CHAPTER 41

Peripheral Vascular Injury

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PRINCIPLES

Background and Importance

Injury to the major peripheral arteries or veins may not always be life-threatening, but it invariably poses a threat to the viability of the affected limb. Historically, due to the rapidity of exsanguination, injury to major vessels was often fatal in the field; and most patients who survived to hospital arrival had relatively minor vascular injuries. However, with the advent of modern emergency medical service (EMS) systems with advanced extrication methods and rapid transport, more patients with major vascular injuries are reaching the emergency department (ED) alive. In addition, the incidence of both penetrating injuries from interpersonal violence and blunt injuries from motor vehicle–related trauma has increased dramatically over the past 50 years. Consequently, emergency clinicians are frequently confronted with critically ill patients harboring overt (or occult) peripheral vascular injuries.

Management of these vascular injuries has also evolved, with advances in diagnostic methods and surgical techniques. Treatment of vascular injuries before and during World War II resulted in limb amputation rates of 50% to 75%. Advances during the Korean and Vietnam wars reduced amputation rates to 5% to 15%, which approach the current rates of amputation for civilian injuries.

Tremendous progress has also been achieved in diagnostic and therapeutic techniques for dealing with peripheral vascular injuries, and several noninvasive diagnostic modalities have emerged as accurate alternatives to surgical exploration and angiography. These techniques are easily used in the ED, and the goal of timely detection and repair of serious vascular injuries is achievable in the majority of cases.

Peripheral vascular injuries are divided almost equally between blunt and penetrating mechanisms. In the United States, up to 90% of these injuries are a result of penetrating wounds, mainly because of the high rate of penetrating trauma in inner-city urban areas.[1] Major venous injuries are present in up to 50% of gunshot wound cases, and more than 80% of these have associated arterial injuries. In addition, due to the increased use of percutaneous endovascular diagnostic and therapeutic procedures, the incidence of iatrogenic vascular injuries has increased and accounts for up to one-third of all cases in some series.[2]

Anatomy and Physiology

The major vessels and their relevant anatomy are described in the following sections (Figs. 41.1 and 41.2).

Upper Extremity

The right subclavian artery arises from the brachiocephalic artery, and the left arises from the arch of the aorta. From their origin, they course posterior and inferior to the clavicles to the outer margins of the first ribs, where they become the axillary artery and vein. The left subclavian artery rises higher than the right and extends into the root of the neck.

The axillary artery courses from the lateral border of the first rib to the inferior border of the teres major muscle, where it becomes the brachial artery. The axillary vein runs medial to the artery. Due to the extensive anastomotic arterial connections around the shoulder joint, up to half of patients with axillary artery injuries will have palpable pulses as a result of collateral circulation. Because of the close proximity of the brachial plexus and the axillary vessels, significant denervation of the upper extremity can occur.

The brachial artery begins at the lower border of the teres major muscle and divides into the radial and ulnar arteries at the level of the proximal aspect of the radial head. The median and ulnar nerves and the basilic vein are in close proximity to the brachial artery. The profunda brachii artery is a major branch that arises slightly after the origin of the brachial artery and often contributes good collateral flow if the brachial artery is injured distal to this branch point.

The radial artery originates in the cubital fossa and runs superficially to the distal end of the radius, where it ultimately joins the deep branch of the ulnar artery to form the deep palmar arch of the hand. The ulnar artery begins in the cubital fossa and runs with the ulnar nerve anterior to the flexor retinaculum, at which point it joins the radial artery to form the superficial palmar arch of the hand.

Lower Extremity

The external iliac vessels become the common femoral vessels at the inguinal ligament. After giving off the profunda femoris artery in the femoral triangle, the femoral artery continues as the superficial femoral artery almost vertically to the adductor tubercle of the femur and enters the popliteal fossa as the popliteal artery. Extensive proximal collaterals are present around the hip joint, including the gluteal, obturator, and pudendal branches of the iliac artery.

The popliteal artery gives off the genicular branches in the popliteal fossa and then divides into the anterior and posterior tibial arteries at the lower border of the popliteus muscle. The peroneal artery arises from the posterior tibial artery slightly after its origin. The anterior and posterior tibial arteries and the peroneal artery form the trifurcation of the popliteal artery, and each runs with a corresponding vein and nerve in different compartments of the leg.

The popliteal artery divides into three branches—the anterior and posterior tibial and the peroneal arteries—at the inferior margin of the popliteal fossa. Injuries below the trifurcation at the knee may need repair if hard signs of arterial injury are apparent in the foot or if two of the three arteries are occluded. The most common blunt trauma cause of popliteal artery injury is a posterior knee dislocation in which bony elements directly lacerate or cause thrombosis of the artery. Anterior knee dislocations may cause excessive stretch on the popliteal vessels resulting in arterial

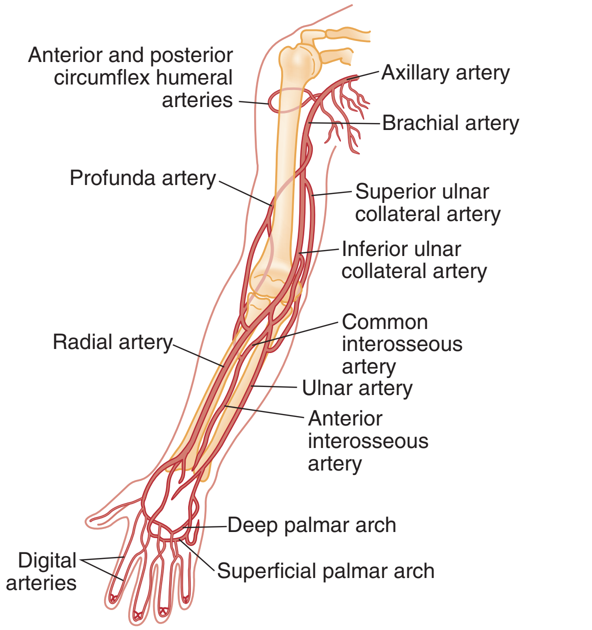

Fig. 41.1. Major arteries of the upper limb. (From Snell R, Smith M, editors: Clinical anatomy for emergency medicine, St Louis, 1993, Mosby.)

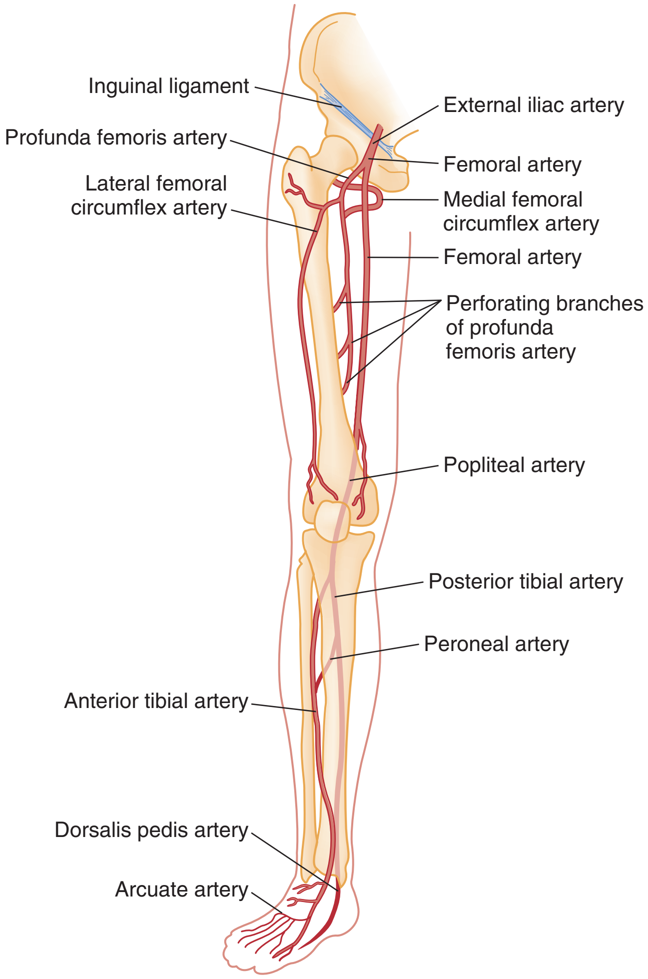

Fig. 41.2. Major arteries of the lower limb. (From Snell R, Smith M, editors: Clinical anatomy for emergency medicine, St Louis, 1993, Mosby.)

thrombosis, but this injury is relatively rare. Up to one-third of knee dislocations result in popliteal artery injury. Twenty-five percent of cases have an associated injury to the peroneal and posterior tibial nerves. A knee dislocation may reduce spontaneously, leaving little evidence of the original trauma, particularly in obtunded patients.

Pathophysiology

Blunt and penetrating types of trauma result in similar spectra of vascular injuries, although their mechanisms of injury differ. Although blunt vascular injuries are less common than penetrating injuries, they are often more severe and more commonly result in amputation because of associated injuries to nerves, bone, and soft tissue. Certain mechanisms of injury, such as animal bites that crush and lacerate vessels, can involve both penetrating and blunt mechanisms.

Penetrating Trauma

Gunshot wounds can cause direct arterial lacerations or transections, in addition to concussive injuries distal to the track of the bullet. These latter injuries tend to be tears in the intima of an artery, with subsequent thromboses that may not become apparent for hours to months after the injury. Bullets may ricochet off bone, making predicting trajectories less accurate than with stab wounds.

Stab wounds cause vascular injuries by completely or partially transecting vessels. Partial laceration of an artery may produce few symptoms of arterial insufficiency on initial evaluation but result in delayed complications. The vascular structures at risk can be predicted more reliably with stab wounds than with gunshot wounds by taking into consideration the anatomic location, causative implement, depth, and direction of the wound.

Shotgun wounds are less common than gunshot or stab wounds, but they can cause injuries varying from minor soft tissue wounds to massive destruction of soft tissue and bone, depending primarily on the range from which the shotgun was fired. The presence of multiple missiles ranging from 9 or 10 (buckshot) to dozens (birdshot) also complicates the evaluation of these injuries because of the many potential sites of potential vascular injury. In addition, close-range shotgun wounds (<3 yards) can cause significant blunt trauma to blood vessels, as well as a higher rate of bone and nerve injury than might occur with gunshot wounds. Migration of pellets or bullets proximally through the venous system to the heart, or migration through an artery with subsequent distal occlusion, has been reported frequently as a delayed complication.[3,4]

Blunt Trauma

Blunt injury involves either avulsion forces that can stretch vessels beyond their capacities or direct crushing injuries that disrupt vessel walls. In addition, fracture fragments resulting from blunt extremity trauma can lacerate or entrap vessels. These vascular injuries can range from small intimal tears to complete avulsions of arteries and nerves. Open avulsion injury of a limb is particularly severe because the skin, which is very pliable, is the final structure to tear. Once torn, it is inevitable that vessels and nerves will tear as well. Vascular injuries should also be suspected in patients with massive soft tissue avulsions or crush injuries, displaced long bone fractures, electrical or lightning injuries, and severe burns, as well as in those with compartment syndrome from trauma or prolonged immobilization as a result of stroke, coma, drug overdose, or other causes. Bites that are inflicted by large animals, such as dogs used by law enforcement, are particularly prone to arterial injury and wound complications.[5] Collateral circulation may continue to perfuse the limb, but injuries that occur proximal to the collateral branch point—or that involve both the main trunk and collateral branches—will preclude adequate flow.

Distal ischemia results from the inability of tissues to continue aerobic metabolism. Eventually, anaerobic metabolism consumes all substrate, thereby resulting in the accumulation of lactic acid. As ischemia progresses, cellular integrity is lost and irreversible cell death occurs. A vicious cycle of tissue edema and further impairment of the blood supply occurs. When no specific measures are taken to cool the limb, it is said that the limb is undergoing “warm ischemia” at ambient temperature. After 6 hours of complete warm ischemia, 10% of patients will have irreversible damage; by 12 hours, 90% will have irreversible damage. Artificially cooling the limb to near freezing temperature (“cold ischemia”) will reduce the metabolic demands and greatly prolong the tissue’s tolerance of ischemia to 24 hours or more.

Two main types of vascular injury can result from trauma: *occlusive injuries* (transections, thromboses, and reversible spasm), in which all perfusion distal to the occlusion is lost, and *nonocclusive injuries* (intimal flaps, dissections, arteriovenous fistulae [AVF], and pseudoaneurysms), which include mechanical defects to vessel walls that may or may not lead to decreased distal blood flow.[6]

Complete Occlusive Injury

Transection. The most common vascular injury is complete transection, in which distal flow is effectively eliminated. Cleanly transected arteries will often retract and undergo spasm to minimize blood loss. With longitudinal arterial lacerations and venous injuries, blood loss cannot be minimized by this physiologic response, and therefore tend to result in greater blood loss. Pulsatile bleeding may quickly lead to exsanguinating hemorrhage and shock.

Thrombosis. Intraluminal thrombosis (Fig. 41.3) may occur in an injured artery acutely (within 24 hours) or may be delayed for many months. Acute thrombosis is initiated by stasis resulting from compression of the artery or from a disruption in the intima of an artery that becomes a nidus for thrombus formation. As the thrombus propagates, complete occlusion of the vessel can occur. Delayed thrombosis can occur months to years after injury if the injured vessel heals with stricture formation, resulting in decreased distal flow, followed by stasis and clot formation.

Reversible Arterial Spasm. The precise cause and incidence of significant reversible arterial spasm after trauma are unknown. In the case of arterial transection, arterial spasm is beneficial and limits hemorrhage. In other cases, however, the segmental arterial spasm occurs at some distance from the site of traumatic injury and can produce severe distal ischemia. Arterial spasm is particularly common in children. In many series, segmental arterial spasm is the most common arteriographic finding (Fig. 41.4). However, symptoms of ischemia should never be assumed to be a result of arterial spasm; that diagnosis is based on arteriographic results only.

Nonocclusive Injuries

Intimal Flap. An intimal flap occurs when there is a break in the vessel intima, generally from excessive stretch or concussive forces. Although flow is not altered by small flaps and the associated soft tissue wounds often appear benign initially, these intimal flaps may become a nidus for thrombosis that can occur hours to months after the initial injury.

Pseudoaneurysm. A true aneurysm contains all three layers of the vessel wall (intima, media, and adventitia) and rarely is caused by trauma. A pseudoaneurysm is formed following a tear in a vessel wherein the hemorrhage is contained by surrounding fascia and the resulting hematoma is gradually encased by a capsule of fibrous tissue, analogous in consistency to the adventitia of a normal vessel (Fig. 41.5). Because it is relatively thin walled, rupture of a pseudoaneurysm is a distinct possibility. In addition, because its diameter inevitably expands under arterial pressure

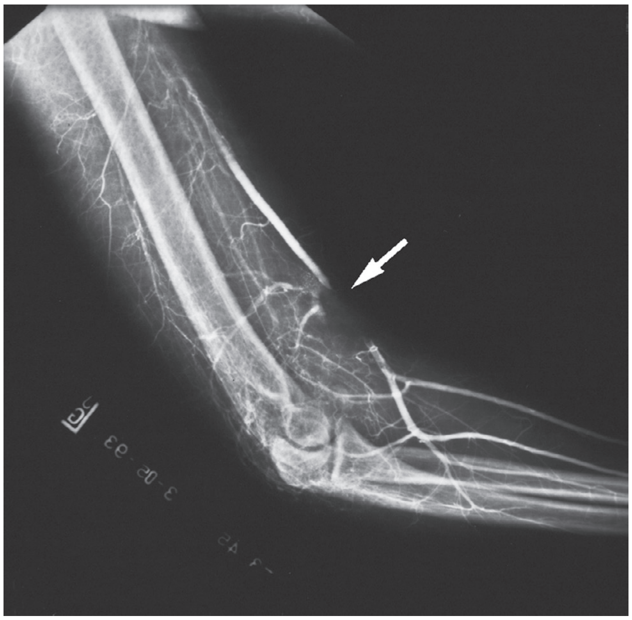

Fig. 41.3. Complete thrombosis *(arrow)* of the distal brachial artery after reduction of a posterior elbow dislocation. (Courtesy D. Demetreades, MD.)

Fig. 41.4. Acute arterial spam of the brachial artery. (From Arquilla B, Gupta R, Gernshiemer J, et al: Acute arterial spasm in an extremity caused by inadvertent intra-arterial injection successfully treated in the emergency department. J Emerg Med 19[2]:139-143, 2000.)

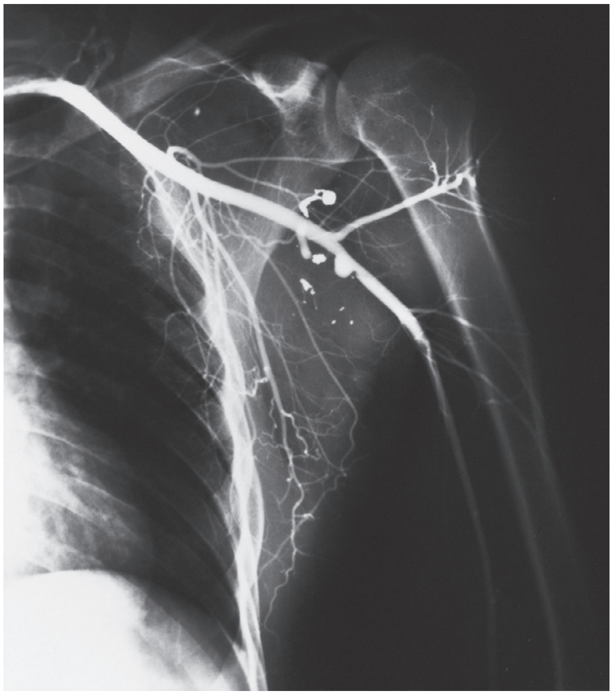

Fig. 41.5. Multiple small pseudoaneurysms of the axillary artery after penetrating injury. (Courtesy D. Demetreades, MD.)

TABLE 41.1

Clinical Features of Vascular Injury

HARD FINDINGS	SOFT FINDINGS
Pulsatile hemorrhage	History of significant hemorrhage at scene
Expanding hematoma	Nonexpanding hematoma
Absent distal pulses	Diminished pulse or ABI of injured extremity
Palpable thrill	Extremity peripheral nerve deficit
Audible bruit	Bony injury or proximate penetrating wound

ABI, Ankle-brachial index.

over days to months, compression of adjacent tissue may result in neuropathy, venous obstruction with resultant peripheral edema and venous thrombosis, and even erosion into adjacent bone. The cavity of a pseudoaneurysm is in direct communication with the lumen of the vessel, so embolization of mural clots may produce distal arterial occlusion. Pseudoaneurysms may be diagnosed months to years after an injury when patients manifest symptoms of compression neuropathy or peripheral arterial embolism or for investigation of a soft tissue "tumor" that represents the growing aneurysm.

Arteriovenous Fistula. An AVF is formed when both an artery and an adjacent vein are injured. Higher-pressure arterial flow is directed into the lower-pressure vein, thereby diverting the blood supply to distal tissues and engorging the distal veins. Because the aperture of the fistula is often relatively narrow and thus results in turbulent flow, a bruit and palpable thrill are common diagnostic findings. Symptoms are primarily those of distal ischemia, but rarely, high-output congestive heart failure may occur when large central vessels are involved. Symptoms are often delayed for months, because it takes time for the fistula to mature.

Compartment Syndrome. Compartment syndrome is most common after crush injury or a long bone fracture but may also be seen after reperfusion of an ischemic limb. Initially, blood flow is diminished and the injury is considered nonocclusive. Progressive edema elevates tissue pressure above capillary pressure, thus ending arterial perfusion and initiating a cascade of events that results in compartment syndrome. The risk for this complication is increased when ischemia time is prolonged; in the presence of combined arterial and venous injury; after ligation or repair of a major artery or vein; or in the presence of significant soft tissue injury, frequently concomitant with a long bone fracture. After restoration of arterial flow to a previously ischemic limb, a cascade of reperfusion injury results from release of oxygen free radicals, lipid peroxidation, and influx of intracellular calcium. These mediators give rise to progressive cellular damage, edema, and necrosis, thereby propagating the vicious cycle that increases compartment pressure. Consequently, frequent reexamination of the limb is indicated to assess compartment pressure after arterial repair or in the high-risk circumstances listed earlier. Compartment syndrome is discussed in more detail in Chapter 42.

CLINICAL FEATURES

Detection and treatment of vascular injuries takes place within the context of the overall resuscitation of the patient according to established principles of trauma care.[7] If the source of bleeding is readily identifiable, it is compressed with digital pressure. Although control of active bleeding is being achieved in this manner, detection and treatment of other life-threatening injuries proceed concurrently. Peripheral vascular injury can occur coincident with other life-threatening trauma, which may take higher priority in resuscitation. In other cases, peripheral vascular injury may be the most serious or only injury, and evaluation and management of this type of injury can proceed directly. Many patients have no evidence of injury but are considered at risk for vascular injury because of penetrating wounds that traverse the course of major neurovascular bundles, or because they have sustained high-risk injuries, such as posterior knee dislocation. In addition, patients without acute trauma, but with symptoms of intermittent claudication or with unexplained peripheral embolization and a history of previous trauma to the limb should be suspected of having occult arterial injury.

Peripheral vascular injury can be divided into three categories by physical examination: hard findings, soft findings, and asymptomatic high-risk wounds based on the mechanism of injury.

Hard Findings of Vascular Injury

Many patients have classic "hard" findings of arterial injury, listed in Table 41.1. The incidence of arterial injury in patients with any hard finding is consistently greater than 90%, and the presence of these findings requires further investigation by emergency angiography/computed tomography angiography (CTA) or, more commonly, immediate surgical intervention, depending on the duration of warm ischemia and the overall status of the patient.[8,9]

Soft Findings of Vascular Injury

An additional group of patients have "soft findings" of vascular injury (see Table 41.1).[8,9] Up to 35% of patients with "soft" findings of vascular injury have positive angiographic studies, although only a small proportion of these injuries require emergency repair.

The significance of prolonged capillary refill (>2 seconds) is controversial; some experts find it to be a reliable sign of vascular injury (when combined with a pulse deficit) and consider delayed capillary refill to be a valid "soft sign" of vascular injury. However, capillary refill is age, gender, and temperature dependent, and an arbitrary 2 second cutoff results in a significant false-positive rate, especially in older patients.[10] Delayed capillary refill by itself is an unreliable predictor of arterial injury, but the presence of delayed capillary refill in conjunction with a proximate penetrating injury or the presence of one or more soft signs warrants, at the least, repeated hourly examination.

Isolated penetrating injury to a peripheral nerve is commonly associated with vascular injury because of the close proximity of these structures within the neurovascular bundles. Vascular injury occurs in up to half of cases of penetrating peripheral nerve injury, and vice versa.[11] It can be difficult to distinguish whether pain, paresthesias, or paralysis are caused by a primary nerve injury, an associated vascular injury causing compression of the nerve, or compartment syndrome. In general, primary nerve injury occurs immediately at the time of injury, whereas vascular neuropathy occurs over minutes to hours after the injury.

Asymptomatic High-Risk Wounds

Major neurovascular bundles include large limb arteries proximal to critical branch points (Table 41.2). Proximity of a penetrating wound to a neurovascular bundle is defined variably as within 1 cm, 1 inch, or 5 cm. This concept is useful in evaluating patients with penetrating injury but without evidence of vascular injury. We consider penetrating wounds that occur within 1 cm of a major neurovascular bundle or whose presumed trajectory has crossed such a bundle to be sufficiently likely to produce an occult vascular injury that they warrant frequent (every 30 to 60 minutes) evaluation for the first 4 to 6 hours to ensure that a developing vascular injury is not missed within the warm ischemia window. Routine imaging is not, however, indicated based on proximity alone.

In addition, a small minority of patients with high-risk injuries, such as bites from large dogs or other animals, displaced fractures, crush injuries, or major joint dislocations (especially knee dislocation), may initially have occult vascular injuries that are not detected on physical examination. The risk of missing such injuries is that the traditional 6-hour window of warm ischemia time will be exceeded, or the patient will experience delayed complications resulting in limb loss. Patients with intimal flaps may be completely asymptomatic initially but can subsequently develop arterial thrombosis. Similarly, pseudoaneurysms progressively enlarge to produce compression of adjacent structures but may be very small and undetectable on initial physical examination. Consequently, these patients also should undergo serial physical examinations.

Due to their noncompressible location, blunt subclavian injuries can be particularly challenging. These are often associated with clavicular fracture or dislocation (however, contrary to long held belief, isolated first rib fracture is rarely combined with vascular injury unless posterior displacement occurs). Shear injury of the subclavian artery can occur as a result of a loose shoulder restraint during a motor vehicle collision (MVC). Interestingly, penetrating subclavian vein injuries are even more lethal than those to the artery, because in addition to massive blood loss, there is a relatively high risk of massive air embolism, which is frequently fatal.

Popliteal artery injuries can often be a result of knee dislocations, most of which will have spontaneously reduced. Patients showing complete ligamentous disruption of the knee on physical examination should be suspected of having a spontaneously reduced knee dislocation. Hemarthrosis may also be absent if the joint capsule is torn because blood can track into the fascial planes.

TABLE 41.2

Major Neurovascular Bundles

MAJOR ARTERY	PROXIMATE PLEXUS/NERVE
Axillary artery	Brachial plexus
Brachial artery	Median nerve
Radial artery	Median and radial nerves
Ulnar artery	Ulnar nerve
Femoral artery	Femoral nerve
Popliteal artery	Tibial nerve

History

In patients who achieve and maintain hemodynamic stability, a more comprehensive history can be obtained. Important historical points to note include the exact time and mechanism of the injury. The time of injury is important because of the significant morbidity that results from prolonged warm ischemia time. The mechanism is of clinical and often forensic importance in that injuries are frequently inflicted during a criminal act or in the workplace. Various mechanisms of injury may mandate special reporting and may alter the patient's ultimate disposition. Certain types of injuries, such as crush or bite wounds, are particularly prone to complications. The occupation, avocation, and hand dominance of the patient are pertinent to determine the best approach to achieve maximum functionality. Comorbid medical conditions may also be important. Patients who are immunocompromised because of diabetes, acquired immunodeficiency syndrome (AIDS), asplenia, cancer, or steroid use are at increased risk for infection and impaired wound healing. Patients with preexisting vascular insufficiency have more tenuous perfusion, are more susceptible to ischemia from elevated compartment pressure, and have a higher incidence of complications. As with most aspects of trauma care, patients whose sensorium is altered by head injury or intoxication, patients with spinal cord injury who cannot perceive pain, and those with significant painful distracting injuries will not reliably be able to report pain or paresthesias suggesting vascular insufficiency, so extra caution should be exercised in these cases.

Evidence of abdominal injury raises concern for injury to the iliac vessels, and virtually all iliac artery and vein injuries have associated trauma to the small or large intestine, bladder, solid viscera, or bony pelvis. The common and external iliac arteries are injured with equal frequency and more often than the internal iliac vessels. Approximately 80% of iliac vessel injuries are caused by penetrating trauma, and the remainder is mainly associated with pelvic fracture. Trauma to the iliac veins is responsible for massive bleeding in displaced pelvic fractures and often requires angiographic embolization.

Physical Examination

Despite advances in technology, meticulous physical examination in combination with comparison of blood pressures in the affected and unaffected limbs is the mainstay of diagnosis of vascular injury.[8] Physical examination is directed at discovering evidence of local wound complications and distal ischemia suggestive of vascular injury. Pulses in the affected extremity are palpated to compare strength and quality between the injured limb and its uninjured counterpart. Isolated detection of a diminished pulse distal to the site of injury merits further evaluation rather than immediate surgery, because palpation of pulses is a relatively inaccurate means of predicting arterial injury.[12] False-positive findings of a pulse deficit may occur because of shock, in which all pulses are diminished; congenital absence of a pulse in one extremity; preexisting vascular disease; operator technique; or arterial spasm or compression. False-negative findings can occur with transmission of the pulse through a "soft clot," past an intimal flap, or through collateral circulation. Distal pulses can persist despite significant arterial injury. Compression of an artery by casts, splints, or dressings may produce a pulseless extremity, and these should be removed if there is evidence of ischemia. Symptoms of limb ischemia may be apparent with absent radial and brachial pulses. However, pulses are completely absent in only a third of cases, because collateral flow from the thyrocervical trunk may provide sufficient perfusion to avoid the symptoms and signs of ischemia.[1] Finally, although the pulse may be absent, the limb may be well perfused by collateral arterial supply, thus making immediate repair of the arterial injury less compelling. Comparative palpation of the injured and unaffected limbs can also detect differences in skin temperature that may suggest hypoperfusion. Testing two-point discrimination on the injured and unaffected limbs may help detect sensory deficits. Auscultation over the site of injury may reveal a bruit, which is present in more than half of patients with AVF. Repeated examination of any hematoma adjacent to a wound is indicated during the first 24 hours to determine whether it is expanding or pulsatile.

Despite the limitations just noted, reliance on the history and physical examination to triage patients to receive immediate surgery, imaging studies, or observation has been found to be relatively dependable, with a sensitivity and specificity for significant vascular injury both exceeding 90%.[8] However, studies of military casualties suffering blast injury or high-velocity gunshot wounds have found physical examination to be less reliable than in studies of civilian casualties, likely because of the high energy nature of military wounds.

Neurologic deficits in the upper extremity occur in more than half of patients. The most severe of these injuries is damage to the brachial plexus, which occurs in nearly half of patients with blunt injury.

DIFFERENTIAL DIAGNOSES

In many cases, peripheral vascular injury will be readily apparent by external bleeding or hematoma formation. In other cases, vascular injury is suspected by the location or nature of the trauma the patient sustained. In all patients, vascular injury is a cue to search for associated injuries, such as bony injuries, injuries to proximate nerves, and soft tissue injuries due to either direct trauma or compression secondary to compartment syndrome. Conversely, some cases of vascular injury may not be obvious on initial examination and should be sought when evaluating patients with potential deep vein thromboses, crush injuries, and other presentations of acute limb pain.

DIAGNOSTIC TESTING

Plain Radiography

Plain radiographs of the affected extremity are indicated to detect fractures, joint penetration, and foreign bodies. With gunshot wounds, the sum of the number of intact bullets seen on radiographs and the number of entrance and exit wounds in the body should be an even number. Rarely, bullets or shotgun pellets can deflect off bone and travel sufficiently far as to not be visible on the radiograph. Bullets or pellets can migrate distally and produce vascular occlusion or migrate proximally through the venous system to the heart. When there is concern for a missing projectile, broaden the radiographic search.

Pulse Oximetry and Near-Infrared Spectroscopy

Pulse oximetry has been found to be a relative insensitive means of identifying limb ischemia after trauma. Clearly, in the absence of a pulse, no reading can be obtained. Beyond that, pulse oximetry should not be considered a discriminatory or useful test for vascular injury. Measurement of tissue oxygenation by near-infrared spectroscopy (NIRS) to quantify muscle oxyhemoglobin showed early promise as a possible noninvasive and simple means of detecting vascular injury; however, small clinical studies have found contradictory results in use of NIRS for this indication.[13,14]

Handheld Doppler

Absent or diminished pulses in an injured extremity should be evaluated using a handheld Doppler. Arterial injury is suggested by absent Doppler signal, or by a change in the usual triphasic quality of the Doppler pulse to a biphasic or monophasic waveform, because the pulse is "damped" by partial occlusion.

Arterial Pressure Index and Ankle-Brachial Index

Measuring systolic blood pressure in the injured versus the uninjured extremity (arterial pressure index [API]) or measuring it in an injured leg at the ankle compared with brachial artery pressure (ankle-brachial index [ABI]) are both accurate means of screening for arterial injury. Systolic pressure is measured by inflating a standard blood pressure cuff proximal to the injury and recording handheld Doppler systolic pressure distal to the injury. The process is repeated on the uninjured limb (or the arm, if calculating an ABI), and a ratio of injured to uninjured systolic pressure is calculated. In general, a ratio less than 0.90 is considered abnormal and indicates need for further investigation. Clinical studies of API/ABI have shown promising results. In several studies, an API/ABI less than 0.90 yielded a sensitivity and specificity for the detection of vascular injury of over 95%, with correspondingly high positive and negative predictive values.[15]

Patients with suspected vascular injury who have an API/ABI of 0.90 to 0.99 merit observation for 12 to 24 hours for repeated physical examination and API measurements to detect potentially evolving injury. Patients with normal physical examination findings and a completely normal (greater than or equal to 1.0) API/ABI can be safely discharged from the ED, provided that there are no other injuries requiring admission.

However, reliance on the API/ABI to screen for arterial injury is not always possible. Comparisons cannot be made when both limbs are injured or when severe soft tissue disruption precludes placement of a blood pressure tourniquet. Certain arteries (eg, the profunda femoris, profunda brachii, and peroneal arteries) normally do not produce palpable pulses, and so API/ABI is of limited usefulness if injuries to these vessels are suspected. Shotgun wounds often are associated with normal API/ABI measurements despite multiple small arterial wounds; catheter-based angiography is the preferred diagnostic modality in this group.

Despite the limitations previously noted, API/ABI has proved effective in screening patients with proximity wounds. The vast majority of injuries missed by API/ABI heal spontaneously. Those that do not heal generally present within 3 months with signs of arterial injury and can be repaired electively.

Ultrasound

Bedside B-mode (real-time) ultrasound, particularly with color flow Doppler (see later), can reliably identify loss of arterial pulsation in major vessels. However, B-mode ultrasound cannot visualize certain anatomic areas accurately (eg, subclavian and iliac vessels) because of inadequate tissue windows, and it is unreliable in detecting a fresh, relatively non-echogenic thrombosis or hematoma. As blood liquefies within a hematoma, it becomes echolucent and more readily distinguishable from surrounding tissues.

Doppler ultrasound interprets sound moving toward or away from the transducer as flow. Venous flow is heard as a low-pitched hum, whereas arterial flow has a higher-pitched triphasic quality. The combination of B-mode and Doppler ultrasound is called *duplex ultrasound* and has enhanced accuracy in examining blood vessels. Duplex scans showing a focal increase in peak systolic velocity suggest partial obstruction of the vessel. However, duplex scanning is slightly less accurate for detecting injuries that do not decrease flow, such as small pseudoaneurysms, AVF, and intimal flaps. Also, it is technically limited in examining certain anatomic areas, such as the profunda femoris and profunda brachii arteries and the iliac and subclavian vessels. Duplex ultrasound findings may be subtle, and as with other applications of ultrasound, its accuracy is operator dependent. Despite these limitations, the sensitivity of duplex ultrasound in comparison with standard angiography ranges from 83% to 100%, with a specificity of 99% to 100% and an accuracy of 96% to 100%.[16]

Color flow Doppler converts Doppler echoes into quantitated visual signals. Flow toward the transducer is seen as red, and flow away from the transducer is seen as blue. The intensity of the color (the number of pixels on the screen) is proportional to flow through the vessel. Small prospective studies have indicated a high rate of accuracy in detecting arterial injury with color flow Doppler. Absence of flow is readily apparent, but subtle injuries, such as intimal flaps and small pseudoaneurysms, can be more difficult to identify than with CTA. The overall sensitivity of color flow Doppler in detecting arterial injury is 50% to 90%, with a specificity of 95% to 99%. The sensitivity for detecting injuries requiring surgical repair is greater than 90% (Figs. 41.6 and 41.7).[9,17]

Computed Tomography and Magnetic Resonance Imaging

With a few important exceptions, CTA has largely replaced catheter-based angiography for the detection of peripheral

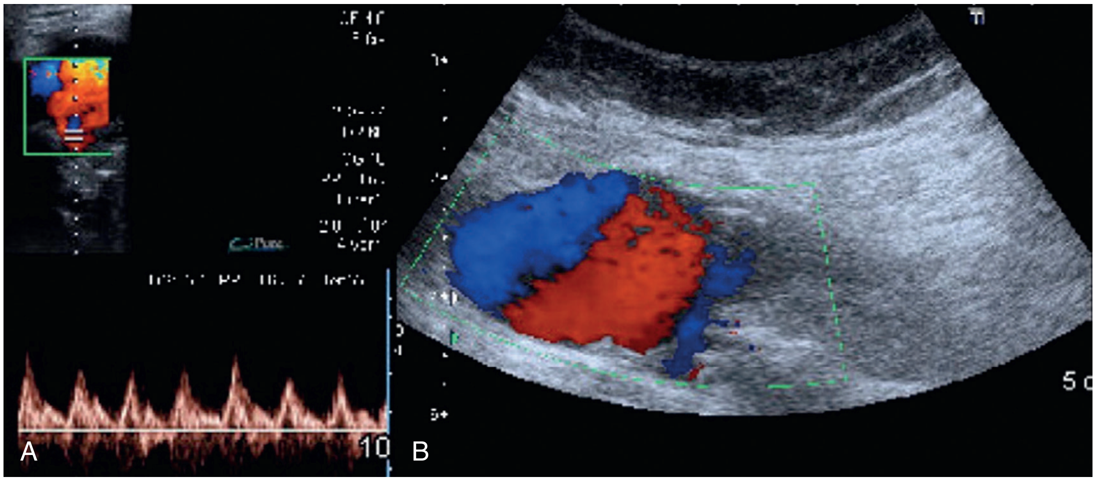

Fig. 41.6. Sonography of popliteal fossa with systolic bruit **(A)** and longitudinal color Doppler ultrasound **(B)** show arterial blood. (From Tejero-Garcia S, Lirola Criado JF, Ast MP, et al: Popliteal pseudoaneurysm after unicompartmental knee replacement: a case report. Knee 21[2]:597-599, 2014.)

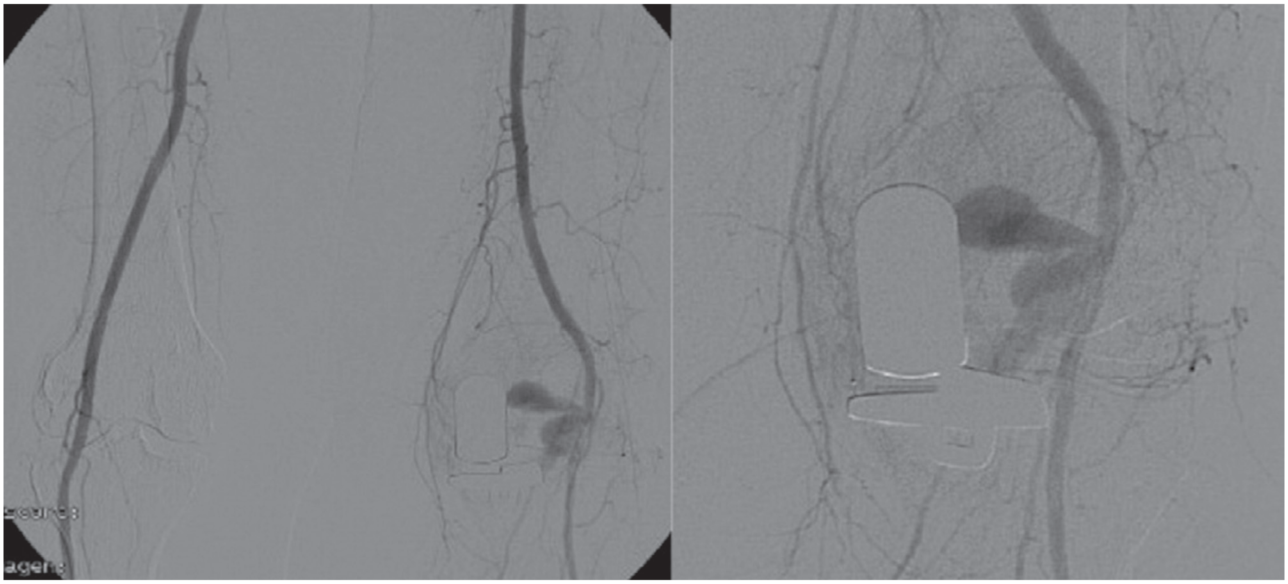

Fig. 41.7. Digital subtraction angiography of both popliteal arteries shows pseudoaneurysm on the *left (zoomed image on the right).* (From Tejero-Garcia S, Lirola Criado JF, Ast MP, et al: Popliteal pseudoaneurysm after unicompartmental knee replacement: a case report. Knee 21[2]:597-599, 2014.)

vascular injury in most trauma centers.[16] Multi-detector helical computed tomography (CT) scanners have proven very accurate for diagnosis of peripheral vascular injury in multiple series with a sensitivity of 93% to 100% and specificity of 87% to 100% compared with catheter-based angiography.[18-21] The advantages of CTA over catheter-based angiography are that it is noninvasive, readily available, and less costly and provides information on other injuries in the region being studied. However, there are several pitfalls to the use of CTA. Metallic artifact from bullets, orthopedic hardware, or other penetrating objects may obscure visualization of parts of a vessel, although with image reconstruction techniques, this problem can be largely overcome. Venous injuries may be missed depending on the phase of the contrast. The rapid image acquisition of current CT scanners makes timing of the contrast bolus more critical, and out-of-phase images may miss arterial injury. In practical terms, though, CTA is very useful in that it can be integrated into an overall plan for diagnostic imaging, including CT of the head and trunk, all of which can be accomplished rapidly.[19] Because of the enhanced detail, accuracy, and speed of image acquisition with 64 and greater slice CT scanners and the ability to perform three-dimensional reconstructions, this modality has become the standard imaging technique for suspected vascular injury. Magnetic resonance angiography (MRA) has been described and accurately detects vascular injuries but has yet to prove clinically useful.[22] MRI is also contraindicated in the presence of ferromagnetic foreign bodies.

Arteriography

Historically, catheter-based contrast angiography was used for diagnosing peripheral arterial injury. However, given the ready availability of CTA and additional steps necessary to obtain an angiography (transfer of the patient, activation of the angiography team, preparation of the angiography suite), CTA has replaced angiography as the initial diagnostic modality of choice in the ED.[23] Even those patients who may need intervention (embolization of pseudoaneurysms, endovascular stent insertion to bypass a dissection or AVF, and injection of thrombolytic agents to dissolve thrombus are routinely performed via intra-arterial catheter) are best served by obtaining a rapidly available CTA to establish the diagnosis.

Diagnosis of Specific Vascular Injuries

Although the aforementioned diagnostic strategies apply to vascular trauma overall, certain injuries bear particular mention.

For subclavian artery injury, the combination of physical examination and chest x-ray findings suggestive of subclavian injury (hemothorax, pneumothorax, apical pleural cap, or wide mediastinum) identifies nearly all injuries, and arteriography is not indicated in the absence of findings. When injury is suspected and the patient is unstable, operative intervention is indicated. If the patient's clinical condition permits, however, angiography can confirm the diagnosis and can locate the injury precisely. APIs are not reliable with proximal thoracic outlet injuries because of collateral arterial flow. Ultrasound techniques are also relatively inaccurate in detecting subclavian injuries because of interference by overlying gas-filled lung tissue. Therefore in cases in which the clinical diagnosis is equivocal (soft signs of injury or proximity wounds), arteriography (CTA or catheter based) is required to detect the injury.

No consensus has been reached on the diagnostic approach to detect popliteal artery injury resulting from documented or suspected knee dislocation. It is, of course, unreasonable to perform routine arteriography on every case of obvious or suspected knee dislocation. Although the exact diagnostic strategy is institution specific and dependent on available resources, our hospital's approach is to perform a CTA in cases of high-energy mechanisms of blunt trauma (eg, auto vs. pedestrian or MVC).[24] For lower energy blunt mechanisms, such as athletic injury, we perform serial clinical evaluations, including ABI. However, patients with *penetrating* trauma and more than one hard sign of popliteal artery injury can be taken directly to the operating room for repair, because delaying these cases to obtain a CTA is unnecessary.

MANAGEMENT

Management of peripheral vascular injury is part of the total care of the trauma patient, including control of active hemorrhage by direct digital pressure. Blind clamping of a bleeding vessel is not recommended because of the risk of crushing adjacent nerves; however, clamping a clearly visible vessel can be effective. Tourniquet use for up to 6 hours is safe and effective, and it has been associated with increased survival in patients with major limb trauma. Tourniquets should be applied if direct pressure is insufficient to control bleeding and left in place until definitive surgical control can be achieved.[25] Few complications are associated with the use of tourniquets, and almost all of these are transient.[26] In cases in which proximal and distal control of large-vessel injuries cannot be readily achieved in the ED, insertion of a Foley catheter into the wound and inflation of the balloon with sterile water can temporarily tamponade the bleeding. Intravenous lines should not be started in the injured extremity, because they may be ineffective in delivering resuscitation fluid or medication and because extravasation from an injured vein may increase compartment pressure. Serial hemoglobin determinations may indicate unexpected blood loss from occult vascular injury. Patients with significant blood loss should have blood typed and crossmatched and may require immediate transfusion for stabilization. Patients with significant vascular injury often remain hypotensive despite such infusion and require further volume infusion or blood transfusion.

The issue of hypotensive resuscitation is controversial with regard to major vascular injuries. A tenuous clot can form in an injured artery and prevent further blood loss as long as the patient remains hypotensive. Once arterial pressure reaches a critical but variable point, the clot may be expelled and massive blood loss can ensue. Therefore, when an arterial injury is inaccessible for occlusion by direct pressure, the target blood pressure for resuscitation should be lowered to a systolic pressure of approximately 90 mm Hg. Overly rapid fluid administration in the field or in the ED can produce transient intravascular hypervolemia and may ultimately increase the rate of blood loss. Closely monitor vital signs and the total volume of fluid infused.[27]

Once a vascular injury has been identified, a specific diagnostic and therapeutic strategy should be developed that is consistent with the severity of the injury, the presence of other injuries, and the resources available. In hospitals without the ability to perform vascular repair, transfer to a trauma center should be initiated early. In cases in which the transfer will involve a delay of several hours, cooling the ischemic limb will avoid exceeding the critical 6-hour cutoff for warm ischemia. To accomplish this, wrap the limb in towels, and apply ice in plastic bags around the limb, avoiding direct contact of the ice to the limb, which can result in frostbite.

Major Vascular Injuries

Major vascular injuries that compromise the viability of a limb should be repaired within 6 hours to avoid irreversible ischemic neuropathy and myonecrosis. Treatment of vascular injury has changed dramatically in the past 10 years. Endovascular treatment with self-expanding stents is currently the preferred technique for repair of these injuries in stable patients, and the majority of arterial repairs in the United States are now done with this technique.

Upper Extremity Arterial Injuries

For brachial artery injuries, limb salvage rates have improved to nearly 100% owing to efficient out-of-hospital transport, improved surgical techniques, and shorter time to first antibiotic dose. Repair is indicated in all cases because the amputation rate is high with ligation.

Injuries to forearm vessels detected by arteriography or ultrasound do not need to be repaired unless there are signs of ischemia in the hand; "hard signs" of arterial injury, such as an expanding hematoma, pseudoaneurysm, or AVF; or injury to both radial and ulnar arteries. However, some authors recommend repairing all these injuries because of the risk of intermittent claudication or cold intolerance in patients who have one artery ligated. Certain patients are almost exclusively dependent on the ulnar arterial supply to the hand because of an underdeveloped deep palmar arch. Clearly, ulnar artery injuries should be repaired in these patients. Ultimately, the decision to repair an arterial injury is in the domain of the vascular surgeon. Compartment syndrome in the forearm is common after repair of proximal arteries and veins and may require fasciotomy.[28]

Lower Extremity Arterial Injuries

In patients with severe injuries to the lower extremities, an initial "damage control" laparotomy with temporary vascular shunting of the iliac vessels is often necessary as resuscitation continues. Distal ischemic complications occur in approximately one-third of repaired iliac arteries, and subsequent amputations are required in up to 20%.

Femoral artery injuries should be repaired as simple ligation of the common femoral artery results in amputation of the lower extremity in 80% of cases.

Factors that place patients at higher risk of amputation include severe soft tissue injury of the extremity, the presence of multiple fractures, major venous repair, or delay in repair exceeding 6 hours of warm ischemia time. Because of the high incidence of compartment syndrome with lower leg injuries, fasciotomy is required in half of cases, and some centers routinely perform fasciotomy in all such cases.[29]

Late Complications of Arterial Injury

Despite timely optimal repair of arterial injuries, approximately one in five patients experiences delayed complications requiring further surgical intervention, including delayed amputation. The most common of such complications is delayed thrombosis, which often occurs after many months as stenosis at the repair site progresses. Other complications include intermittent claudication, chronic pain or edema of the limb, and aneurysm formation in the graft.

Venous Injuries

Venous injuries may be primarily ligated if the patient's condition makes them unable to tolerate prolongation of surgery. However, the current trend is to repair major venous injuries if possible, particularly in the lower extremity, because wound healing is improved and the incidence of compartment syndrome, venous thrombosis, pulmonary embolism, and chronic edema is decreased. Extensive venous collaterals in the upper extremity make surgical repair less compelling.

Minor Vascular Injuries

Increasingly, minor nonocclusive vascular injuries are being treated expectantly. Criteria for observation of vascular injuries include low-velocity missile wounds, intact distal circulation, absence of active hemorrhage, and minimal arterial wall disruption on angiography if performed. Angiographic or CTA findings meeting these criteria include intimal flaps extending less than 5 mm and pseudoaneurysms smaller than 5 mm in diameter. Follow-up of these injuries with repeat angiography or ultrasound reveals that approximately 85% resolve spontaneously. Patients meeting these criteria can be monitored as outpatients for 3 months, with repeat physical examination and ultrasound to detect delayed complications. Most intimal flaps heal spontaneously, and asymptomatic injuries that do not disrupt perfusion of the limb can be treated conservatively with early administration of antiplatelet agents, such as clopidogrel or aspirin. However, almost all pseudoaneurysms ultimately require repair and, once discovered, should be repaired electively rather than undergoing continued observation. Failure to detect and repair occult arterial injuries in children often results in severe differential limb growth. Thus, a more aggressive policy of repairing arterial injuries that causes a relatively minor decrease in blood flow to a child's growing limb may be justified.

Arterial Spasm

Isolated arterial spasm usually reverses with conservative treatment (topical warm saline or topical nitroglycerin paste), but prolonged spasm may require infusion of vasodilators, such as nitroglycerin, calcium channel blockers, alpha-blockers, nitroprusside, specific prostaglandin inhibitors, or warm saline.

Antibiotics

Current guidelines call for empirical gram-positive and gram-negative antibiotic administration for all patients with peripheral vascular injuries associated with open fractures, as well as those with extensive soft tissue injury.[30] Appropriate coverage might include a first-generation cephalosporin (eg, cefazolin 1 to 2 g intravenously preoperatively) and gentamicin 5 to 7 mg/kg intravenously every 24 hours during the perioperative period.

DISPOSITION

Patients with confirmed injury to major vessels, equivocal findings on diagnostic tests, or symptoms of limb ischemia should be admitted to the hospital or ED observation unit for further investigation or serial physical examinations. Frequent vascular and neurological checks will be necessary in these patients, so step-down or intensive care unit levels of care may be necessary. Consultation with a vascular surgeon is indicated as soon as vascular injury is strongly suspected or the need for emergency operative repair established. Patients who are unstable because of vascular or other injuries may undergo further investigation or exploration in the operating room. If the treating hospital is incapable of performing vascular surgery or appropriate investigations, transfer to a trauma center should be initiated. Obtaining angiograms for proximity wounds in centers that are incapable of acting on positive results is unwise, because this may delay definitive care beyond the safe limits of warm ischemia time.

KEY CONCEPTS

- The overall condition of the patient determines the extent of emergency department (ED) evaluation and stabilization. Critically injured patients may require immediate surgery, which should not be delayed for confirmatory studies of obvious vascular injury.
- Arterial injury may be readily apparent or clinically occult. In patients with high-energy blunt mechanisms, computed tomography angiography (CTA) should be the initial diagnostic modality of choice. In patients with lower-energy mechanisms, serial physical examinations may be performed instead.
- Symptoms of arterial injury may be delayed by hours to months after the initial injury. Late onset of symptoms suggests delayed thrombosis, pseudoaneurysm or arteriovenous fistulae (AVF) formation, compartment syndrome, or intermittent claudication, resulting from stenosis or reliance on small-caliber collateral vessels for arterial perfusion.
- Compartment syndrome frequently develops in limbs with arterial injury, particularly injuries of the lower leg, and fasciotomy is often required.
- Many vascular injuries are amenable to endovascular treatment with self-expanding stents. This results in fewer complications, lower cost, and earlier discharge from the hospital.

The references for this chapter can be found online by accessing the accompanying Expert Consult website.

REFERENCES

1. Franz RW, Shah KJ, Halaharvi D, et al: A 5-year review of management of lower extremity arterial injuries at an urban level I trauma center. J Vasc Surg 53:1604–1610, 2011.
2. Marmagkiolis K, Lendel V, Best JF, et al: Management of transradial access complications in the cardiac catheterization lab. Int J Cardiol 173(3):521–524, 2014.
3. Huebner S, Ali S: Bilateral shotgun pellet pulmonary emboli. J Radiol Case Rep 6(4):1–10, 2012.
4. Vaquero-Puerta C, San Norberto EM, Merino B, et al: Shotgun wound and pellet embolism to the intracranial carotid artery. J Vasc Surg 55(2):535–537, 2012.
5. Benfield R, Plurad DS, Lam L, et al: The epidemiology of dog attacks in an urban environment and the risk of vascular injury. Am Surg 76:203–205, 2010.
6. Higgins JP, McClinton MA: Vascular insufficiency of the upper extremity. J Hand Surg Am 35(9):1545–1553, 2010.
7. American College of Surgeons: Advanced trauma life support (ATLS) student course manual, ed 9, Chicago, 2012, American College of Surgeons.
8. Inaba K, Branco BC, Reddy S, et al: Prospective evaluation of multidetector computed tomography for extremity vascular trauma. J Trauma 70:808–815, 2011.
9. Halvorson JJ, Anz A, Langfitt M, et al: Vascular injury associated with extremity trauma: initial diagnosis and management. J Am Acad Orthop Surg 19:495–504, 2011.
10. Schriger DL, Baraff L: Defining normal capillary refill: variation with age, sex, and temperature. Ann Emerg Med 17(9):932–935, 1988.
11. Levy BA, Zlowodzki MP, Graves M, et al: Screening for extremity arterial injury with the arterial pressure index. Am J Emerg Med 23:689–695, 2005.
12. Feliciano DV, Moore FA, Moore EE, et al: Evaluation and management of peripheral vascular injury. Part 1. Western Trauma Association/critical decisions in trauma. J Trauma 70(6):1551–1556, 2011.
13. Shuler MS, Reisman WM, Kinsey TL, et al: Correlation between muscle oxygenation and compartment pressures in acute compartment syndrome of the leg. J Bone Joint Surg Am 92:863–870, 2010.
14. Bariteau JT, Beutel BG, Kamal R, et al: The use of near-infrared spectrometry for the diagnosis of lower-extremity compartment syndrome. Orthopedics 34:178, 2011.
15. Feliciano DV: Management of peripheral arterial injury. Curr Opin Crit Care 16: 602–608, 2010.
16. Patterson BO, Holt PJ, Cleanthis M, et al: Imaging vascular trauma. Br J Surg 99(4): 494–505, 2012.
17. Sheehan SE, Dyer GS, Sodickson AD, et al: Traumatic elbow injuries: what the orthopedic surgeon wants to know. Radiographics 33(3):869–888, 2013.
18. White PW, Gillespie DL, Feurstein I, et al: Sixty-four slice multidetector computed tomographic angiography in the evaluation of vascular trauma. J Trauma 68:96–102, 2010.
19. Uyeda JW, Anderson SW, Sakai O, et al: CT angiography in trauma. Radiol Clin North Am 48:423–438, ix–x, 2010.
20. Fritz J, Efron DT, Fishman EK: Multidetector CT and three-dimensional CT angiography of upper extremity arterial injury. Emerg Radiol 22(3):269–282, 2014.
21. Adibi A, Krishnam MS, Dissanayake S, et al: Computed tomography angiography of lower extremities in the emergency room for evaluation of patients with gunshot wounds. Eur Radiol 24(7):1586–1593, 2014.
22. Tocci SL, Heard WM, Fadale PD, et al: Magnetic resonance angiography for the evaluation of vascular injury in knee dislocations. J Knee Surg 23:201–207, 2010.
23. Jens S, Kerstens MK, Legemate DA, et al: Diagnostic performance of computed tomography angiography in peripheral arterial injury due to trauma: a systematic review and meta-analysis. Eur J Vasc Endovasc Surg 46(3):329–337, 2013.
24. Deleted in review.
25. Rush RM, Arrington ED, Hsu JR: Management of complex extremity injuries: tourniquets, compartment syndrome detection, fasciotomy, and amputation care. Surg Clin North Am 92(4):987–1007, ix, 2012.
26. Kragh JF, O'Neill ML, Walters TJ, et al: Minor morbidity with emergency tourniquet use to stop bleeding in severe limb trauma: research, history, and reconciling advocates and abolitionists. Mil Med 176(7):817–823, 2011.
27. Morrison CA, Carrick MM, Norman MA, et al: Hypotensive resuscitation strategy reduces transfusion requirements and severe postoperative coagulopathy in trauma patients with hemorrhagic shock: preliminary results of a randomized controlled trial. J Trauma 70(3):652–663, 2011.
28. Farber A, Tan T-W, Hamburg NM, et al: Early fasciotomy in patients with extremity vascular injury is associated with decreased risk of adverse limb outcomes: a review of the National Trauma Data Bank. Injury 43(9):1486–1491, 2012.
29. Branco BC, Inaba K, Barmparas G, et al: Incidence and predictors for the need for fasciotomy after extremity trauma: a 10-year review in a mature level I trauma centre. Injury 42(10):1157–1163, 2011.
30. Hoff WS, Bonadies JA, Cachecho R, et al: East Practice Management Guidelines Work Group: update to practice management guidelines for prophylactic antibiotic use in open fractures. J Trauma 70(3):751–754, 2011.

CHAPTER 41: QUESTIONS & ANSWERS

41.1. An 18-year-old man presents complaining of left lower leg pain. He was involved in a motor vehicle collision (MVC) 1 month earlier and requires surgical repair of a left femur fracture. Which of the following is the *least* likely cause of the patient's symptoms?

A. Compartment syndrome
B. Intimal flap
C. Pseudoaneurysm
D. Thrombosis
E. Vessel stricture formation

Answer: A. Delayed thrombosis can occur months to years after injury if the injured vessel heals with stricture formation and decreased blood flow distally, followed by stasis and clot formation. Although flow is not altered by small intimal flaps, and the associated soft tissue wounds often appear benign initially, they may become a nidus for thrombosis that can occur hours to months after the initial injury. The cavity of a pseudoaneurysm is in direct communication with the lumen of the vessel, so embolization of mural clots may produce distal arterial occlusion. Patients with pseudoaneurysm are commonly seen months to years later with symptoms of compression neuropathy or peripheral arterial embolism. The delayed presentation of this patient makes compartment syndrome the least likely cause of his leg pain.

41.2. A 45-year-old man complains of right leg pain and edema shortly after surgery for a mid-shaft femur fracture. Physical examination reveals decreased distal pulses in the extremity. What is the most important diagnosis to consider in this patient?

A. Anemia causing poor tissue oxygenation
B. Compartment syndrome
C. Intimal flap
D. Pseudoaneurysm
E. Vessel stricture

Answer: B. After restoration of arterial flow to a previously ischemic limb, a cascade of reperfusion injury has been identified that results from release of oxygen free radicals, lipid peroxidation, and influx of intracellular calcium. These mediators give rise to progressive cellular damage, edema, and necrosis, thereby propagating the vicious cycle that increases compartment pressure.

41.3. After vascular injury to an extremity, how many hours are generally required before irreversible damage occurs?

A. 2 hours
B. 6 hours
C. 10 hours
D. 12 hours
E. 24 hours

Answer: B. Although individuals may vary, 6 hours of complete warm ischemia is generally considered the point at which irreversible nerve and muscle damage begins to occur. After 6 hours of warm ischemia, 10% of patients will have irreversible damage; by 12 hours, 90% will have irreversible damage. Artificially cooling the limb to just higher than freezing temperature will reduce the metabolic demands of ischemic tissues and greatly prolong the tissue's tolerance of ischemia to 24 hours or more.

41.4. A 25-year-old man who sustained a gunshot wound to the right leg has an ankle-brachial index (ABI) of 0.9. What is the most appropriate next step in this patient's management?

A. Admit for observation and repeat examinations.
B. Discharge the patient home with surgical follow-up.

C. Obtain an emergent computed tomography (CT) angiogram.
D. Obtain immediate vascular consultation.
E. Perform a Doppler ultrasound scan.

Answer: A. Patients with an ABI of 0.90 to 0.99 merit observation for 12 to 24 hours for repeat examinations and ABI measurements to detect evolving injury. In general, a ratio of less than 0.90 is considered abnormal and is an indication for further investigation, such as computed tomography angiography (CTA).

41.5. Which of the following is *least* likely to cause vascular injury to an extremity?
A. Close-range shotgun wound
B. Crush injury
C. Electrical injury
D. Gunshot wound from a long distance
E. Massive tissue avulsion

Answer: D. Close-range shotgun wounds can cause significant blunt trauma to vessels, as well as a higher rate of bone and nerve damage than gunshot wounds. An open avulsion injury to limb is particularly severe because the skin is the final structure to be disrupted, and there is inevitable injury to deeper vessels and nerves. Vascular injury must be suspected in patients with massive soft tissue avulsion or crush injury, displaced long bone fractures, and electrical or lightning injuries.