Vascular injury associated with extremity trauma occurs in <1% of patients with long bone fracture, although vascular injury may be seen in up to 16% of patients with knee dislocation. In the absence of obvious signs of vascular compromise, limb-threatening injuries are easily missed, with potentially devastating consequences. A thorough vascular assessment is essential; an arterial pressure index <0.90 is indicative of potential vascular compromise. Advances in CT and duplex ultrasonography are sensitive and specific in screening for vascular injury. Communication between the orthopaedic surgeon and the vascular or general trauma surgeon is essential in determining whether to address the vascular lesion or the orthopaedic injury first. Quality evidence regarding the optimal fixation method is scarce. Open vascular repair, such as direct repair with or without arteriorrhaphy, interposition replacement, and bypass graft with an autologous vein or polytetrafluoroethylene, remains the standard of care in managing vascular injury associated with extremity trauma. Although surgical technique affects outcome, results are primarily dependent on early detection of vascular injury followed by immediate treatment.

Vascular injury secondary to extremity trauma is rare, with a reported incidence of <1% in patients with long bone fractures. In the setting of knee dislocation, the incidence of vascular injury has been reported to be as high as 16% based on the combined results of five retrospective studies. A high index of suspicion for vascular injury should be maintained in patients with high-risk fractures or fracture characteristics, such as comminuted tibial plateau fracture, severely displaced fracture, open fracture, and segmental shaft fracture, as well as in patients with injuries associated with blunt trauma, floating joint, crush injury, and dislocation. Successful management requires a multidisciplinary approach that includes the orthopaedic surgeon and a vascular or general trauma surgeon. Prompt and accurate diagnosis of vascular compromise is imperative because delays in diagnosis are associated with a lower extremity amputation rate as high as 86%. Although arterial injury can occur with upper and lower extremity trauma, most of the literature focuses on the diagnosis, initial management, treatment considerations, and outcomes of vascular injury associated with lower extremity trauma.
Incidence

The overall incidence of vascular injury following extremity trauma varies widely by population (military versus civilian), geographic location (urban versus rural), and mechanism (penetrating versus blunt trauma). The rate of vascular injury depends on the type of injury. For example, closed diaphyseal long bone fracture carries a reported risk of vascular injury as low as 0.1%.2-4 Severe open tibial fractures are associated with a 9% incidence of vascular injury,9 whereas knee dislocations have been associated with vascular injury in ≤16% of cases.4 Diagnostic methodology differs between studies, which makes it difficult to determine the true incidence for a given injury pattern. The surgeon must maintain a high index of suspicion when examining the patient with extremity trauma, especially one with injuries associated with a high risk of vascular injury.

For example, we treated a patient who sustained a subtrochanteric femoral fracture secondary to a gunshot wound (Figure 1). Initial vascular surgery consult was obtained in the emergency department; the consultants felt that no acute intervention or further vascular workup was necessary. Despite normal physical examination findings and normal ankle-brachial index (ABI), the patient's hemoglobin continued to fall during hospitalization. Subsequent arteriography demonstrated transection of the profunda femoris artery, which was successfully coiled with interventional radiology. The patient improved and was discharged without further complication.

Anatomy

Damage to vascular structures may occur as a result of direct or indirect trauma. Direct trauma includes puncture wounds or lacerations of a vessel caused by a stabbing mechanism of injury, projectile, or sharp fracture fragment. Indirect trauma involves stretching or shear forces that act on a vessel, which may lead to intimal tear. Indirect mechanisms are responsible for most vascular injuries associated with dislocation or a severely displaced fracture. Recoil of the soft tissues is common; in general, displacement seen at presentation is not representative of the displacement that occurs at the time of injury.12

Injury to the popliteal artery is common with knee dislocation.13 The popliteal artery consists of three distinct layers. From outside to inside, these layers are the tunica adventitia, tunica media, and tunica intima. The tunica intima can be further subdivided into the endothelium, subendothelium, and basement membrane. Aneurysms, intimal tears and/or flaps, fistulas, and other traumatic injuries are often defined by their occurrence within a specific layer of the vessel. Anatomic location of arteries also influences the degree of injury.7,13 Following vascular injury or occlusion, uninterrupted tissue perfusion is dependent on collateral circulation. For example, collateral circulation about the knee is generally considered to be poor, contributing to the relatively high rate of...
amputation associated with vascular trauma about the knee.\textsuperscript{14} As the energy imparted to an injury (eg, fracture, dislocation) increases, so too does the possibility of vascular insult.\textsuperscript{12,13}

**Initial Assessment**

Diagnosis of vascular injury in the setting of blunt trauma begins with physical examination and radiographic assessment. However, physical examination can be misleading or initially unimpressive; a normal pulse examination may be present in 5\% to 15\% of patients with vascular injury.\textsuperscript{15} Figure 2 illustrates an example of a severely comminuted open tibial plateau fracture. Initial pedal pulses were normal, but subsequent CT angiography demonstrated disruption of the popliteal artery with reconstitution distally.

**Physical Examination**

Initial trauma evaluation begins with the Advanced Trauma Life Support protocols, including assessment of airway, breathing, and circulation. The secondary survey should include clinical examination of all the extremities, followed by radiographic evaluation of the affected extremities. Thorough motor, neurologic, and vascular examinations should be performed on arrival prior to any in-
In the setting of vascular injury, physical examination findings can be classified as hard or soft signs (Table 1). Hard signs, such as pulselessness, pallor, and paresthesia, prompt immediate surgical intervention by the orthopaedic surgeon, vascular surgeon, and/or traumatologist. When localization of the vascular injury is required prior to intervention, an arteriogram can be performed in the operating room or in an arteriography suite. Soft signs, such as history of bleeding in transit and proximity-related injury, occur in conjunction with a palpable pulse or Doppler pressure measurement. Soft signs are associated with vascular injury in 3% to 25% of cases. Treatment algorithms based on these signs vary by institution. Our proposed diagnostic algorithm is presented in Figure 3.

Identification of vascular injury is the key to management. However, best practices for injury detection remain controversial. Arteriography is the current standard of care, but this procedure is not without risk. Complications such as entry site hematoma, vessel thrombosis, embolization, and contrast reaction have been reported in 2% of patients. These findings have prompted investigation into less invasive methods of detecting injury.

Conflicting data have been published regarding the reliability of physical examination in detecting vascular injury. Numerous studies indicate that physical examination alone has 94% to 100% specificity and negative predictive value for exclusion of vascular lesions requiring surgical repair. However, some data suggest that physical examination may be less reliable than was initially thought. In a meta-analysis of vascular injury associated with knee dislocation, Barnes et al reported a 13% incidence of normal pedal pulses in patients with vascular lesions that required surgical repair, leading to an overall positive predictive value of 75% and a negative predictive value of 93%. Many surgeons believe that a normal physical examination on presentation warrants only close observation.

The arterial pressure index (API) is a quick and inexpensive screening modality that is readily available in the emergency department. The API is calculated by measuring the systolic pressure of two extremities. One blood pressure cuff is placed distal to the lower extremity injury, and another is placed on an uninjured upper extremity. A Doppler probe is then used to determine the systolic pressure of both extremities. The systolic arterial pressure in the injured extremity is divided by the systolic pressure in the unaffected upper extremity to calculate the API. The ABI is calculated in much the same way, in that the systolic arterial pressure in the injured lower extremity is divided by the systolic arterial pressure in an uninjured upper extremity.

An API or ABI value of ≤0.90 necessitates further workup for potential vascular injury. This value was established by Lynch and Johansen, who prospectively evaluated 100 consecutive injured limbs (93 patients) with blunt or penetrating trauma for vascular injury. All patients in the study had documented APIs followed by arteriography. Use of the API value of 0.90 as a cutoff resulted in an overall accuracy rate of 97% in detecting vascular injury, with positive and negative predictive values of 91% and 99%, respectively. Mills et al confirmed this finding, reporting positive and negative predictive values of 100% with an ABI of ≤0.90 in their prospective study of 38 patients with knee dislocation. They found a statistically significant correlation between peroneal nerve palsy and vascular injury.
(P = 0.004). These results highlight the importance of physical examination and the presence of soft signs in detecting underlying vascular injury. Johansen et al22 have shown that the API is not only effective in diagnosing vascular injury but also may be cost effective. They documented a nearly 9% reduction in the number of arteriograms performed in patients with extremity trauma when API was used as an initial screening test.

API findings may be misleading, however, particularly in persons with injury to vessels such as the profunda femoris or peroneal arteries that do not extend distally or are not palpable12 and in persons with vascular lesions that may not cause a decrease in blood flow (ie, intimal flaps). Furthermore, API measurement assumes normal patient vasculature, anatomy, and tissue perfusion for accurate assessment. Patient condition may preclude adequate API assessment, as when the location of wounds or fracture precludes placement of a blood pressure cuff, or in the setting of hypovolemic shock. Medical conditions such as severe peripheral vascular disease and diabetes may provide false results, given the inherent changes in the patient’s vasculature that affect peripheral blood flow.

**Imaging**

The role of duplex sonography in clinical practice is evolving. This noninvasive procedure can be performed rapidly at the bedside, and it has the potential to identify vascular lesions more quickly and with fewer complications than CT angiography or arteriography. Two prospective studies evaluated the accuracy of duplex sonography in detecting vascular injury. Bynoe et al23 reported only two false-negative results in 198 patients, with an overall accuracy of 98%. Knudson et al24 evaluated 77 patients and reported no missed vas-
cular injuries on clinical follow-up. Duplex sonography may be used to monitor the progression of lesions,\(^{25}\) avoid repeat administration of contrast, and avoid more invasive studies. However, not all centers have duplex sonography equipment or adequately trained technicians.

Recently, CT angiography has been advocated for patients who do not present with hard signs of vascular injury but in whom soft signs or deterioration of the physical examination are suggestive of such injury.\(^{18,26}\) In a prospective study, Seamon et al\(^{26}\) reported on the accuracy of CT angiography in patients who presented with an ABI of <0.90 without hard signs of vascular injury. CT angiography findings were confirmed in 21 of 22 patients (95%) on subsequent arteriography. Cost analysis of CT angiography versus arteriography at their institution demonstrated a savings of approximately $13,000 in patient charges associated with CT angiography. CT angiography appears to be a quick, cost-effective, and reliable option for diagnosis of vascular injury associated with extremity trauma.

Assessment and diagnosis of penetrating trauma to an extremity is similar to that of blunt trauma. Physical examination and API measurement are used to determine whether further evaluation is required. In two retrospective series, occult vascular injury in association with gunshot wounds involving long bone fracture was reported in 11%\(^{27}\) and 28%\(^{28}\) of patients (30 of 270 and 17 of 61, respectively). These proximity-related wounds are often located near large named neurovascular structures (eg, injury to the antecubital fossa or popliteal fossa). However, significant injury is rare in the absence of hard or soft signs of vascular injury; such lesions seldom require surgical intervention.\(^{29,30}\) Thus, a proximity-related injury and/or missile injury is not an indication for arteriography in the setting of normal physical examination and API.

**Management**

**Orthopaedic**

For the orthopaedic surgeon, the goal in managing the traumatized extremity with associated vascular injury is to stabilize the extremity while protecting the vascular repair. Patients with these injuries often have multiple trauma and significant resuscitation requirements; thus, discussion between general trauma, vascular, and orthopaedic teams is paramount for optimal patient care. A predetermined management strategy helps to streamline diagnosis and management, thereby decreasing ischemia time and optimizing patient care and outcomes. Our proposed treatment algorithm is presented in Figure 4.

When limb salvage is required, the surgical teams must determine the timing of orthopaedic and vascular repair. The sequence of fracture fixation and vascular repair remains controversial.\(^{2,10,31,33}\) Proponents of performing orthopaedic intervention before vascular repair argue that bony stabilization is required to protect the vascular repair and that manipulation, reduction, and fixation may endanger a fresh repair. Decreasing warm ischemia time remains the primary argument in support of performing vascular repair first. Time to limb revascularization may be delayed an average of 4 to 5 hours when orthopaedic stabilization is done before vascular repair.\(^{33}\) However, a recent meta-analysis showed no statistical difference in overall amputation rate whether vascular repair or orthopaedic repair was performed first (13% and 11.6%, respectively).\(^{2}\) Likewise, evidence does not indicate an increased incidence of vascular disruption or damage when orthopaedic manipulation is performed after vascular repair.\(^{2,31}\) Sequence of repair and fixation should be determined by the surgical teams on a case-by-case basis using predetermined protocols.

Temporary versus definitive fracture stabilization at the index procedure is also controversial. Placement of an external fixation device is fast and allows quicker stabilization of the extremity in situations in which orthopaedic intervention precedes vascular repair or in which the patient’s resuscitation status rules out a long, definitive procedure. External fixation is also useful when soft-tissue injury precludes immediate stabilization. Definitive procedures allow for fewer trips to the operating room and provide more stable fracture stabilization. However, open procedures are associated with increased surgical time and with the risk of increased dissection and stripping, leading to further devascularization of the collateral circulation to the extremity.

No high-level evidence exists to definitively indicate whether external or internal fixation is superior for fixation at the index procedure, nor is there an indication which type of internal fixation is preferred (ie, plate, intramedullary device). Howard and Makin\(^{3}\) recommended external fixation for index stabilization after finding a statistically significant increase in amputation rates following initial definitive fixation \(P < 0.01).\) Allen et al\(^{1}\) reported nonunion and malunion in five of nine patients who underwent internal fixation, and they surmised that external fixation may be beneficial. In an 18-year period, Schlickewei et al\(^{11}\) reduced their use of internal fixation and increased their use of external fixation. However, internal fixation remained the standard of care in their practice, and fracture fixation was performed.

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**Figure 4.**
while the vascular surgeon harvested the graft. Although recent trends indicate a preference for external fixation, further study is required to determine the rates of secondary amputation, malunion, nonunion, and infection with this treatment.

**Vascular Repair**

Open vascular repair techniques have evolved from Ambrose Pare's description of arterial ligation in the 1500s to the first use of autogenous vein grafts during the Korean War. Current therapeutic options include a host of endovascular techniques and a spectrum of open reconstruction options.

Nonsurgical management of arterial injuries remains controversial. Some authors have proposed that all detected arterial injuries warrant intervention. Others believe that nonsurgical management is reasonable when clinical and radiographic criteria indicate low-velocity injury, adherent or downstream protrusion of intimal flaps, intact distal circulation, no active hemorrhage, and minimal arterial wall disruption (<5 mm) for intimal defects and pseudoaneurysms. Serial neurovascular testing and close follow-up are essential in nonsurgical management.

Endovascular therapy in the setting of trauma involves therapeutic occlusion of a vessel or use of a covered stent graft to line the injured artery. Therapeutic occlusion may be useful...
in select injuries such as arteriovenous fistula, arterial pseudoaneurysm, and bleeding from noncritical arteries. Typically, endovascular occlusion is accomplished with transcatheter delivery of thrombogenic coils, Gelfoam suspension (Pfizer, New York, NY), glue, or a combination thereof. Stent grafts exclude the arterial injury while maintaining luminal patency. However, evidence from large long-term studies is lacking. Endovascular therapy for arterial trauma in an extremity requires the availability of high-quality angiographic imaging, specialized support staff, appropriately sized supplies, procedural expertise, and favorable patient anatomy. Particularly in smaller hospitals, logistics and patient factors may preclude an endovascular approach.

Open surgical management is the standard of care for peripheral vascular trauma. The patient’s overall injuries and hemodynamic status must be assessed when considering this treatment option. Vascular reconstruction is often performed prior to orthopaedic fixation, and the vascular surgeon should inspect the repair after fixation and before wound closure. Patency must be documented before leaving the operating room; it can be assessed with arteriography or duplex sonography or by checking palpable pulses.

The contralateral extremity is placed in the surgical field for potential harvest of autogenous vein should the ipsilateral vein be unsuitable for use as a graft. To minimize blood loss during exposure, proximal and distal control may be achieved with direct temporary occlusion of the involved vessel, digital pressure, proximal pneumatic compression, or endoluminal balloon occlusion. Once the injury is identified, the involved artery must be débrided back to normal artery to ensure successful repair. Balloon mounted catheters (eg, Fogarty) are carefully passed proximally and distally to remove intraluminal clots. Local heparinization through the proximal and distal site of injury is essential. Systemic heparinization is believed to prevent propagation of distal small-vessel thrombosis and has been shown to have a significant effect on limb salvage; however, it may be contraindicated in a patient with multisystem trauma.

Once the extent of the arterial injury has been identified, the appropriate method of repair can be selected. Options include direct repair with or without arteriorrhaphy, interposition replacement, and bypass graft. The most common conduit options for interposition or bypass grafts are the autologous vein and polytetrafluoroethylene (PTFE). We prefer to use the contralateral saphenous vein. Donor site morbidity is low with contralateral vein harvest, and potential problems associated with the ipsilateral vein (eg, inadequate graft, injury to the vein) are avoided. The use of PTFE in above-knee traumatic vascular reconstruction is controversial. Although patency rates for PTFE are similar to those of vein grafts in this setting, there is concern regarding placement of artificial material into a contaminated field. The durability of vein grafts for below-knee revascularization following traumatic injury is well documented, and they are the best option. Ligation of a bleeding arterial vessel may be an option in noncritical vessels. In the setting of damage control, use of intravascular shunts to quickly restore temporary perfusion is controversial; no large cohort studies have been performed. Gifford et al reported that in the setting of damage control, temporary vascular shunting does not lead to worse outcomes and may convey some benefit.

Extensive soft-tissue defects may pose unique barriers to vascular reconstruction. Tissue unavailability such as in a large mid thigh defect or marginal viability at the usual arterial anastomotic sites may create problems with tissue coverage of a vascular graft. Typical tunnel paths for bypass grafts may travel through injury zones, thereby exposing the graft and affecting tissue flap options or hardware placement. These situations require creativity and close coordination with all involved surgical teams to provide a solution that works with the overall limb salvage plan.

Outcomes

Limb salvage outcomes are affected by the mechanism of injury, associated injuries, and time to diagnosis and/or intervention. Recent analysis of the National Trauma Data Bank indicates an amputation rate of 14.5% in the setting of traumatic popliteal injury. Compared with a penetrating mechanism of injury, blunt vascular disruption of the popliteal artery is associated with longer hospital stays, worse functional outcomes, lower limb salvage rates, and a significantly higher amputation rate (9% versus 27%, respectively; P < 0.001). High-velocity gunshot wounds (ie, muzzle velocity >1,500 ft/sec) are nearly twice as likely as low-velocity wounds to result in subsequent amputation. Extensive injury to surrounding soft-tissue structures is likely the common factor in increased rates of amputation following blunt trauma and high-velocity gunshot trauma.

Few studies have examined the relationship between vascular injury and the rate of fracture union. Brinker and Bailey found no statistical correlation between vascular injury and fracture union in terms of method of vascular repair, soft-tissue
management, sequence of the orthopaedic and vascular procedures, or Gustilo open fracture type. They did, however, find that posterior tibial arterial injuries were associated with a 75% incidence of nonunion.

Time to intervention is the most important factor under the surgeon’s control. To avoid permanent soft-tissue damage, arterial continuity should be restored in a warm ischemia time of <6 hours. Delay >8 hours is associated with an amputation rate of up to 86%. The Lower Extremity Assessment Project (LEAP) study showed that prolonged ischemia time was the most important factor associated with amputation in patients with popliteal injury related to knee dislocation, whereas the extent of soft-tissue damage and nerve dysfunction were the primary determinants of limb salvage. In patients with dysvascular knee dislocation, limb salvage affords a statistically significant trend toward better functional outcomes than amputation (average Sickness Impact Profile score, 7.0 and 16.1, respectively; \( P = 0.32 \)). However, based on Sickness Impact Profile scores of LEAP cohort patients, long-term functional outcomes appeared to be relatively equal at 7-year follow-up. The LEAP study also challenged the validity of historical measures of extremity severity that rely heavily on ischemia time or the presence of vascular injury (eg, Mangled Extremity Severity Score; Limb Salvage Index; Predictive Salvage Index; Nerve Injury, Ischemia, Soft-Tissue Injury, Skeletal Injury, Shock, and Age of patient score). Ly et al demonstrated little correlation between these historical measures of extremity trauma and functional outcome. This contradicts findings reported in a review of the National Trauma Data Bank, in which fracture and vascular injury, along with nerve injury and Extremity Abbreviated Injury Score were found to be predictors of amputation following lower extremity trauma. All of this information must be discussed with the patient and his or her family.

Limb salvage has been shown to result in an increased number of procedures and hospitalizations in addition to a higher rate of complications. In some cases, early amputation may provide the best functional result. In these cases, amputation should be thought of not as a failure but as an option that enhances the patient’s functional capacity.

### Summary

Vascular injury in extremity trauma is a relatively rare entity with serious complications. Prompt recognition is the key to limb salvage, along with coordinated management between the orthopaedic surgeon and the vascular surgeon or general surgery traumatologist. Numerous diagnostic modalities are available to detect vascular injury associated with extremity trauma, including CT angiography and duplex sonography. Direct communication between surgical teams is essential to determine the appropriate sequence of the orthopaedic and vascular intervention. Further studies are warranted to define the role of temporary external fixation and definitive internal fixation at the time of the index procedure. Overall outcomes of vascular injury associated with extremity trauma appear to be primarily dependent on the time to intervention, but the patient’s medical status and the presence of associated injuries are important factors, as well.

### References

**Evidence-based Medicine**: Levels of evidence are described in the table of contents. In this article, references 5, 8, 23, and 45 are level I studies. References 2, 4, 11-15, 17, 20-22, 24-26, 28, 30, 35, 43, and 44 are level II studies. References 1, 9, 18, 27, 32, and 39 are level III studies. References 3, 6, 7, 10, 16, 19, 29, 31, 33-37, and 40-42 are Level IV studies.

References printed in **bold type** are those published within the past 5 years.

Vascular Injury Associated With Extremity Trauma: Initial Diagnosis and Management


