13 INJURIES TO THE PERIPHERAL BLOOD VESSELS

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Before and during World War II, management of extremity vascular trauma consisted of vessel ligation, which resulted in amputation rates as high as 70%. As surgical techniques improved and primary arterial repair became standard, amputation rates declined to approximately 30%. By the time of the Vietnam War, the use of routine angiography and repair had reduced amputation rates to 15%.[1] On the modern battlefield, the incidence of extremity injury remains high, with 88% of vascular injuries occurring in the extremities.[2] Current management of extremity arterial trauma yields amputation rates ranging from 5% to 20%.[2-4]

In this chapter, we outline the current standard of care for vascular injuries in the extremities. Management of such injuries requires knowledge of mechanisms of injury, awareness of high-risk injury patterns, familiarity with modern diagnostic techniques and their indications, and comprehensive understanding of the assessment, triage, and management decisions that influence outcome in this setting.

Mechanisms and Sites of Extremity Vascular Injury

BLUNT VERSUS PENETRATING TRAUMA

Arterial trauma is typically classified according to the general mechanism of injury—that is, blunt or penetrating—because different mechanisms tend to produce different types of injuries. After blunt trauma, the vascular injury most commonly seen is avulsion, in which the artery is stretched. This stretching results in disruption either of the tunica intima alone or of both the tunica intima and the tunica media, leaving the highly thrombogenic tunica externa to maintain temporary vessel continuity [*see Figure 1*]. Complete occlusion typically occurs when significant intimal damage leads to thrombosis of the artery. Injuries that do not produce occlusion may give rise to an intimal flap, a pseudoaneurysm (secondary to partial arterial injury), or an arteriovenous (AV) fistula.

Penetrating trauma may transect the vessel completely and may be manifested as thrombosis resulting from vessel spasm or frank bleeding. If the vessel is only partially transected, it may contract and continue to bleed; even if it is initially controlled, it may rebleed as the patient is resuscitated and arterial pressure rises toward normal. In many cases of penetrating trauma, the location of a presumed vascular injury may be determined simply by following the path of the penetrating object. If there is evidence of ongoing bleeding from a penetrating vascular injury, prompt operative intervention, without further evaluation, is indicated. The risk of amputation varies: stab wounds are unlikely to lead to amputation, whereas high-velocity firearm injuries with concomitant blast effect and tissue loss are considerably more likely to do so.[5] In modern military contexts, blast injuries account for 50% to 70% of cases of vascular trauma.[2] Vascular trauma from blast wounds may present as thrombosis (related to intimal injury resulting from the application of kinetic force to the tissue) or as deep cavitary injuries with vessel disruption and even segmental arterial loss.

LOCATION OF INJURY AND RISK OF AMPUTATION

Extremity vascular trauma is commonly encountered by surgeons in both urban and rural practices. In urban settings, upper- and lower-extremity injuries account for 40% and 20% of all vascular injuries, respectively.[6] In rural settings, extremity injuries account for approximately 50% of all vascular injuries.[3]

Current military data indicate that the most frequently injured lower-extremity vessel in the setting of penetrating trauma is the superficial femoral artery (SFA), followed by the popliteal artery, the profunda femoris, the tibial arteries, and the common femoral artery (CFA); the most frequently injured upper-extremity vessel

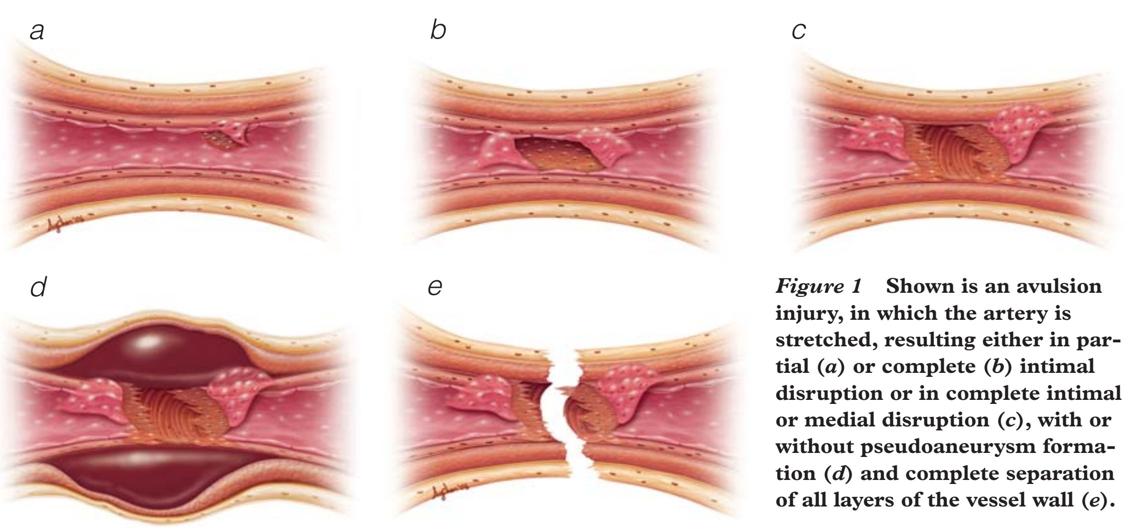

Figure 1 **Shown is an avulsion injury, in which the artery is stretched, resulting either in partial (*a*) or complete (*b*) intimal disruption or in complete intimal or medial disruption (*c*), with or without pseudoaneurysm formation (*d*) and complete separation of all layers of the vessel wall (*e*).**

is the brachial artery, followed by the radial artery and the ulnar artery.[2] In civilian settings, injuries leading to limb loss often include damage to bones and nerves.

Stepwise logistic regression analysis demonstrates that the following are independent risk factors for amputation: occluded grafts, combined above-the-knee and below-the-knee injury, tense compartments, arterial transections, and associated compound fractures.[5]

Initial Assessment

HISTORY

Assessment of an injured extremity starts with a history, which can be obtained in parallel with the physical examination. The information that should be collected includes the patient's bleeding history at the scene, the time of injury, and the mechanism of injury.

PHYSICAL EXAMINATION

The physical examination is the most important part of the assessment. A careful evaluation of the extremities can provide information on the location and severity of vascular injuries; identify the trajectory and the entrance and exit points of wounds; and suggest appropriate triage and management of vascular injuries.

The initial part of the examination should follow advanced trauma life support (ATLS) guidelines, with attention paid to the ABCs (*A*irway, *B*reathing, and *C*irculation). Areas of obvious hemorrhage should be addressed in the primary survey; more specific evaluation of the extremities for vascular injury can be carried out during the secondary survey. Blood pressure, temperature, and distal pulses are evaluated. Side-to-side symmetry is important; thus, injured extremities should be compared with their uninjured counterparts.

If pulses are absent and a joint dislocation or fracture-dislocation is present, then reduction should be done. Frequently, a pulseless extremity regains pulses once the fracture or dislocation is reduced. If pulses return after reduction, the assessment may move on to the next priority. If pulses do not return, vascular injury is assumed, and treatment of such injury becomes the immediate priority.

Once the initial part of the examination has been carried out, a neurologic examination should be done. Motor and sensory function should be assessed in a distal-to-proximal direction on each extremity. Any gross limb deformities should be reduced and splinted to yield a more anatomic alignment of the extremity and relieve any compromise of neural or vascular structures.

CLINICAL CATEGORIZATION OF VASCULAR INJURY

Traditionally, clinical evidence of vascular injury has been divided into hard and soft signs. Hard signs of extremity vascular injury include arterial bleeding, ongoing hemorrhage with shock, an expanding or pulsatile hematoma, a palpable thrill or audible bruit over the injured area, absent distal pulses, and limb ischemia. When a patient presents with hard signs of vascular injury, immediate surgical exploration and vascular repair are warranted. The exception to this rule is the case where the patient presents with multilevel trauma to an extremity and the level of arterial injury is in question. In this situation, arteriography is indicated—preferably intraoperative angiography to minimize delay in repairing the injury and to facilitate intraoperative decision making.

Soft signs of vascular injury include a history of severe hemorrhage at the scene; hypotension; a stable, small hematoma that is not expanding or pulsatile; diminished or unequal pulses; a neurologic deficit (primary nerve injury occurs immediately after injury, whereas the onset of ischemic neuropathy may be delayed for minutes to hours); and a wound that is in proximity to vascular structures.[7] Management of patients with soft signs of injury presents a more difficult diagnostic dilemma and is discussed in more detail elsewhere (see below).

It is important to keep in mind that palpation of a pulse is a subjective measure and is thus prone to wide interobserver variation. Furthermore, pulses may be palpable distal to major arterial lesions, including complete arterial disruptions.[7,8] These limitations notwithstanding, a precise and well-documented physical examination is an appropriate screening tool for vascular injuries.

NONINVASIVE EVALUATION IN CONJUNCTION WITH PHYSICAL EXAMINATION

In patients with soft signs of arterial injury, the ankle-brachial index (ABI)—also known as the arterial pressure index (API), the Doppler pressure index (DPI), or the ankle-arm index (AAI)—is a highly useful adjunct to the physical examination. The ABI is obtained by placing a blood pressure cuff on the supine patient proximal to the ankle or wrist of the injured limb. The systolic pressure is determined with a Doppler probe at the respective posterior tibial and dorsalis pedis arteries or at the ulnar and radial arteries. The ratio of the highest systolic pressure obtained in the affected extremity to the systolic pressure in an unaffected extremity (most often a brachial artery) is the ABI [*see Figure 2*].

A 1991 study assessed the sensitivity and specificity of Doppler-derived arterial pressure measurements in trauma patients undergoing evaluation for possible extremity vascular injury.[9] An ABI was obtained in 100 consecutive injured limbs, and all patients then underwent contrast arteriography. An ABI lower than 0.90 was 87% sensitive and 97% specific for arterial injury. The authors concluded that in the absence of hard signs of arterial injury, ABI is a reasonable substitute for screening arteriography, particularly if continued observation can be ensured.

The use of the ABI has been extended to the management of blunt extremity trauma associated with high-risk fractures and dislocations. In a controlled trial that included 75 consecutive patients with blunt high-risk orthopedic injuries, the negative predictive value of a Doppler-derived ABI higher than 0.9 was 100%. In the 70% of patients who had an ABI higher than 0.9, clinical follow-up revealed no major or minor arterial injuries. Of the 30% who had an ABI lower than 0.9, 70% had an injury that was diagnosed by arteriography, and 50% of these injuries necessitated operative repair.[10,11]

It is important to remember that there are several situations in which a vascular injury may not lead to an abnormal ABI. For example, an injury that is considered nonaxial (e.g., an injury to the profunda femoris in the thigh or the profunda brachii in the arm) may not lower the ABI and thus may be missed. In addition, a lesion that does not disrupt arterial flow (e.g., an intimal flap or a transected artery that is maintained in continuity by connective tissue) may yield a normal ABI. Finally, an AV fistula may be associated with a normal ABI.

Certain patient characteristics may affect the ABI as well. For example, noninvasive measurement of the ABI may fail to detect an injury if the patient is severely hypotensive or in shock and the clinical circumstances do not permit placement of a cuff around an injured site or extremity. Moreover, elderly patients may have abnormal preinjury ABIs as a consequence of atherosclerosis. In these situations, the concept of symmetry is crucial. It is also important to consider the possibility that the patient may have previously undergone peripheral vascular surgery, though this is rarely the case in the typical trauma population.

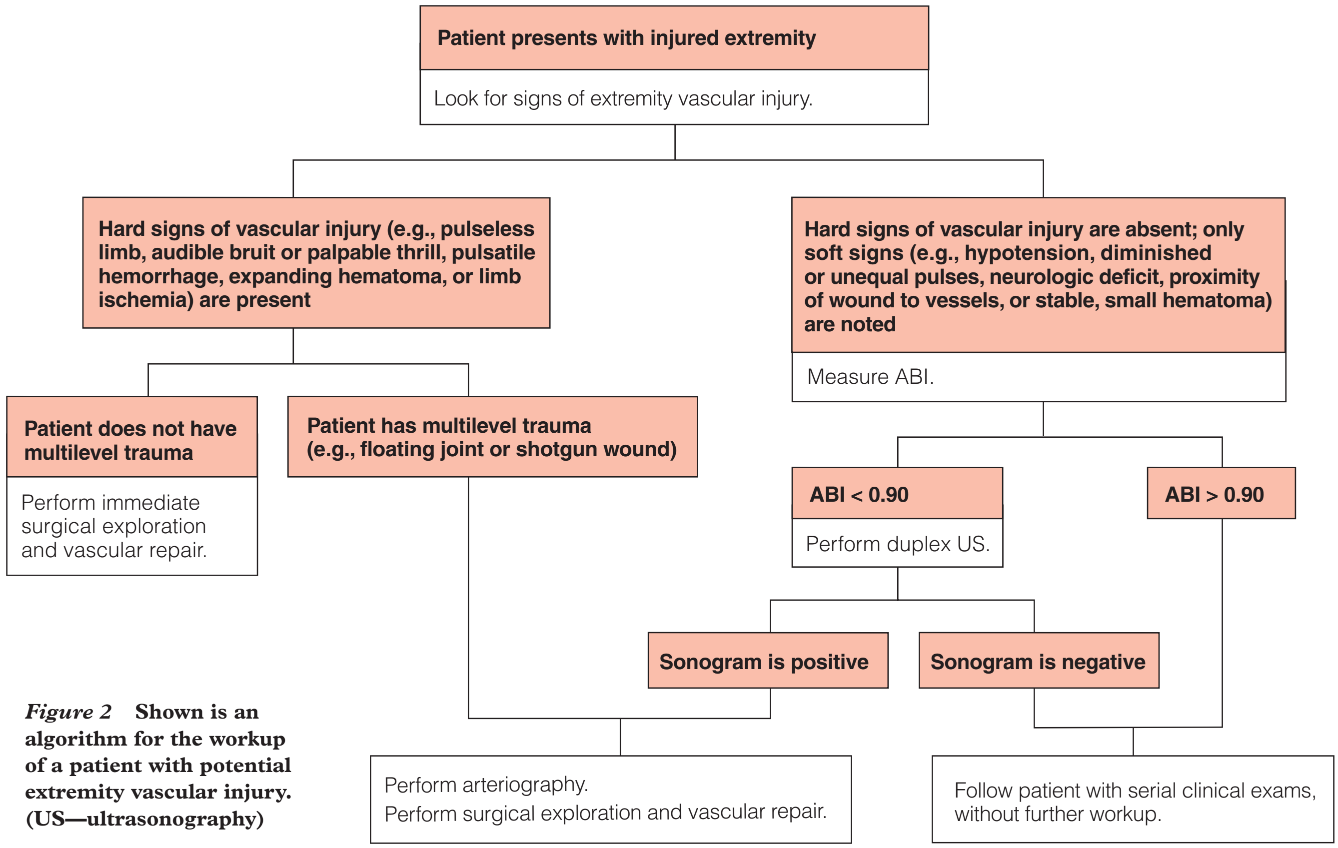

Figure 2 **Shown is an algorithm for the workup of a patient with potential extremity vascular injury. (US—ultrasonography)**

IMAGING

Diagnostic Angiography

Arteriography has a sensitivity of 95% to 100% and a specificity of 90% and 98% and is therefore considered the gold standard for evaluation or confirmation of arterial injury.[12,13] In the setting of extremity injury, however, nonselective angiography has not been found to be cost effective, and it is often overly sensitive, detecting minimal injuries that do not call for further management.[14-16] Furthermore, arteriography can be time consuming, can delay definitive treatment, and can give rise to complications of its own, including renal contrast toxicity and pseudoaneurysm formation.[16]

Angiography should be reserved for patients with soft signs of vascular injury and an abnormal ABI; there is little reason to perform angiography in a patient with hard signs of injury, unless an intraoperative angiogram is needed to delineate the anatomy. In no case should transport to the OR for definitive treatment be delayed so that arteriography can be performed. Several reviews have supported reserved use of arteriography in this setting. A 2002 report concluded that physical examination in conjunction with measurement of the DPI (i.e., the ABI) was an appropriate method of identifying significant vascular injuries caused by penetrating extremity trauma.[17] Patients with normal physical examinations and normal DPIs could safely be discharged; angiography was indicated only for asymptomatic patients with abnormal DPIs.[17]

Duplex Ultrasonography

Several studies have evaluated the efficacy and accuracy of duplex ultrasonography in the setting of extremity vascular trauma. The sensitivity of duplex ultrasonography is between 90% and 95%, the specificity is in the range of 99%, and the overall accuracy is between 96% and 98%. These figures approach those reported for arteriography in the evaluation of similar vascular trauma patients. Duplex ultrasonography has no inherent risks, and it may be more cost-effective for screening certain injuries than either arteriography or exploration. Duplex ultrasonography has been shown to be a reliable method of diagnosis in patients with potential peripheral vascular injuries.[18,19]

The advantages of duplex ultrasonography notwithstanding, it is important to remember that this imaging modality may not be equally appropriate in all scenarios. As an example, given that duplex ultrasonography is highly operator dependent, the results of duplex examination may not be reliable in situations where the examiner has not had sufficient access to the technology or experience with the technique. As another example, injuries in certain anatomic locations (e.g., injuries in regions where bone structures interpose themselves, injuries in areas with concomitant soft tissue injuries, injuries that dive into the pelvis or chest, and injuries in patients with a large body habitus) may not be well visualized by duplex ultrasonography. Such considerations are important in assessing patients with potential extremity vascular injuries; if either applies in a given case, angiography may be required.

Computed Tomographic Angiography

Ongoing radiologic advances have led some centers to consider using computed tomographic angiography (CTA) to evaluate arterial injury. To date, this approach has been formally evaluated in only a modest number of studies, though there is reason to believe that it will be more widely used in the future. A few small series found CTA to have a sensitivity and specificity of approximately 90% in the evaluation of large arteries; other studies suggested that this modality might be a reasonable alternative to conventional arteriography for diagnosis of traumatic arterial injuries. Before CTA can be considered equivalent to the gold standard, large randomized trials will have to be performed.[20,21]

MANAGEMENT ALGORITHMS

On the basis of the data available on noninvasive assessment and diagnostic imaging, an effective management algorithm can be created [*see Figure 2*].[22,23] If the ABI is higher than 0.9, the patient may be followed clinically without further workup. If the ABI is lower than 0.9, arteriography or duplex ultrasonography should be performed, the results of which will dictate the final plan of action. It is impossible to define every single clinical scenario that could possibly give rise to arterial trauma. The ABI fulfills the requirements of a useful screening tool, in that it is sensitive, specific, reproducible, noninvasive, and inexpensive.

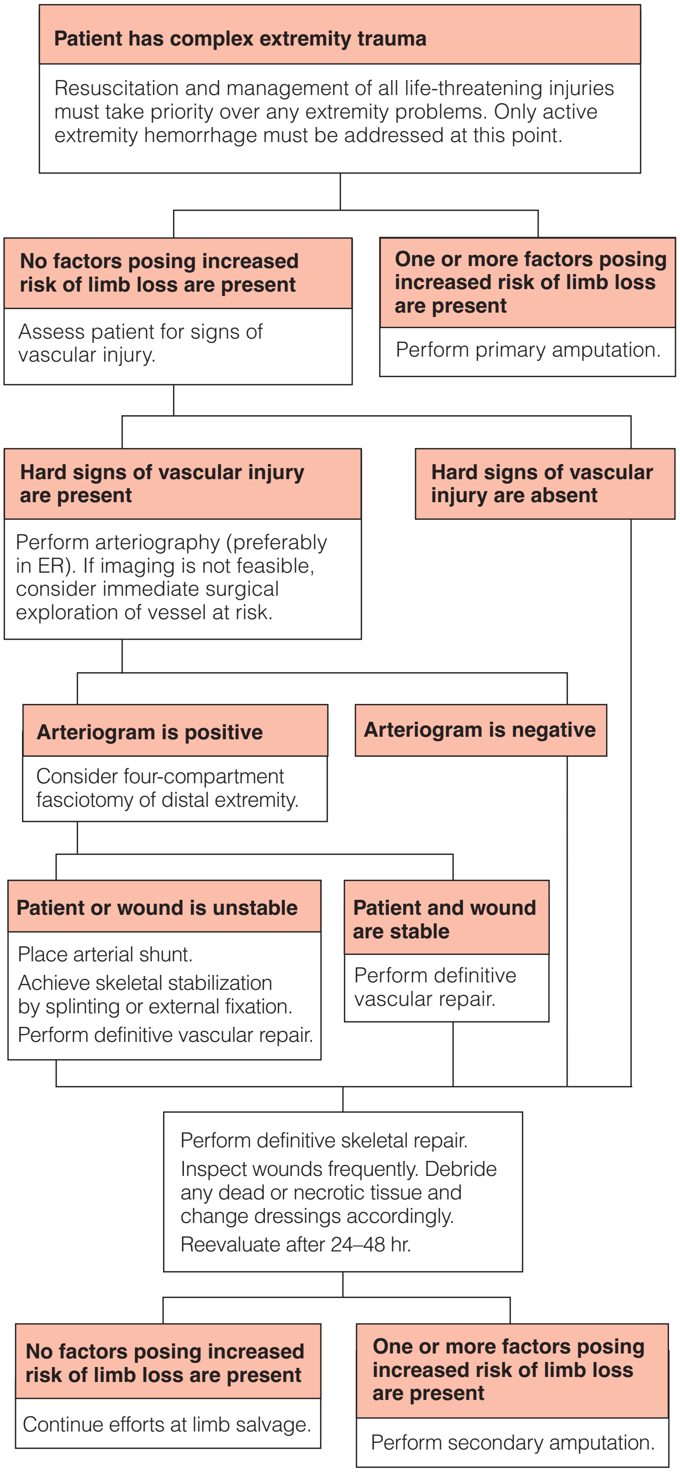

Figure 3 **Shown is an algorithm for the management of complex extremity trauma, adapted from an algorithm developed by the ACS Committee on Trauma. The full annotated version of the ACS algorithm is available at the ACS Web site (http://www.facs.org/trauma/publications/mancompexttrauma.pdf).**

Management of complex extremity trauma involving soft tissue, nerve, and arterial injury must include consideration of primary amputation to increase patient survival. This issue is well addressed by an algorithm for complex extremity trauma created by the Committee on Trauma of the American College of Surgeons (ACS) [*see Figure 3*].[24] The algorithm incorporates the environment, the type of injury sustained, and the stability of the patient into the process of deciding whether to attempt limb salvage or perform amputation.

HIGH-RISK LOWER-EXTREMITY INJURIES

Certain lower-extremity injuries—such as knee dislocations, displaced medial tibial plateau fractures and other displaced bicondylar fractures around the knee, open or segmental distal femoral shaft fractures, floating joints, gunshot wounds in proximity to neurovascular structures, and mangled extremities—are associated with a particularly high incidence of vascular trauma.[25] The most commonly injured lower-extremity artery in the setting of blunt trauma is the popliteal artery, which starts below the adductor hiatus and ends at the soleus arch. Because the vessel's start and end points areas are relatively fixed, there is a potential for significant stretch injury at the knee joint. A purely ligamentous knee dislocation is associated with a high risk of arterial injury, despite the lack of sharp fracture fragments. The risk of popliteal injury may be as high as 40% in patients with knee dislocations. Although the arterial disruption may be only a minor intimal tear and examination may reveal no evidence of injury, such internal tears are thrombogenic and may result in delayed thrombosis. Because lower extremities are often splinted and covered during stabilization, delayed thrombosis may not be recognized in a timely fashion.

Workup of a patient with a posterior knee dislocation may or may not require angiography. Some authors maintain that angiography is unnecessary in routine evaluation of patients with blunt lower-extremity trauma who present with a normal neurovascular examination and that angiography or duplex ultrasonography should be used selectively for patients with diminished pulses who lack associated indications for mandatory operative exploration.[26] In addition, the use of the ABI has been validated in the setting of blunt lower extremity trauma. The ABI has proved to be a rapid, reliable, noninvasive tool for diagnosing vascular injury associated with knee dislocation. At present, the evidence suggests that routine arteriography for all patients with knee dislocation is not indicated but that a secondary study should be ordered when the ABI is low or the neurovascular examination yields abnormal results.[10,12,27] When managing a posterior knee dislocation, one should have a high index of suspicion for vascular injury and a low threshold for obtaining secondary studies.

Management

INITIAL TREATMENT CONSIDERATIONS

Time to Repair

A warm ischemia time of less than 6 hours is generally accepted as the standard interval within which arterial continuity must be restored to prevent permanent damage to the soft tissues.[28,29]

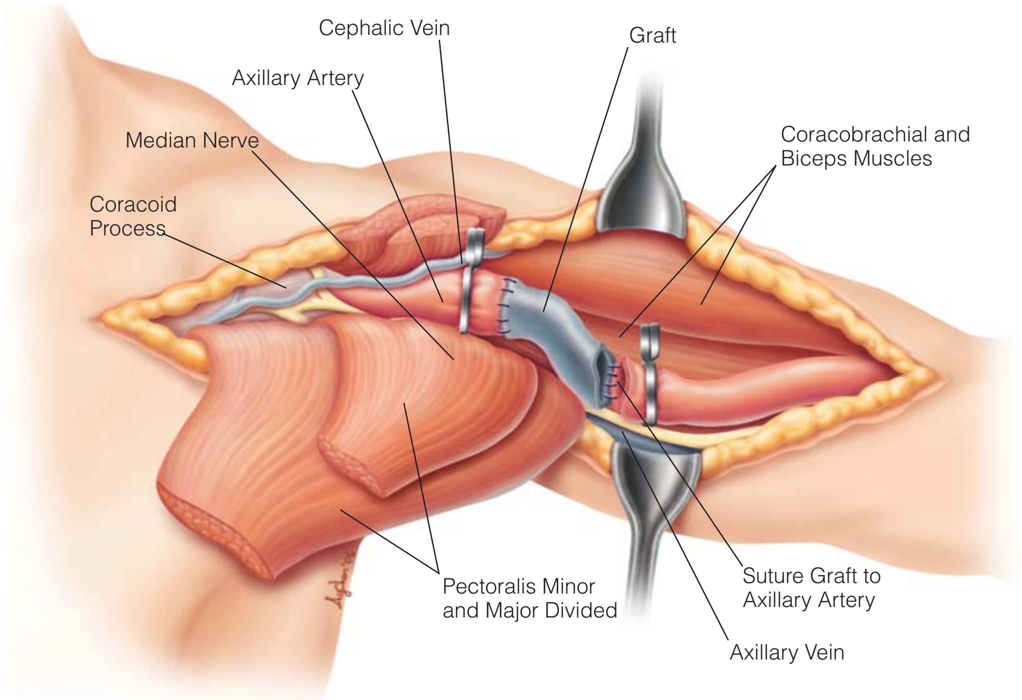

Figure 4 **Depicted is exposure of the axillary artery.**

This interval may vary depending on several factors, including the level of injury, previous vascular disease, the presence of collateral vessels, and previous extremity surgery.

Vascular Control

As has long been a dictum in vascular surgery, it is important to gain proximal control of the injured vessel—meaning control at a point one level higher than the injured area—before assessing the site of the injury. This maneuver reduces blood loss from the injury during repair and minimizes hematoma formation and subsequent loss of tissue planes. Entering an injured area without first obtaining proximal control can be dangerous, can cause additional injury to other neurovascular structures, and can result in belated attempts to gain proximal control in a hurried fashion, which may cause secondary injury to the vessel. In situations where proximal control has not yet been obtained or cannot be obtained, an intraluminal or intra-arterial balloon (e.g., a Fogarty catheter or even a Foley catheter, in larger arteries) may be used to achieve temporary control. This simple technique sometimes proves to be lifesaving.

Use of Tourniquets

Surgeons have long debated the use of tourniquets in the management of vascular trauma. Undoubtedly, the tourniquet can be a lifesaving addition to the surgeon's armamentarium if used correctly and appropriately. Proximal application of a tourniquet may facilitate examination, permit definitive control of a bleeding point, and help determine whether significant nerve, muscle, or tendon injury has occurred. Even if a tourniquet is kept in place for only a short period, it may be invaluable for the control of hemorrhage.

When a tourniquet is used, it must be applied correctly. Incorrectly applied tourniquets actually increase bleeding from an extremity wound and increase the risk of early exsanguination. This paradoxical effect results from occlusion of the lower-pressure venous outflow and inadequate occlusion of the higher-pressure arterial inflow. A properly applied tourniquet causes substantial pain, which should be managed with intravenous or intramuscular analgesics.[30]

Tourniquets are often placed on hypotensive patients before resuscitation, and these patients sometimes start bleeding through their tourniquets when resuscitation is initiated. Accordingly, tourniquets should be continuously monitored and tightened for maximal effectiveness during resuscitation. In the hospital setting, pneumatic tourniquets may be used as temporizing proximal clamps in patients with multiple injuries, as well as patients with blast injuries, massive soft-tissue destruction, or mangled extremities.[30]

EXPOSURE OF INJURY

Once the decision has been made to transport the patient to the operating room, the next step is to determine the operative approach that will optimize exposure of the injury. Often, exposures of upper-extremity arteries prove more challenging than exposures of lower-extremity vessels, primarily because they are performed less frequently. A thorough discussion of all extremity vascular exposures is beyond the scope of this chapter. Accordingly, in what follows, we discuss those exposures of the upper and lower extremities that are particularly useful in the trauma setting.

Upper Extremity

Operative exposure of potential vascular injuries in the upper extremity requires detailed knowledge of the anatomy of the axillary and brachial arteries. The axillary artery is surrounded by muscle on all sides, including the chest wall, the pectoral girdle, and the brachium. The vessel itself is divided into three segments by the pectoralis minor: the medial segment, the posterior segment, and the lateral segment. The specific operative approach depends on which of these three segments has been injured.

To gain access to the first (medial) segment of the axillary artery, the infraclavicular region must be exposed [*see Figure 4*]. This approach may also be useful for proximal control of more distal injuries, depending on the location and type of injury being treated. A horizontal incision is made 2 cm below the middle third of the clavicle, and dissection continues through the subcutaneous fascia, the pectoral fascia, the pectoralis fibers, and the clavipectoral fascia. At this level, the neurovascular bundle can be identified,

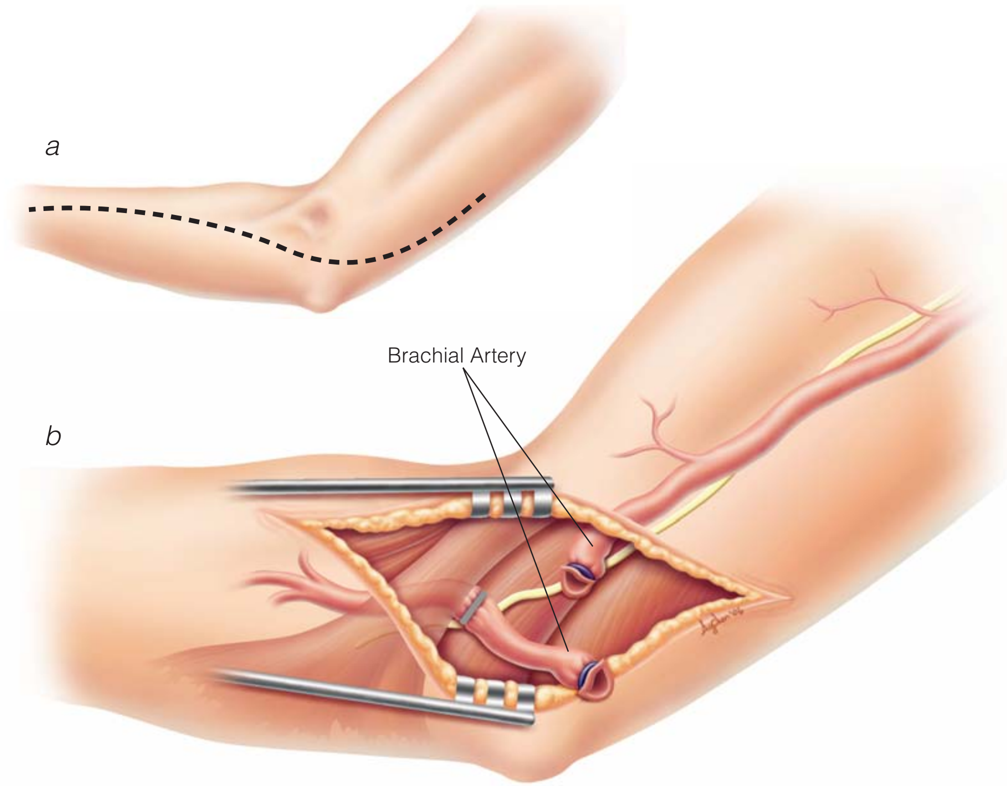

Figure 5 **(*a*) Depicted is exposure of the brachial artery, with removal of an occluded segment to restore blood flow to the hand and forearm. (*b*) The incision is extended onto the forearm in an S shape to afford complete exposure.**

with the artery lying superior and deep to the axillary vein. Exposure and control of the artery are obtained by means of sharp dissection. To gain access to the second (posterior) and third (lateral) portions of the axillary artery, an incision is made along the lateral border of the pectoralis major from the chest wall to the biceps. The coracobrachialis can then be identified; the neurovascular sheath is located at the posterior border of this muscle.[31]

As an alternative, the deltopectoral approach may be employed to gain access to any of the segments of the axillary artery. An incision is made from the midpoint of the clavicle along the anterior border of the deltoid muscle. The incision is deepened through subcutaneous tissue to reach the intramuscular groove. The cephalic vein is retracted, and the axillary artery may then be traced proximally and distally.

To expose the brachial artery, a longitudinal incision is made in the medial arm between the biceps and the triceps [*see Figure 5*], and dissection is carried out through the subcutaneous tissue. The basilic vein can then be identified. This vein is retracted inferiorly, and the neurovascular bundle is exposed by opening the deep fascia at the medial border of the biceps. To expose the brachial artery along with the arteries in the forearm, an S-shaped incision is made over the antecubital fossa. The superior portion of the incision follows the medial border of the biceps muscle and extends horizontally in the antecubital fossa; the inferior portion is made laterally on the volar forearm. Such an incision affords complete exposure of all of the target vessels. On subcutaneous dissection, multiple veins can be seen, including the median cubital vein, the cephalic vein, and the basilic vein. Exposure of the deep fascia and entrance into the bicipital aponeurosis allows exposure of the median nerve, the brachial artery, and two deep veins. The incision can be extended to track the radial and ulnar arteries.[31]

Lower Extremity

In addressing potential vascular injuries in the lower extremity, it is essential to be able to expose the CFA and the popliteal artery. To gain access to the femoral artery, a vertical skin incision is made midway between the superior iliac spine and the pubic tubercle [*see Figure 6*]. This incision is opened to expose the superficial epigastric and superficial circumflex branches. The fascia lata is incised along the medial portion of the sartorius up to the inguinal ligament, and the femoral sheath is exposed and opened. (In an emergency situation where retroperitoneal or abdominal exposure is not warranted, the inguinal ligament can also be divided if necessary for more proximal control). The CFA can then be identified lateral to the femoral vein and can be tracked downward to the point where it bifurcates into the profunda femoris and the SFA. Typically, the profunda femoris branches laterally off of the CFA 3 to 5 cm distal to the inguinal ligament; the SFA lies superior to the profunda femoris. The incision may be extended inferiorly as necessary to locate more distal vascular injuries.[31]

In the setting of trauma, exposure of the popliteal artery is best accomplished via a medial approach. To expose the proximal (supragenicular) popliteal artery, an incision is made in the distal portion of the thigh along the anterior border of the sartorius [*see Figure 7*]. The fascia can be incised, the muscle retracted posteriorly, and the popliteal vessels may be identified. It may be necessary to divide the adductor tendon or the semimembranous muscle for exposure. If necessary, this incision can be extended down the leg for exposure of the tibial vessels. To expose the distal (infragenicular) popliteal artery, an incision is made just behind the posteromedial surface of the tibia [*see Figure 8*]. The gastrocnemius is retracted posteriorly, and the semitendinous, gracilis, and sartorius muscles are retracted superiorly. (These muscles may also be divided if more exposure is needed.) The popliteal vein is the first and most superficial portion of the neurovascular bundle. The tibial nerve is posterior and medial to the popliteal artery and should always be identified and protected during the dissection. If necessary, this exposure can be extended inferiorly to the tibial peroneal trunk for control of the distal arteries.[31]

DEFINITIVE REPAIR OF INJURY

Primary Repair versus Grafting

Once the need for operation has been established and the exposure chosen, the next step to determine which type of repair will be performed. Primary repair is preferred when possible; substantial proximal and distal mobilization of the artery may be required to allow a tension-free anastomosis.

Choice of Conduit

Often, the extent of the injury is such that primary repair is impossible and a conduit (autogenous or prosthetic) must be placed. It is crucial that the contralateral leg be prepared, so that a venous segment can be harvested if needed. In view of the possibility that the extremity arterial injury may be accompanied by significant venous injury, harvesting vein from the ipsilateral leg is discouraged. The most commonly used conduit is the great saphenous vein (GSV), which can be cut and made to form a larger conduit by using a spiral technique or a panel graft technique.[32] The superficial femoral vein (SFV) may also be used as a conduit,[33] but the dissection required is tedious and time-consuming and may be associated with significant morbidity.

Autogenous conduits should be used in contaminated wounds when direct vascular repair is not feasible. Nonautogenous conduits (e.g., polytatrafuoroethylene [PTFE] or Dacron grafts) may also be employed, but as a rule, they should be reserved for extreme situations in which native vein is not available. For patients with severe peripheral vascular injuries but without adequate available vein, PTFE appears to be an acceptable choice for primary reconstruction; graft infection is rare if the graft is covered with healthy tissue.[34,35]

Management of Arteries in Distal Extremity

On occasion, arteries in the distal extremities (e.g., the radial, ulnar, or tibial arteries) may have to be repaired or ligated after

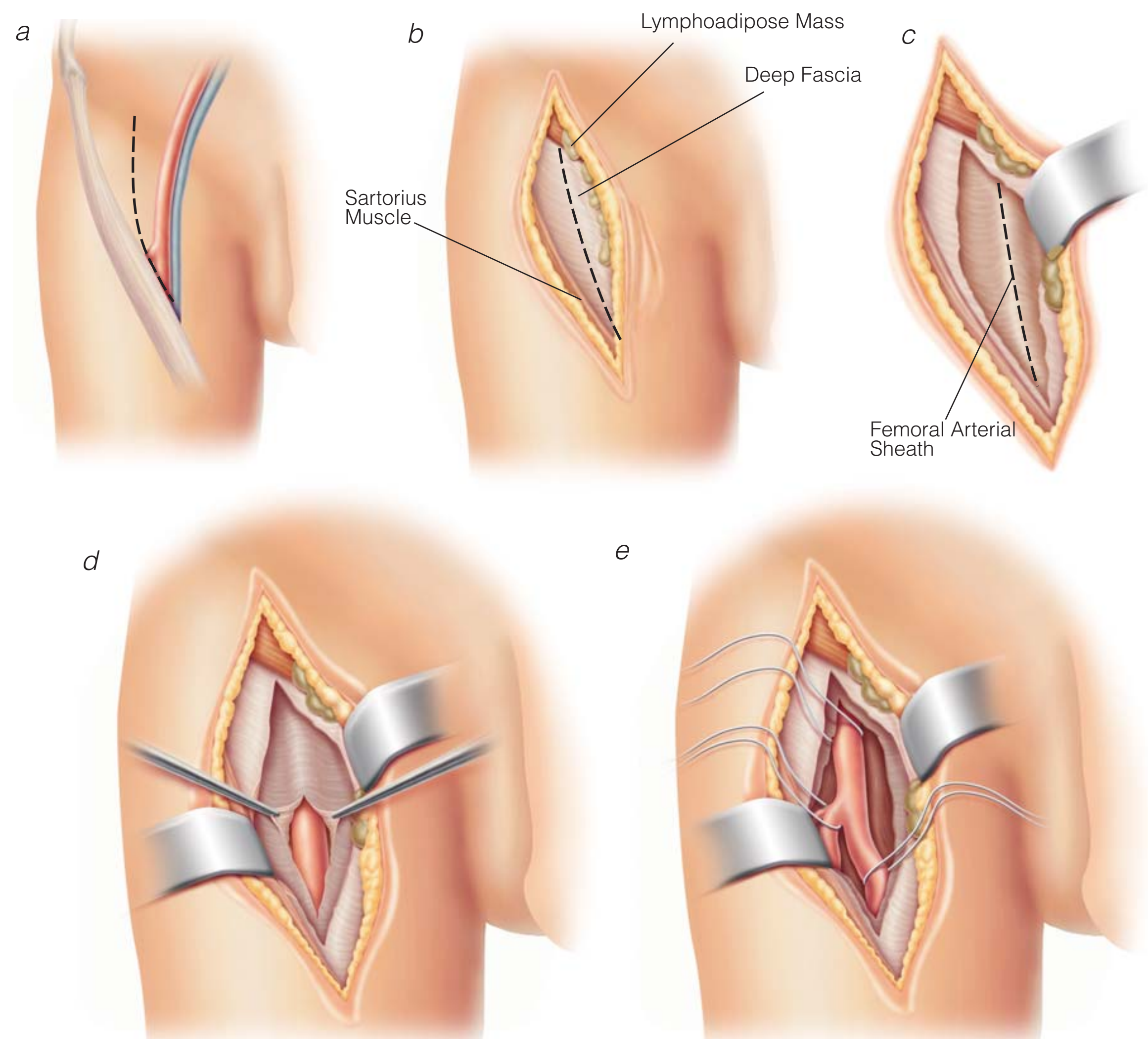

Figure 6 **Depicted is exposure of the femoral artery. (*a*) A curved 10 to 12 cm. skin incision is made slightly lateral to the pulsation of the femoral artery. (*b*) Lymphoadipose tissue is retracted to expose the deep fascia overlying the course of the femoral artery. (*c*) The deep fascia is incised, exposing the femoral arterial sheath, which is then opened along its axis (*d*). (*e*) The common and superficial femoral arteries are mobilized and encircled with Silastic vessel loops.**

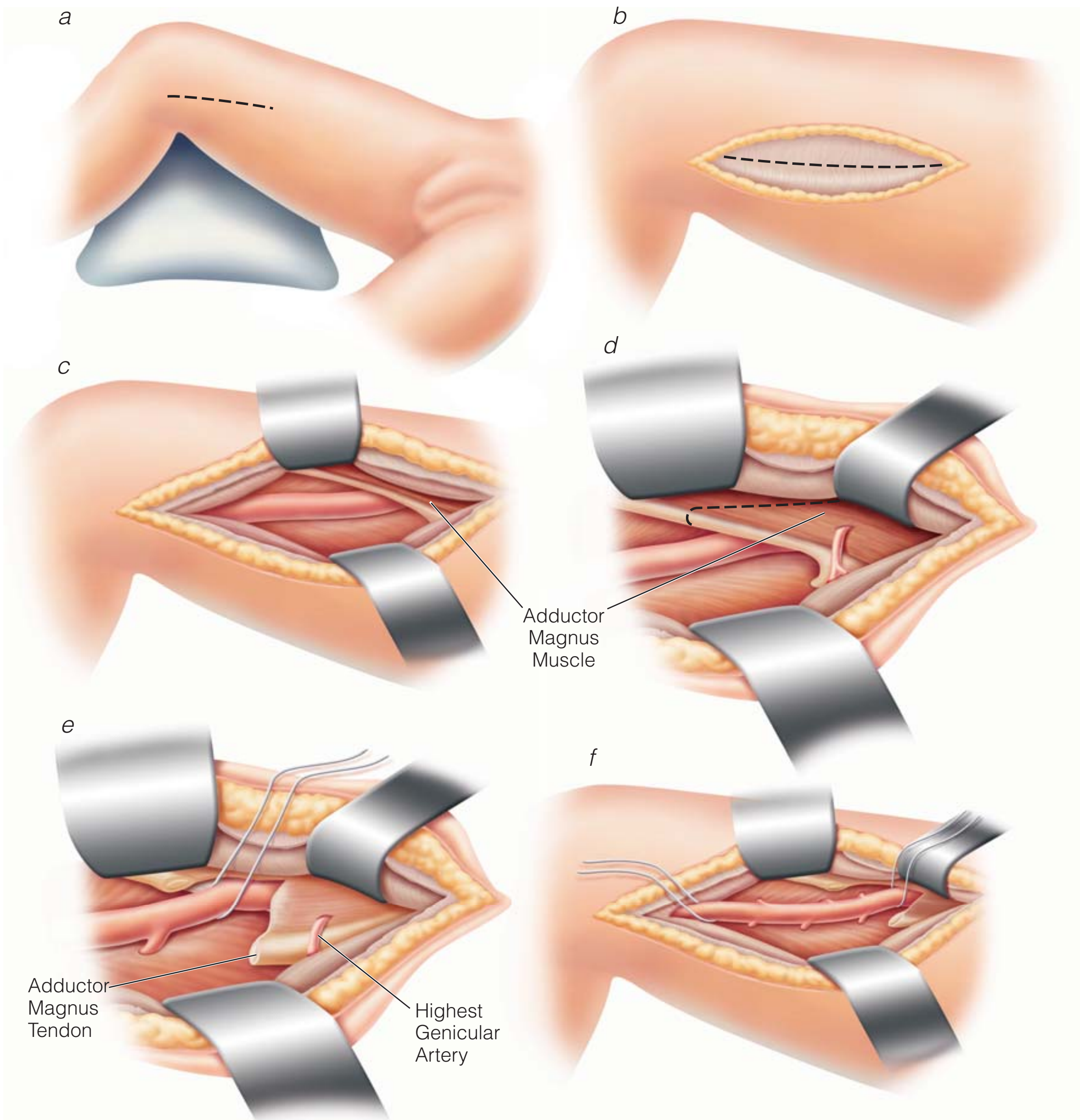

Figure 7 **Depicted is medial exposure of the proximal popliteal artery. (*a*) An incision is made in the lower third of the thigh, anterior to the sartorius muscle. (*b*) The deep fascia is incised, and the sartorius muscle is retracted posteriorly, allowing the popliteal artery to be readily palpated. (*c*) The popliteal arterial sheath is opened, exposing the vessel and its surrounding venules. The adductor magnus tendon may be seen covering the proximal end of the artery (*d*), and it may have to be divided (*e*) to provide better exposure of the artery. (*f*) The popliteal artery, freed of the venous plexus, is mobilized between two vessel loops.**

trauma. In most patients, there is little need for repair of these arteries, which can typically be ligated without deleterious effects. The safety of ligation is predicated on the presence of adequate arterial flow from the nonaffected arteries, as well as retrograde blood flow from an intact palmar or plantar arch.[36,37] Repair of injuries to these arteries is associated with the possibility of embolization or other surgical problems. In addition, the patency rate for grafts in the distal extremities tends to be low.[38]

Repair of Venous Injuries

In most regions of the extremities, repair of any concomitant venous injuries is recommended, on the grounds that it may help keep an arterial repair open and prevent postoperative edema. Primary repair involves closing the venotomy transversely; this may be facilitated by mobilizing the proximal and distal venous structures. If primary repair is not possible, a patch is recommended. To augment venous flow and help maintain patency, an AV fistula may be created, then ligated at a later point. The administration of heparin and the use of a foot pump may also help maintain the patency of a venous repair, as well as reduce the hypercoagulability associated with Virchow's triad and venous occlusion.

If the vein cannot be repaired, it may have to be ligated. For injuries to the tibial vein and some injuries to the brachial vein or a more distal arm vein, ligation may be chosen over repair, with few deleterious consequences. For injuries to the popliteal vein or the SFV, repair is recommended when possible to optimize continued venous drainage of the extremity. As noted [*see* Choice of Conduit, *above*], if vein is harvested, it should come from the contralateral leg so as to permit continued outflow from the injured lower extremity.[39,40]

If proximal ligation of a lower-extremity vein is required, it should be performed on the common iliac vein rather than the external iliac vein. Higher ligation allows cross-pelvis collateral circulation via the internal iliac veins. In addition, ligation of the external iliac vein is fraught with difficulty. Every attempt should be made to repair the vein to prevent major morbidity, including poor venous return and resultant severe edema. Ligation of the common femoral vein (CFV) is also not ideal, because of the risk of leg edema; however, if ligation at the level of the CFV proves necessary, it does allow some venous return flow via the cruciate collateral vessels, the obturator vein (from the medial circumflex femoral vein), and the gluteal vein (from the lateral circumflex femoral vein).

Postoperative Care

After repair of a vascular injury, patients require 24 hours of monitoring in the intensive care unit for serial pulse and Doppler assessments, monitoring of hemodynamic status, and evaluation of the site of the repair. In addition, patients must be watched for the development of metabolic derangements (e.g., metabolic acidosis, hyperkalemia, myoglobinuria, and renal failure) after hemorrhagic shock and reperfusion of ischemic limbs. Changes in the findings from physical examination, the neurologic status of the extremity, or the ABI warrant immediate investigation, usually beginning with duplex ultrasonography. Typically, a duplex examination is also performed in the early postoperative period to establish a baseline for subsequent surveillance of the graft or repair.

MANAGEMENT OF COMPARTMENT SYNDROME

Compartment syndrome is a condition characterized by abnormally high pressure within a closed space. The elevated tissue pressure leads to venous obstruction within the space. When the pressure continues to increase, the intramuscular arteriolar pressure is eventually exceeded. At that point, blood can no longer enter the capillary space, and the result is shunting within the compartment. If the pressure is not released, muscle and nerve ischemia occurs, leading to irreversible damage to the contents of the compartment.[41]

Underlying pathologic processes that reduce the size or increase the contents of a compartment include hemorrhage, reperfusion edema, a tight cast, constrictive dressings, and pneumatic antishock garments. Crush injury may be associated with rapid development of swelling and rigid compartments. The key to the diagnosis of compartment syndrome is continuous assessment of any extremity injury in which elevated pressures may develop. It must always be remembered that the diagnosis is a clinical one; although compartment pressures may be measured, clinical suspicion and findings suggestive of compartment syndrome on physical examination should suffice to mandate therapy.

Current management of compartment syndrome is derived from a 1970 review by Patman and Thompson, in which fasciotomy was performed after arterial reconstruction in 164 patients with peripheral vascular disease.[42] The investigators concluded that fasciotomy could result in limb salvage and implied that it should be considered after restoration of arterial inflow to an extremity. Indications for fasciotomy included pain on palpation of the

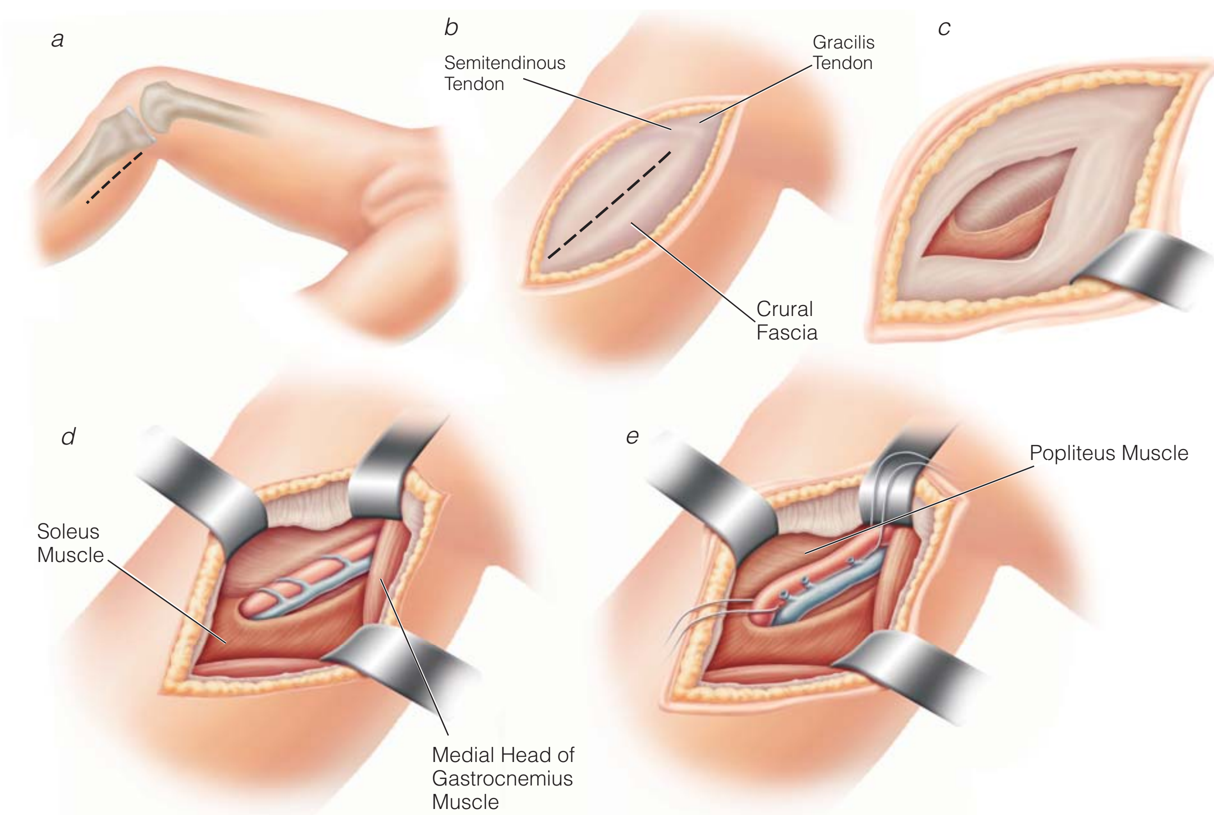

Figure 8 **Depicted is medial exposure of the distal popliteal artery. (*a*) An incision is made just behind the posteromedial surface of the tibia. (*b*) The crural fascia is exposed. (*c*) The fascia is incised, exposing the vascular bundle. (*d*) The medial head of the gastrocnemius muscle is retracted posteriorly, exposing the distal popliteal vessels and the arcade of the soleus muscle. (*e*) The distal popliteal artery is freed and mobilized between vessel loops.**

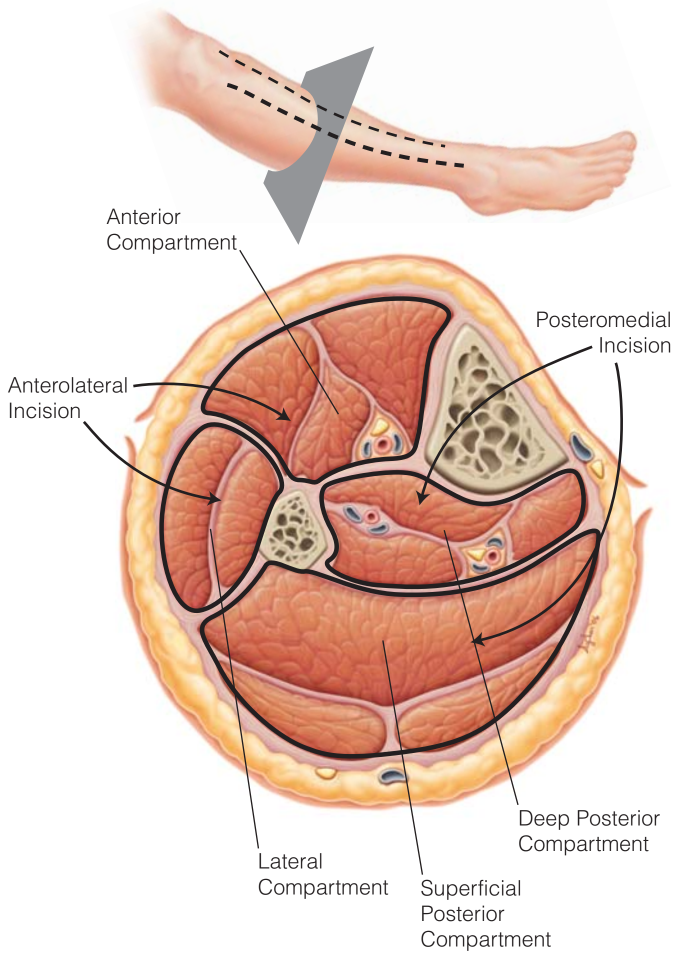

Figure 9 (*a*) **Illustrated is the two-incision technique for lower leg decompression in compartment syndrome. Two vertical skin incisions are made from knee to ankle, separated by a skin bridge at least 8 cm wide. (*b*) Fasciotomies are then performed in all four compartments along the dashed lines.**

swollen compartment, reproduction of symptoms with passive muscle stretch, a sensory deficit in the territory of a nerve traversing the compartment, muscle weakness, diminished pulses (a very late sign), and compartment pressure exceeding 30 to 35 mm Hg.

It has been noted that the difference between the diastolic pressure and the measured compartment pressure may be a more reliable clinical indicator of compartment syndrome than the compartment pressure by itself. A difference of less than 30 mm Hg between the two pressures is significant and may be the most reliable indicator of when fasciotomy is warranted.

There are a number of clinical situations in which fasciotomy should be considered: when there is a 4- to 6-hour delay before revascularization, when arterial injuries are present in conjunction with venous injuries, when crush injuries or high–kinetic energy injuries have been sustained, when vascular repair has already been performed (reperfusion), when an artery or vein has been ligated, when a patient is comatose or has a head injury and physical examination is impossible, and when a patient has tense compartments or elevated compartment pressures. In these scenarios, fasciotomy should be considered as a prophylactic maneuver.

Fasciotomy

The lower leg contains four osseofascial compartments: the anterior compartment, the lateral compartment, the superficial posterior compartment, and the deep posterior compartment. The thigh contains three osseofascial compartments: the quadriceps, the hamstrings, and the adductors. For fasciotomies of the lower leg, there are two techniques: perifibular fasciotomy and the double-incision technique. Perifibular fasciotomy affords access to all four compartments of the leg via a single lateral incision that extends from the head of the fibula to the ankle, following the general line of the fibula. The double-incision technique employs two vertical skin incisions that are separated by a bridge of skin at least 8 cm wide [*see Figure 9*]. The first incision extends from knee to ankle and is centered over the interval between the anterior and lateral compartments; the second also extends from knee to ankle and is centered 1 to 2 cm behind the posteromedial border of the tibia.[41] Although decompression in the lower extremity may be achieved via either of the two techniques, the double-incision technique is preferred in the setting of trauma because it readily ensures that all four compartments have been decompressed.

The forearm consists of three osseofascial compartments: the superficial flexor compartment, the deep flexor compartment, and the extensor compartment. To decompress the upper extremity, a volar fasciotomy, a dorsal fasciotomy, or both may be performed. A volar fasciotomy decompresses the superficial and deep flexor compartments of the forearm via a single skin incision.[41] This incision begins medial to the biceps tendon, crosses the elbow crease, proceeds toward the radial side of the forearm, and extends distally along the medial border of the brachioradialis, finally continuing across the palm along the thenar crease [*see Figure 10*]. After the superficial and deep flexor compartments of the forearm are decompressed, intraoperative pressure measurements may be obtained to help determine whether fasciotomy is necessary to decompress the extensor compartment. If the pressure continues to be elevated in the extensor compartment, a dorsal fasciotomy should be performed. With the arm pronated, a straight incision is made from the lateral epicondyle to the midline of the wrist.[41]

After fasciotomy, both the fascia and the skin are left widely open. The skin defects may be closed with skin grafts at the time of original operation, provided that this can be done without excessive tension or pressure. Alternatively, the patient may be returned to the OR after the swelling resolves for delayed skin closure (with the fascia left open) or split-thickness skin grafting, as indicated.

It is important to consider fasciotomy in patients with arterial injuries associated with crush injury and venous injury or occlusion. These secondary injuries may be associated with a higher risk of compartment syndrome than either isolated arterial injuries or ischemia-reperfusion alone.[43] In any setting, the most important concerns in performing a fasciotomy are that the procedure must be done in a timely manner and that all of the compartments must be completely decompressed.

Special Considerations

MANAGEMENT OF INTIMAL INJURIES

How best to manage small traumatic intimal injuries identified by means of angiography has been the subject of considerable debate. In general, patients who have injuries shorter than 2 mm and involving less than 50% of the vessel circumference, with no noted pulse deficits, may be placed on an antiplatelet regimen and followed clinically; evidence from animal studies supports this approach.[44] There is some clinical evidence to suggest that antiplatelet medication (e.g., acetylsalicylic acid) and observation alone may be adequate treatment in such patients; however, addi-

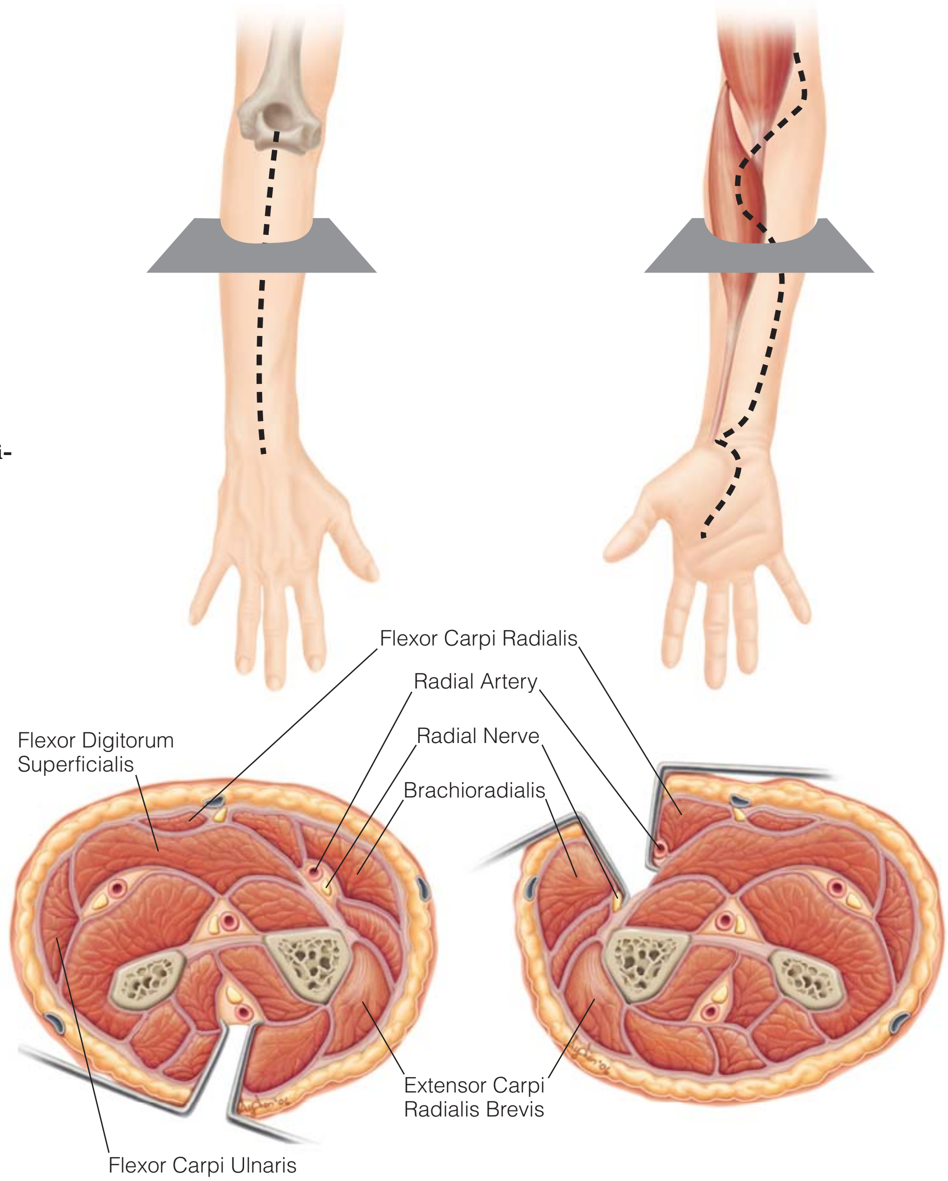

Figure 10 **Shown are incisions for forearm decompression in compartment syndrome.**

tional follow-up studies are required before this recommendation can be confirmed.[45]

Even though some cases can be treated conservatively, it is important not to underestimate the potential importance of angiographically identified intimal injuries. Patients with such injuries are at risk for the development of a pseudoaneurysm, AV fistula, dissection, or even thrombosis.[44,46,47]

ANTICOAGULATION

Whether anticoagulation is indicated in patients with vascular trauma is also debatable. It has been suggested that early administration of systemic anticoagulant therapy (heparin, 100 U/kg) may reduce amputation rates by preventing microvascular thrombosis. There is some evidence that anticoagulation may improve limb salvage rates while posing only a minimal risk of bleeding complications.[48] Systemic anticoagulation may be contraindicated in certain situations, such as active hemorrhage, coagulopathy, and craniocerebral injury. If heparin cannot be given systemically, it may be administered locally during the operation, at the site of the arterial repair.

ENDOVASCULAR INTERVENTION

At present, although there are several potential uses for endovascular techniques in the trauma setting, there are no clear indications for such interventions in the management of extremity vascular injuries. The reality is that there are few long-term data on the use of stents in the peripheral arteries even in nontrauma settings. For example, the patency rate for endoluminal stents in the SFA is between 60% and 80% at 2 years, a range lower than that of primary repairs or interposition grafts.[49] In addition, many patients who sustain extremity trauma are younger than the average vascular stent patient and have poorer access to health care; consequently, close long-term follow-up after an endovascular intervention may be harder to carry out in this population.

Endovascular therapy may be considered in certain instances of extremity vascular trauma, such as when systemic conditions rule out operative repair and a temporizing measure is warranted. It should be kept in mind, however, that endovascular repair of peripheral vascular injuries is still a developing form of treatment and not the standard of care.[50,51]

TIMING OF ORTHOPEDIC REPAIR VIS-À-VIS VASCULAR REPAIR

Another issue that continues to evoke controversy is the timing of repair of concomitant vascular and orthopedic injuries—in particular, the order in which these injuries should be repaired. In general, vascular repair should take precedence over orthopedic reconstruction when possible. Vascular surgeons have long been concerned about the instability of knee dislocations and distal femoral or proximal tibial fractures, fearing that a fragile vascular reconstruction might be undone by subsequent orthopedic maneuvers; however, the data do not support this fear. There is some evidence that in patients with combined injuries, giving priority to revascularization over orthopedic fixation leads to shorter hospital stays and a trend toward lower fasciotomy rates. In a 2002 study, revascularization before fracture fixation was not found to result in iatrogenic disruption of the vascular repair.[43]

When an extremity has been substantially destabilized as a consequence of bony injury, short-term external fixation may be employed to facilitate vascular repair. A temporary intraluminal shunt is often used to maintain perfusion during initial orthopedic stabilization. One study demonstrated that routine use of intraluminal shunts in patients with complex extremity vascular injuries had the potential to reduce excessive morbidity (e.g., the need for fasciotomy and the resultant prolonged hospital stay) from prolonged arterial insufficiency.[52] In selected patients with combined skeletal and vascular injuries to the upper or lower limb, temporary vascular shunting may reduce complications resulting from prolonged ischemia and permit an unhurried and reasonable sequence of treatment.[53]

SALVAGE OF SEVERELY INJURED OR MANGLED EXTREMITIES

When an extremity is severely injured or mangled, a decision must be made whether to attempt salvage or perform amputation. Because of the need to take the patient's emotional and medical concerns into account, evaluation of an extremity for potential salvage is a difficult undertaking. Several scoring systems have been developed to help make this decision-making process somewhat easier. The most commonly used system is the Mangled Extremity Scoring System (MESS), which uses four objective criteria to predict the likelihood of amputation after lower-extremity trauma: skeletal/soft tissue injury, limb ischemia, shock, and patient age. A MESS score of 7 or higher predicts amputation with an accuracy approaching 100%. However, it is essential to remember that each patient must be carefully evaluated and that attempts at limb salvage must not be base solely on a high MESS score.[54,55]

The need for amputation may be best predicted by the occurrence of severe injuries to the sciatic or tibial nerves, the presence of associated fractures, and the failure of arterial repair.[5] Often, the decision to amputate is not made at the time of presentation or during the initial operation. If, after revascularization and skeletal stabilization, the extremity is clearly nonviable or remains insensate, then delayed amputation may be performed under more controlled circumstances.[56]

The optimal approach to evaluating a severely injured extremity involves a multispecialty group, including the trauma surgeon, the vascular surgeon, and the orthopedic surgeon. With full knowledge of the patient's condition, an attempt at limb salvage may be appropriate. In some cases, though, amputation may be preferable to preservation of an insensate, nonfunctional limb.

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