal. Special care must be taken to preserve the saphenous nerve lying on the anterior aspect of the artery.

Popliteal artery injuries result in limb loss more often than any other peripheral vascular injury. Amputation rates as high as 20% have been reported, especially from blunt trauma. The collateral arterial system around the knee is not well developed and is very susceptible to interruption by significant trauma, making delays in diagnosis and treatment particularly unforgiving. Posterior dislocation of the knee is associated with popliteal artery injury in one of every 3 to 5 patients, but other types of blunt trauma around the knee, such as a bumper injury to the proximal tibia or any injury that causes an unstable knee joint, are also likely to damage the artery. Most patients present with a clearly ischemic extremity, where the indication for an urgent surgical exploration is obvious. In the absence of associated injuries, some surgeons administer IV heparin preoperatively to prevent thrombosis of the distal capillary bed, a major concern with popliteal injuries. A full fasciotomy is performed before the vascular exploration in a grossly ischemic leg. In about 30% of patients, the clinical presentation is less

clear because the limb is not grossly ischemic. The key to avoiding undue delays is a high index of suspicion and a low threshold for angiography whenever significant blunt trauma has affected the area around the knee.

The proximal popliteal artery is exposed through an incision along the anterior border of the sartorius muscle above the knee. The deep fascia is incised, and the sartorius is retracted, providing access to the popliteal space between the semimembranosus muscle and the adductor magnus tendon. The distal artery is approached through a medial incision immediately behind the posterior border of the tibia. The crural fascia is incised, and the popliteal space is entered between the medial head of the gastrocnemius and the soleus muscles. Wide exposure of the entire length of the popliteal artery can be achieved by joining the incisions and dividing the tendons of the semitendinosus, semimembranosus, gracilis, and sartorius and then dividing the medial head of the gastrocnemius. In most patients, the artery is repaired using a saphenous vein interposition graft from the contralateral extremity. On completion of the reconstruction, an intraoperative angiogram is obtained. An associated vein injury is repaired if the clinical circumstances allow, but venous reconstruction does not affect the eventual outcome of the arterial repair. In the absence of active bleeding from the injured popliteal artery, a more expedient approach is a bypass and exclusion technique. The proximal and distal popliteal artery is exposed and isolated through separate incisions, a saphenous vein graft is then tunneled between the exposed segments to bypass the injury and anastomosed proximally and distally using an end-to-end technique, thus excluding the injured segment without exposing it.

Penetrating injuries to the lower leg arteries below the popliteal trifurcation usually present with bleeding and progressive swelling of the calf. If one of the three shank arteries is involved, hemostasis can be achieved either by angiographic embolization or operative ligation. Patients with severe blunt trauma to the lower leg usually present with a combination of extensive bone and soft tissue damage as well as diminished or absent pedal pulses. Physical examination is unreliable under these circumstances, and angiography is used to diagnose or exclude an arterial injury. The traditional teaching to maintain patency of at least two shank arteries after blunt trauma is unproved. Exploration and repair of the lower leg arteries is technically difficult in the hostile circumstances created by adjacent bone and soft tissue injuries and can safely be avoided in the presence of a single patent artery. There is, however, evidence to suggest that if the only remaining intact vessel is the peroneal artery, this may not suffice to prevent foot ischemia.

Exposure of the lower leg arteries is best begun proximally, away from the area of injury (Fig. 67-13). The distal popliteal artery is exposed below the knee through a medial approach, and dissection is continued distally by detaching the soleus muscle from the posterior border of the tibia, thus providing access to the posterior tibial and peroneal arteries. The anterior tibial artery is approached through a separate anterolateral incision between the tibialis anterior and the extensor hallucis longus muscles.

Most axillary artery injuries are penetrating, resulting in hemorrhage or distal ischemia. In most published series, injuries to the subclavian and axillary vessels are treated as a single clinical entity. Extending a subclavian incision into the medial aspect of the abducted upper arm exposes the axillary artery. The incision is carried through the pectoral fascia, and the pectoralis major muscle can be either split or divided depending on the exposure required. The pectoralis minor muscle is then retracted or divided, and the clavipectoral fascia is opened, exposing the neurovascular bundle in the axillary sheath.

Injuries to the brachial artery account for 20% to 30% of peripheral arterial injuries, making this vessel the most frequently injured artery in the body. The artery is exposed through a medial arm incision in the groove between the biceps and triceps muscles. The first structure encountered in the neurovascular bundle is the median nerve, which must be isolated and preserved. If the brachial artery is exposed in the proximal arm, the deep brachial artery is identified and controlled at the lateral border of the teres major muscle.

Most isolated ulnar or radial artery injuries can be ligated with impunity. An ischemic hand (due to an incomplete palmar arch or injury to both arteries) requires an arterial reconstruction. In the presence of associated bone and soft tissue injury, it is often safest to begin the exposure of a radial artery proximally at the brachial bifurcation and then proceed distally to the injured segment. A lower medial arm incision is carried into the antecubital fossa in an S-shaped configuration to avoid a longitudinal incision across the antecubital skin crease. The bicipital aponeurosis is divided to expose the brachial bifurcation, and the radial artery is identified and isolated. Exposure of the ulnar artery in the proximal forearm is more difficult because of the deeper location of the artery at this level. It is found deep to the antebrachial fascia, between the flexor carpi ulnaris and flexor digitorum superficialis muscles.

CONCLUSION

There are several important differences between vascular trauma and other types of vascular disease. One salient feature of vascular trauma is the constant need to consider the injury and the various therapeutic options within the context of the patient's overall trauma burden. Purposeful delay in the operative repair of blunt aortic injury and the decision to employ damage control tactics during laparotomy for combined vascular and hollow visceral injury are but two examples of this key principle.

In the severely injured patient, management priorities change constantly, and the surgeon must not only tailor the technical solution to the specific clinical circumstances but also be prepared to modify it or improvise a new solution as the circumstances change. The sequencing of the orthopedic and vascular repairs in the severely wounded extremity illustrates this need for flexibility.

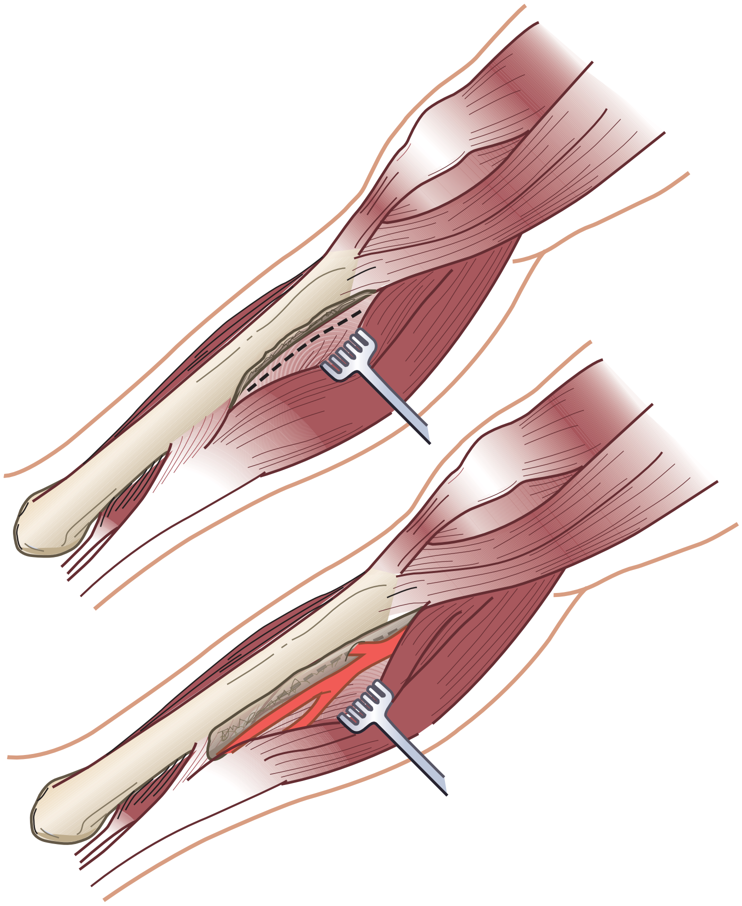

Figure 67-13 **Exposure of tibial vessels.** (Illustration by Jan Redden. © Kenneth L. Mattox, MD.)

The successful management of major vascular trauma hinges on the adaptation of standard vascular surgical techniques to nonstandard situations. The use of temporary intraluminal shunts and balloon catheter tamponade demonstrates how standard technical adjuncts have been adapted to provide new solutions in difficult situations.

Endovascular therapy offers a new array of management options for vascular trauma, and its minimally invasive nature is particularly suited to the critically injured patient with strained physiologic reserves. Endovascular solutions are playing an increasing role in the management of truncal vascular injuries in nonbleeding patients.

Current advances in understanding the pathophysiology of trauma and innovative technology for vascular diagnosis and therapy are rapidly converging to provide the trauma surgeon of the future with an exciting selection of new tools. These tools will be used to further push the therapeutic envelope and continuously improve outcome in the management of the patient with major vascular injury.

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