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Penetrating Vascular Trauma of the Upper and Lower Limbs

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Abstract Patients with penetrating extremity vascular injury and hard clinical signs should undergo immediate surgery. If the arterial injury needs to be localized, on-table arteriogram in the operating room or in a hybrid suite is performed. Computed tomographic angiography can also be used if patient's condition permits to evaluate extremity vascular injury. A tourniquet can be used as hemorrhage control during early resuscitation and for proximal vascular control during surgery. An intravascular shunt may be inserted in a damage control situation. Definitive arterial and venous repair is performed with standard vascular techniques. There is a role for endovascular techniques for specific and limited arterial injuries after penetrating trauma, but the technique needs further evaluation. This review article focuses on the specific management of penetrating vascular injuries in the upper and lower limbs.

Keywords Vascular injuries · Penetrating · Upper extremity · Lower extremity · Operative management vascular trauma

This article is part of the Topical Collection on *Penetrating Injuries To Major Vessels*

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Introduction

Penetrating injuries to the upper and lower limbs may cause a large variety of complex injuries depending on the penetrating energy transferred into the tissues. Although high-energy injuries are more frequent in the military setting, they can be seen also in the civilian setting and in particular after terror attacks. In the military setting, the use of body armor protects to some extent from lethal injuries but combined severe soft tissue, bone, vascular, and nerve injuries of the extremities are common. In the civilian setting, penetrating injuries to the limbs are observed in between 5 and 15 % according to, for example, trauma registries in the USA, Germany, or Sweden [1–3], although the number of injuries can be higher in some other countries [4]. Stab wounds cause the majority of injuries in Europe although gunshot injuries are dominating in countries where firearms are more commonly used. Shotgun injuries cause vascular injuries in 5 % of the time.

This article focuses on the specific management of vascular injuries in the upper and lower limbs but will also briefly mention some principles of general management as well as wound evaluation and surgical wound debridement.

Types of Vascular Injuries

Vascular injuries can be divided in five different types [5]:

1. Intimal injuries (subintimal hematomas, flaps, disruptions)
2. Total wall defects with bleeding, hematomas, or pseudoaneurysm
3. Total disruptions with bleeding and/or occlusions
4. Arteriovenous fistulas
5. Spasm

According to their location and severity (involvement of vessel circumference), the Committee of the American Organ Injury Scaling grades these injuries into four grades, probably most useful for research [6].

Clinical Presentation

The clinical evaluation of the injured extremity after penetrating trauma is of outmost importance. Clinical signs of vascular injury are generally divided into "hard" or "soft" signs of injury. The hard signs are as follows: active hemorrhage, rapidly expanding hematomas, absent pulses, pallor, paresthesia, pain, paralyses, poikilothermia, or palpable thrill or audible bruit. The soft signs are as follows: history of arterial bleeding at the scene of injury, diminished distal unilateral pulse, small hematoma, neurological deficit, abnormal flow velocity wave on Doppler examination, or abnormal ankle-brachial pressure index (ABI, <0.9).

The presence or not of hard clinical signs may decide whether the patient needs an immediate operation, can undergo further investigation, or may only need continuous observation [7]. The presence of hard signs in penetrating trauma during the physical examination usually determines the anatomic level of vascular injury and the need for immediate surgery. If vascular status is difficult to assess, further investigations are required by calculating the ankle-brachial index followed most frequently by imaging with CT angiography.

Diagnostic Imaging

There is no role for routine imaging in penetrating extremity trauma [5, 7]. When computed tomography (CT) is available and the patient physiology and injury allow for further evaluation, the CT angiography (CTA) has become the gold standard for diagnosing and to further decide whether the vascular injury can be treated by open surgery or by endovascular techniques [8, 9]. CT angiographic signs of arterial injury include active extravasation of contrast, abrupt narrowing of artery or loss of opacification of an arterial segment, pseudoaneurysm, and arteriovenous fistula. However, when metal fragments remain in the wound, streak artifacts may be a limiting factor for adequate diagnosis [10]. If CT angiography is not available, conventional angiography can be performed in the operating room with a C-arm or in a hybrid suite depending on local facilities.

Depending on available resources and early access of endovascular treatment, the algorithm at the Karolinska University Hospital in Stockholm which is a slightly modified version of the one presented by the Western Trauma Association is shown in Fig. 1 [11].

Management and General Principles

The general management of patients with penetrating limb injuries follows the Advanced Trauma Life Support-principles [12]. All patients need to be assessed for other life-threatening injuries. For severe bleeding from the limbs, the control of bleeding and early restoration of the distal circulation should be prioritized.

Hemorrhage Control

Bleeding control of the arterial or venous limb injury can be achieved in most cases by manual compression and pressure bandages. The application of tourniquets may be necessary in more extensive injuries and also to secure safe transfer to definitive treatment. In the military setting where these injuries are more common, the tourniquet application has been proven to save lives [13, 14]. In the civilian setting, tourniquet application has a low complication rate; the use may lead to the same result but further studies are needed [15, 16].

The use of resuscitative endovascular balloon occlusion of the aorta (REBOA) as an adjunct in patients with noncompressible hemorrhage from the abdomen and pelvis is feasible and effectively controls hemorrhage [17]. This technique uses a minimally invasive, transfemoral balloon catheter, which is rapidly inserted retrograde and inflated for aortic occlusion, and may control inflow and allow time for hemostasis [18]. The use of REBOA in penetrating extremity vascular injury for resuscitation and later proximal control is not defined. It is important that this new technique will be evaluated rigorously and transparently before widespread adoption [19].

Principles of Wound Debridement

Dependent on the energy transfer from the foreign body to the soft tissues and underlying bone as well the density of the receiving tissues, the wound lesion will be more or less extensive. A thorough wound evaluation is therefore important as to evaluate the extent of the underlying damage. In the civilian setting, the vast majority of stab or gunshot wounds will cause limited soft tissue damage, muscle ischemia, and/or simple fractures that demand no or very limited wound debridement and bone fixation. The vascular injury can be treated early on without considering the other tissue damage.

High energy penetrating soft tissue injuries, mostly seen in the military setting, cause frequently major soft tissue damage with sometimes small and large entry and exit holes, extensive wound contamination, and soft tissue ischemia as well as compound fractures. These injuries need, in general, early restitution of blood flow of the large damage vessels, e.g.,

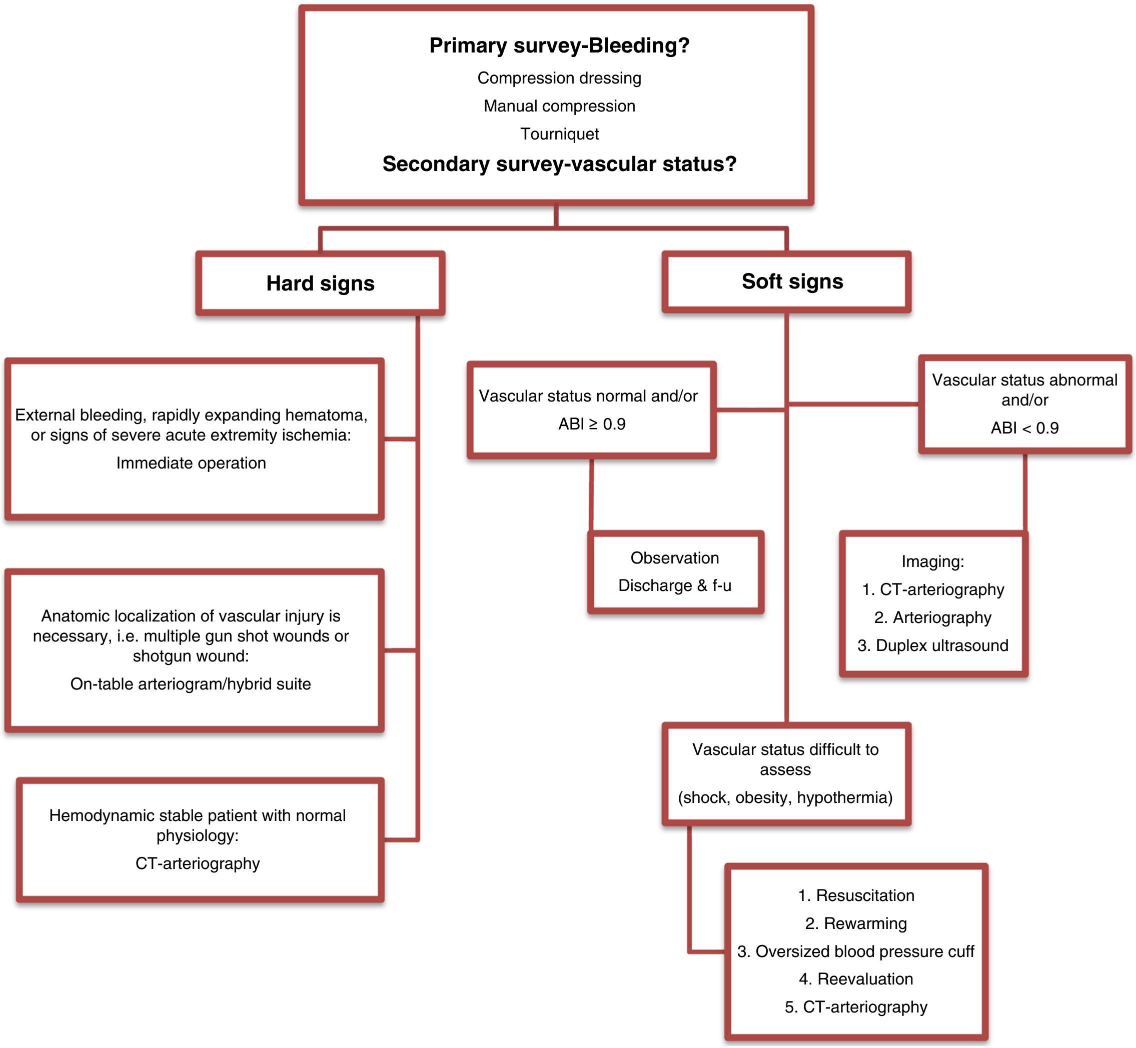


Fig. 1 Clinical presentation and management algorithm in penetrating extremity vascular trauma (modified from the Western Trauma Association) [11]

by shunts while time is consumed by initial wound debridement and necessary fracture stabilization.

Although many authors have described the wound debridement principles, they are based on empiric data, multidisciplinary consensus meetings, as no randomized control studies are available [20]. Over the years, the principles remain mainly unchanged despite the introduction of new devices, e.g., ultra-high pressure hydrosurgery and negative pressure wound treatment. The importance is that the debridement should be undertaken under adequate anesthesia, in the operation room and as soon as feasible [20].

Techniques of Debridement

The skin damage at entry or exit sites should be dealt with limited excisions, as skin is resistant and very much needed for delayed wound closure. Nevertheless, an extension of the wound incision may be necessary to allow access to deeper structures. Underlying muscle fascia should be opened up as to permit deep wound exploration and excision of necrotic or ischemic muscle. The four "C-signs" of nonviable muscle (lack of contractility, consistency, normal color, and capillary bleeding) are quite reliable in fresh wounds, but when doubtful signs are present, a more conservative attitude is appropriate. Sutures should not be used to mark injured nerves and tendons. Vascular shunts can be used until definitive repair can be achieved (please see operative management). The vascular injury is in an optimal situation repaired when the fracture is stabilized, and the wound offers viable soft tissue/muscle for cover. Definitive vascular repair in large soft tissue defects often require rotation of flaps to cover the vascular reconstruction.

The excision of loose bone fragments without any periosteal attachments should be performed as well as rinsing out dirt and loose foreign bodies. The evidence for routine exploration and removal of retained bullet or metal fragment is weak unless they are located in a joint, hand, or foot, or cause infectious problems.

Antibiotics in Penetrating Extremity Trauma

Broad-spectrum antibiotics should be given especially if open fractures or severe soft tissue injury. Antibiotic treatment should be initiated early and the length of the treatment should be short, at best only one per-operative dose [21]. The evidence for different antibiotic and prophylactic regimens according to the wound contamination is lacking although the antibiotics certainly should be targeted as much as possible toward cultured microorganism [22].

General Principles of Operative Management of the Vascular Injury

Patients with external bleeding or a rapidly expanding hematoma should undergo immediate operation. Exploration of a vascular injury is best performed under general anesthesia in the operating room or if possible in a hybrid suite. If signs of acute extremity ischemia are present and there are no other sites of hemorrhage, intravenous heparin should be administered. An operative management algorithm, slightly modified from the Western Trauma Association [23•], is presented in Fig. 2.

The entire injured extremity should be prepared and draped to ensure proximal and distal vascular control. An uninjured extremity should also be included in the operative field to allow harvesting of vein graft. A longitudinal incision that can be extended in both directions is made over the area of injury. Large hematomas can be best explored by gaining proximal control of the uninjured part of the vessel through tissue adjacent to the injury site. However, active bleeding may require an approach through the traumatic wound and direct digital control. The tourniquet is helpful to achieve proximal control in more distal extremity vascular injuries. Endovascular balloon occlusion placed under fluoroscopic guidance from uninjured femoral or brachial artery can provide temporary proximal control in more difficult situations [18, 24].

The vascular injury is assessed after proximal and distal control has been achieved. Local thrombus is removed with Fogarty balloon catheter, and systemic and/or local heparin is administered in appropriate dosage. Minimal debridement to normal vessel wall at both ends is performed. A smaller laceration is repaired primarily with continuous or interrupted technique using 5-0 to 7-0 polypropylene sutures.

If patient's physiologic status precludes immediate definitive vascular repair, e.g., other potentially life-threatening injuries or orthopedic injuries requiring fixation, a temporary intravascular shunt may be indicated [25•]. Specialized vascular shunts, such as the Javid™ or Pruitt-Inhara™ shunts, may be used if available, but a sterile nasogastric or chest tube that corresponds reasonably to the vessel inner diameter works well. Reports have described the efficacy of vascular shunts to restore distal arterial circulation but also to promote drainage on the venous side [26, 27•]. The shunt is usually left briefly in the vessel and removed when definitive vascular repair is performed. The shunt is also a reasonable bailout option before patient transfer and can remain patent for up to 24 h without systemic heparin [21].

A definitive vascular repair should be performed in a situation with more normalized physiology. Patch angioplasty with vein or synthetic graft is not a common repair technique in penetrating trauma but can be used for larger lacerations. An end-to-end anastomosis is performed if there is no excessive tension; otherwise or if significant segmental loss, an interposition graft is inserted. The primary graft choice is the greater saphenous vein from the uninjured leg. The lesser saphenous, the cephalic, or the basilic veins are good alternatives. Prosthetic grafts of Dacron or polytetrafluoroethylene (PTFE) can be used if vein material is not available. A standard completion arteriogram is performed if necessary. The vascular reconstruction should be covered with soft tissue. After vessel repair, distal vascular status should be examined and the limb assessed for eventual compartment syndrome. Early lower leg fasciotomy should liberally be applied when there has been prolonged ischemia or associated injuries [25•].

Endovascular techniques treating arterial injuries have increased dramatically during the last decade, in particular among severely injured blunt trauma patients [28, 29]. A 9-year analysis of the US National Trauma Data Bank (2002–2010) showed a statistically significant increase in endovascular procedures for penetrating trauma (0.2 to 2.3 %). There are limited data on routine use of endovascular techniques following lower extremity penetrating arterial trauma [25•]. Arterial embolization for extremity branch vessel occlusion, i.e., deep femoral artery or tibial branch bleeding, seems safe and therapeutic for selected patients [11]. Infrainguinal stent grafting for penetrating trauma has been used for treating pseudoaneurysms and arteriovenous fistulas but lacks large case series and long-term follow-up data [25•, 30]. Hemodynamically unstable patients are usually not candidates for endovascular management. However, in centers that run a 24/7 hybrid suite and can rapidly mobilize specialized staff, hemodynamically unstable patients may be considered for endovascular management [31, 32].

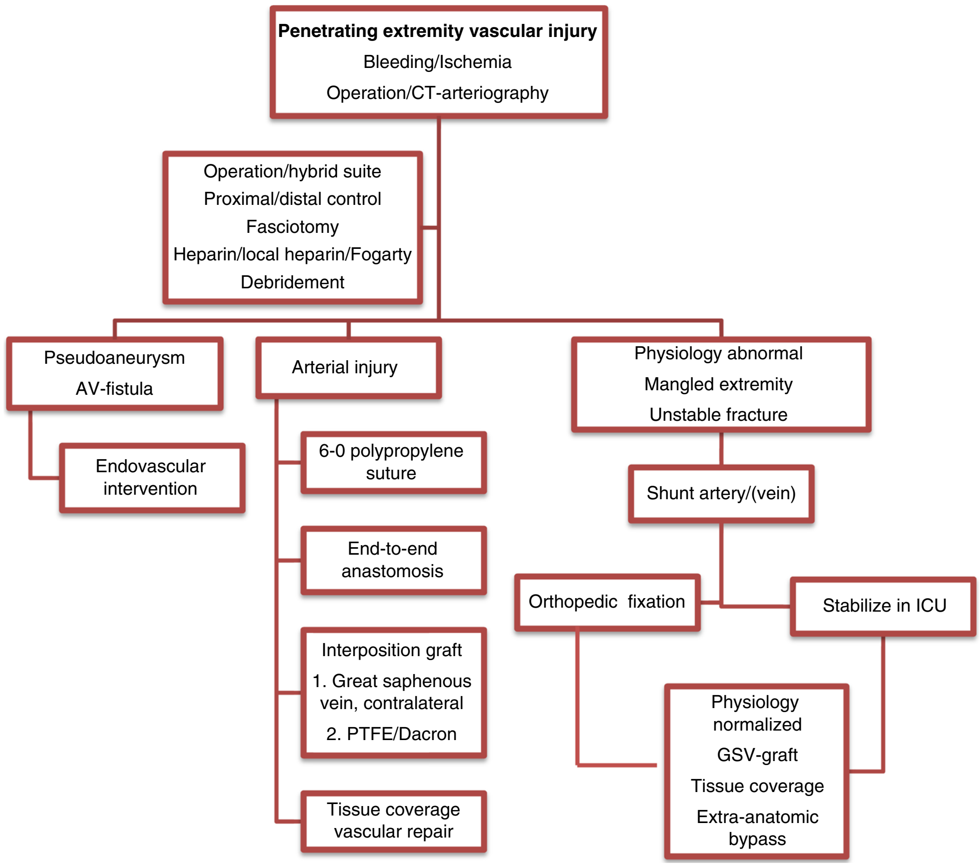


Fig. 2 Operative management algorithm in penetrating extremity vascular trauma (modified from the Western Trauma Association) [23•]

Specific Vascular Injuries

In the upper extremity, penetrating trauma mechanism is most common (73 %) and the majority of patients (78 %) suffer concomitant upper extremity injuries with soft tissue and nerve injuries being most prevalent [33]. Forearm arterial injuries are most common followed by brachial and axillary arterial injury.

Axillary Vessels

The axillary vessels are less protected than the subclavian vessels and therefore slightly more prone to injury. The penetrating trauma mechanism is clearly dominating. The first portion of the axillary artery is exposed through an infraclavicular approach starting with a horizontal incision below the midportion of the clavicle. The incision can be extended into the deltopectoral groove to expose the rest of the axillary artery. Vascular clamp for proximal control of the artery should be carefully placed without injuring the axillary vein or brachial plexus. Surgical treatment of the axillary artery is recommended with venous interposition/bypass grafting [33]. A temporary intraarterial shunt may be placed in a damage control situation. Endovascular intervention with covered stent graft can be considered in hemodynamic stable patients with pseudoaneurysm or arteriovenous fistula. A review of the medical literature from 1990 to 2012 identified ten axillary artery injuries undergoing endovascular stenting with promising early results but limited data on late follow-up [34]. In a recent retrospective study from two high-volume trauma centers, endovascular intervention of axillo-subclavian arterial injuries was associated with improved survival and lower complication rates compared to open repair using propensity score matching [35]. Case series has previously shown shorter operative time and less blood loss with an endovascular approach in selected patients with an arterial subclavian–axillary injury [36, 37].

The axillary vein should be repaired if the patient's hemodynamic situation and physiology permits. Primary repair or end-to-end anastomosis is the best alternative. If the situation is not permitting vein reconstruction or when there is more extensive venous damage, ligation of the axillary vein is acceptable with minimal long-term sequelae [38].

Brachial Artery

Although vascular injuries in the arm rarely lead to fatal bleeding, ischemic consequences are common. Penetrating and iatrogenic trauma are dominating, and the brachial artery injury is commonly accompanied with neurological and skeletal injuries [33, 39]. The upper part of the brachial artery is exposed via a longitudinal incision in the groove between the biceps and triceps muscles on the medial aspect of the arm. The incision can be extended as needed to increase proximal or distal exposure. To expose the brachial artery in the antecubital fossa, an S-shaped incision is preferred in the trauma setting. The brachial bifurcation is most easily exposed by dissecting the brachial artery more distally and there achieving proximal control of the radial or ulnar arteries.

In a damage control situation, a temporary shunt can be placed quickly. Ligation of the common brachial artery carries a 55 % amputation rate compared to 25 % below the profunda [40]. Small lacerations are repaired with interrupted 6-0 polypropylene sutures. More extensive arterial injury is repaired with a vein patch, end-to-end anastomosis, or interposition vein grafting [33].

Radial and Ulnar Artery

Approximately 95 % of arterial injuries in the forearm are due to penetrating mechanism [41]. The radial or ulnar artery in the forearm is exposed through a longitudinal incision over the course of the artery. Single arterial injury in the forearm needs no repair and ligation is reasonable. If both radial and ulnar arteries are injured or when there is an incomplete palmar arch, repair is required. The ulnar artery should preferentially be repaired because it is usually the dominating vessel [24, 41].

Lower Extremities

The most common anatomic location of penetrating trauma is the superficial femoral artery followed by the popliteal and common femoral arteries [42]. Penetrating mechanism of injury is about 80 % in the common and the superficial femoral arteries. The mechanism of popliteal artery injury is penetrating in 39–51 % of patients, and gunshot injuries dominate [43–45]. Few penetrating injuries (7 %) present with severe concomitant trauma compared to blunt popliteal injury (74 %) which is associated with higher amputation rates [43].

Femoral Artery

For exposure of the femoral vessels, a standard longitudinal incision is placed in the groin. Proximal control can be gained by exposing the external iliac artery via a separate oblique incision above and parallel to the inguinal ligament. The femoral vessels can also be controlled by creating an opening just above the inguinal ligament, but in a more difficult situation, it is reasonable to just cut the ligament to gain exposure [46]. Mid-thigh vessel injuries are approached from a longitudinal incision over the anterior border of the sartorius muscle. The superficial femoral vessels are exposed distally by dividing the adductor magnus tendon.

The femoral arteries should, in general, be repaired. Amputation rate after ligature is high—around 80 and 55 % following ligation of the common femoral artery and the superficial femoral artery, respectively [47]. The main branch of the deep femoral artery should preferably be repaired, but its branches can be ligated without morbidity.

Primary repair is performed if possible. Saphenous vein interposition grafting is the best procedure for more severe injuries of the superficial femoral artery (Fig. 3). For the common femoral artery, the vein diameter may not be adequate. A synthetic graft is here an acceptable alternative and can also be used if vein is not available, e.g., due to extensive soft tissue injury. The proximal deep femoral artery is repaired if the patient's physiology permits with short interposition graft or reimplantation to the superficial femoral artery.

Endovascular stentgraft in the superficial femoral artery has been used in small patient series with good results [48] (Fig. 4).

Popliteal Artery

In the trauma setting, exposure of the popliteal artery is best and safest accomplished via a medial approach. An isolated penetrating injury directly behind the knee can be approached from a posterior S-shaped incision [49]. Reverse saphenous interposition/bypass grafting is the most common surgical repair [45]. Primary repair is rare and require a limited clean tangential laceration, mostly from stab wounds [50]. Vein patch angioplasty may be used to avoid stenosis due to the relatively small popliteal artery. Amputation rate after ligation of the popliteal artery is around 70 % [47]. There is no solid data describing endovascular management in penetrating popliteal injuries, and we believe that stent grafts in this area may be at high risk of thrombosis [48, 51].

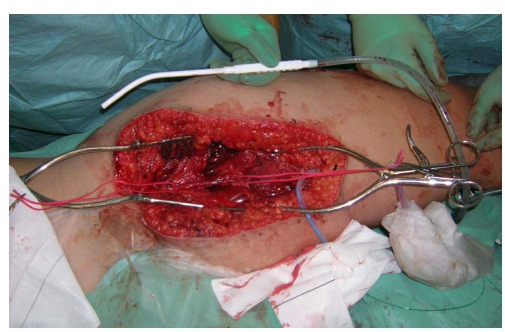


Fig. 3 Stabbed superficial femoral artery repaired with venous interposition graft

Infrapopliteal Arteries

Isolated occlusive injury to one infrapopliteal artery rarely results in limb ischemia [24]. As a general rule, the anterior or the posterior tibial artery must be intact. Also, injury to the tibioperoneal trunk usually requires vascular repair [24]. Extravasation or pseudoaneurysm can be treated with open ligation or with angiographic embolization [11] (Fig. 5). Computed tomography angiography (CTA) or duplex ultrasound should be performed 3–5 days postembolization to rule out acute pulsatile hematoma or pseudoaneurysm developing from distal backflow [11].

Femoral and Popliteal Veins

There has been an ongoing discussion on how to best manage extremity venous injury [38, 41, 46, 47]. Injury to the common femoral and the popliteal vein should preferably be repaired in order to improve the outcome of arterial reconstruction and to minimize postoperative swelling and compartment syndrome. In patients with abnormal physiology and other life-threatening injuries, ligation of extremity venous injuries is still recommended. Venous shunting should be considered in a damage control situation.

In penetrating trauma, venous injury is most commonly concomitant to adjacent arterial injury. More recent war surgery data suggest that limb salvage benefits from venous

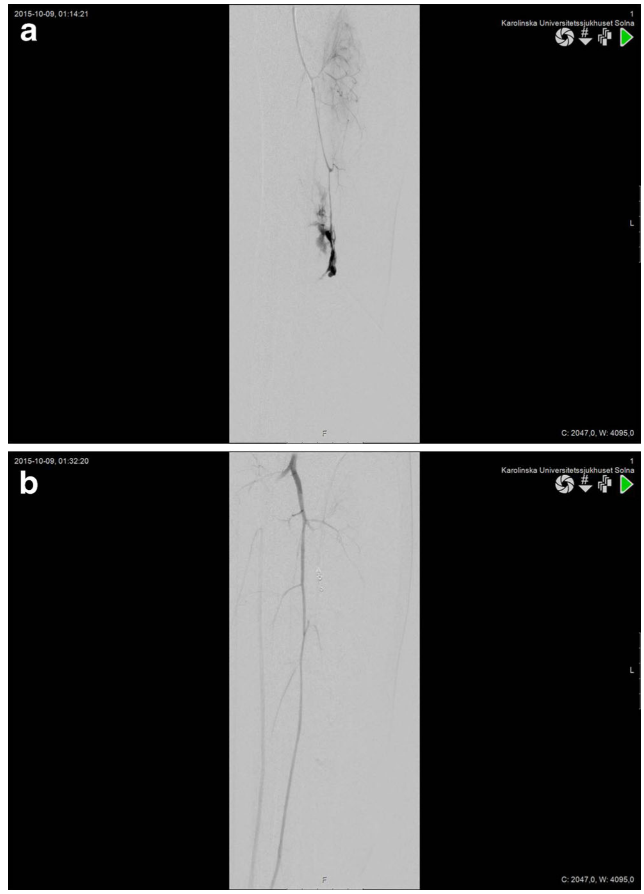
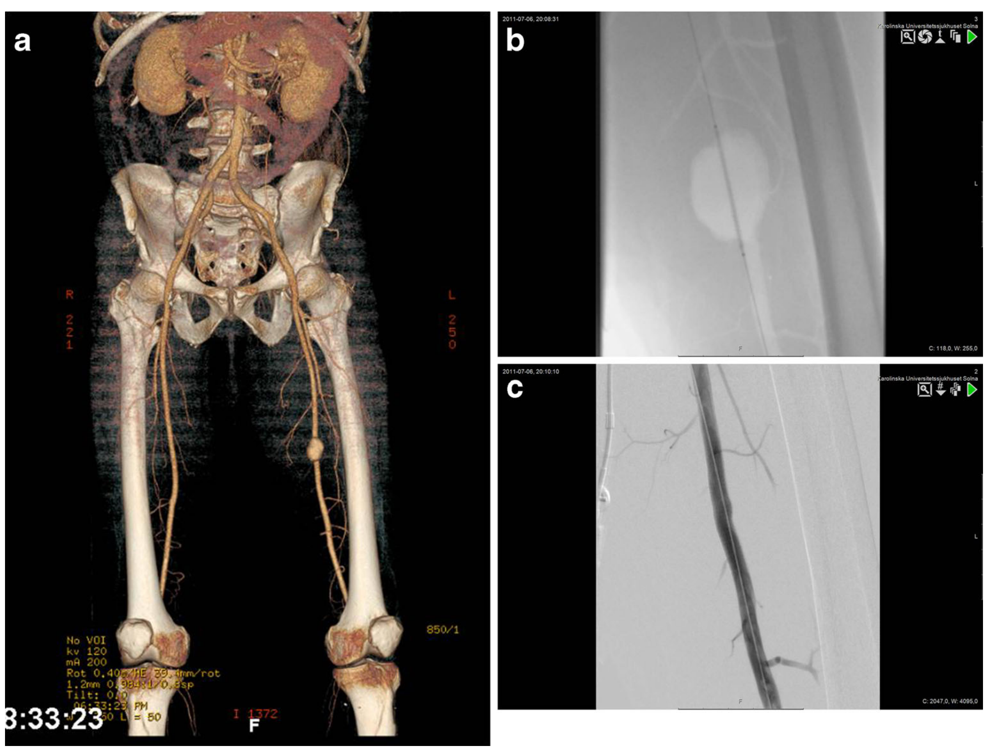


Fig. 5 Extravasation posterior tibial artery after gunshot trauma to the lower extremity. Angioembolization of tibial posterior artery was performed

Fig. 4 Endovascular stentgraft treatment of a pseudoaneurysm in the superficial femoral artery after stab wound



repair in combined arterial and venous injuries [52, 53]. In a recent review by Williams and Clouse, vein repair was recommended for isolated extremity injury or vascular injury with other non-life-threatening injuries [54]. In multiple vascular injuries, only simple vein repair by single or running suturing is performed. In patients with vascular injury and other life-threatening injuries or hemodynamic instability, there is, in general, no indication for vein repair and ligation should be done. Delayed venous repair could be considered if reasonable.

Minor venous injuries are repaired with lateral suture technique, but not more than 50 % luminal narrowing is accepted [54]. Vein patch angioplasty should be considered for larger lacerations, and for segmental loss, an interposition graft is required. Autogenous vein is used if the right size match, and if there is no contamination and good tissue coverage, a ringed PTFE graft may be considered. The long-term patency of prosthetic grafts can definitively be questioned, but in our own small experience, they can serve as a bridge to improved arterial patency and minimized postoperative swelling. Spiral grafts have been described and they are time-consuming. Even in isolated injuries, a more extensive venous injury is probably best treated by ligation.

Outcome

In isolated lower extremity vascular trauma, mortality is more common in injuries to the common and superficial femoral arteries (4.8 %), than in injuries to the popliteal or tibial arteries (1.4 %) [42]. However, popliteal artery injury is associated with a higher incidence of amputation [50]. The secondary amputation rate after penetrating lower extremity trauma is about 5 % [55•]. A review of 24 civilian published case series of penetrating popliteal artery injuries resulted in a 10.5 % overall amputation rate and seems to be even lower in contemporary reports [45, 50]. Prognostic factors for amputation following surgical repair of lower extremity trauma include multiple arterial injuries, associated major soft tissue injury and fracture, compartment syndrome, ischemia time exceeding 6 h, and age over 55 years [55•].

Long-term vascular patency is, in general, very good for femoral artery repair [24]. For popliteal injuries, the long-term results are dependent on the extent of associated neurologic and musculoskeletal injury [41]. Mortality and amputation are rare following axillary and brachial injuries.

Conclusion

Patients with penetrating extremity vascular injury and hard clinical signs should undergo immediate surgery. Tourniquet has a low complication rate and may be used as hemorrhage control during early resuscitation, transfer, and for proximal vascular control during surgery. If the arterial injury needs to be localized, on-table arteriogram in the operating room or in a hybrid suite is performed. Computed tomographic angiography can also be used if patient's condition permits to evaluate penetrating extremity vascular injury. An intravascular shunt may be inserted in a damage control situation. Definitive arterial and venous repair is performed with standard vascular techniques. There is a role for endovascular techniques for specific and limited arterial injuries after penetrating trauma, but the technique needs further evaluation.

Compliance with Ethical Standards

Conflict of Interest Drs. Wahlgren and Riddez declare no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance

1. National Trauma Data Bank, NTDB Annual report 2015.
2. Trauma Register 2014. Section NIS of the German Trauma Society DGU.
3. Swedish Trauma Register. Annual report 2014, www.swetrau.se.
4. Kruger A, Florido C, Braunish A, Walther E, Han Yilmaz T, Doll D. Penetrating arterial trauma to the limbs; outcome of a modified protocol. World J Emerg Surg. 2013;8:51.
5. Feliciano DV. Evaluation and treatment of vascular injuries. In: Browner BD, Jupiter JB, Levine AM, Trafton PG, Krettek C, editors. Skeletal trauma. Basic science, management and reconstruction. Philadelphia: Saunders Elsevier; 2009. p. 323–40.
6. Moore E, Malangoni M, Cogbill T, Peterson N, Champion H, Jurkovich G, et al. Organ injury scaling VII: cervical, peripheral vascular, adrenal, penis, testis, and scrotum. J Trauma. 1996;41:523–4.
7. Dennis JW, Frykberg ER, Veldenz HC, Huffman S, Menawat S. Validation of nonoperative management of occult vascular injuries and accuracy of physical examination alone in penetrating extremity trauma; 5 to 10 year follow-up. J Trauma. 1998;44:243–53.
8. Soto JA, Munera F, Morales C, Lopera J, Holguin D, Guarin O, et al. Focal arterial injuries of the proximal extremities: helical CT arteriography as the initial method of diagnosis. Radiology. 2001;218:188–94.
9. Inaba K, Potzman J, Munera F, McKenney M, Munoz R, Rivas L, et al. Multi-slice CT angiography for arterial evaluation in the injured lower extremity. J Trauma. 2006;60:502–6.
10. Miller-Thomas M, West C, Cohen A. Diagnosing traumatic arterial injury in the extremities with CT Angiography: pearls and pitfalls. RadioGraphics. 2005;25:S133–42.

11. Feliciano DV, Moore FA, Moore EE, Davis JW, West MA, Davis JW, et al. Evaluation and management of peripheral vascular injury. Part 1.Western Trauma Association/Critical Care Decisions in Trauma. J Trauma. 2011;70:1551–6.
12. American College of Surgeons Committee on Trauma: Advanced Trauma Life Support for Doctors, ATLS Student Course Manual Chicago: American College of Surgeons; 2008.
13. Kragh JF, Walters TJ, Baer DG, Fox CJ, Wade CE, Salinas J, et al. Survival with emergency tourniquet use to stop bleeding in major limb trauma. Ann Surg. 2009;249:1–7.
14. Kragh JF, Littrel MI, Jones JA, Walters TJ, Baer DG, Wade CE, et al. Battle casualty survival with emergency tourniquet use to stop limb bleeding. J Emerg Med. 2011;41:590–7.
15. Inaba K, Siboni S, Resnick S, Zhu J, Wong MD, Haltmeier T, et al. Tourniquet use for civilian extremity trauma. J Trauma Acute Care Surg. 2015;79(2):232–7.
16. Passos E, Dingley B, Smith A, Engels P, Ball C, Faidi S, et al. Tourniquet use for peripheral vascular injuries in the civilian setting. Injury. 2014;45:573–7.
17. Brenner ML, Moore LJ, DuBose JJ, Tyson GH, McNutt MK, Albarado RP, et al. A clinical series of resuscitative endovascular balloon occlusion of the aorta for hemorrhage control and resuscitation. J Trauma Acute Care Surg. 2013;75(3):506–11.
18. Stannard A, Eliason JL, Rasmussen TE. Resuscitative endovascular balloon occlusion of the aorta (REBOA) as an adjunct for hemorrhagic shock. J Trauma. 2011;71(6):1869–72.
19. Biffl WL, Fox CJ, Moore EE. The role of REBOA in the control of exsanguinating torso hemorrhage. J Trauma Acute Care Surg. 2015;78(5):1054–8.
20. Guthrie HC, Clasper JC, Kay AR, Parker PJ, on behalf of the Limb Trauma and Wounds Working Groups, ADMST. Initial Extremity War Wound Debridement: A Multidisciplinary Consensus. J R Army Med Corps. 2011;157:170–5.
21. Boffard KD. Manual of Definitive Surgical Trauma Care. 3rd ed. Hodder Arnold; 2011.
22. Murray CK, Hsu JR, Solomkim JS, Keeling JJ, Andersen RC, Ficke JR, et al. Prevention and management of infections associated with combat-related extremity injuries. J Trauma. 2008;64:S239–51.
23.• Feliciano DV, Moore EE, West MA, Moore FA, Davis JW, Cocanour CS, et al. Western Trauma Association critical decisions in trauma: evaluation and management of peripheral vascular injury, part II. J Trauma Acute Care Surg. 2013;75(3):391–7. **Guidelines for management of vascular trauma**.
24. Patel KR, Rowe VL. Vascular trauma: Extremity. In: Cronenwett JL, Wayne Johnston K, editors. Rutherford's Vascular Surgery. 7th ed. Philadelphia: Saunders Elsevier; 2010. p. 2343–60.
25.• Fox N, Rajani RR, Bokhari F, Chiu WC, Kerwin A, Seamon MJ, et al. Evaluation and management of penetrating lower extremity arterial trauma: an Eastern Association for the Surgery of Trauma practice management guideline. J Trauma Acute Care Surg. 2012;73(5 Suppl 4):S315–20. **Evidenced based guidelines for evaluation and management of penetrating lower extremity arterial trauma**.
26. Subramanian A, Vercruysse G, Dente C, Wyrzykowski A, King E, Feliciano DV. A decade's experience with temporary intravascular shunts at a civilian level I trauma center. J Trauma. 2008;65(2):316–24.
27.• Percival TJ, Rasmussen TE. Reperfusion strategies in the management of extremity vascular injury with ischaemia. Br J Surg. 2012;99 Suppl 1:66–74. **Review of extremity ischemia and reperfusion following vascular trauma**.
28. Reuben BC, Whitten MG, Sarfati M, Kraiss LW. Increasing use of endovascular therapy in acute arterial injuries: analysis of the National Trauma Data Bank. J Vasc Surg. 2007;46(6):1222–6.
29. Branco BC, DuBose JJ, Zhan LX, Hughes JD, Goshima KR, Rhee P, et al. Trends and outcomes of endovascular therapy in the management of civilian vascular injuries. J Vasc Surg. 2014;60(5):1297–307.
30. Alam HB, DiMusto PD. Management of lower extremity vascular trauma. Curr Trauma Rep. 2015;1:61–8.
31. Jacks R, Degiannis E. Endovascular therapy and controversies in the management of vascular trauma. Scand J Surg. 2014;103(2):149–55.
32. Trellopoulos G, Georgiadis GS, Aslanidou EA, Nikolopoulos ES, Pitta X, Papachristodoulou A, et al. Endovascular management of peripheral arterial trauma in patients presenting in hemorrhagic shock. J Cardiovasc Surg. 2012;53(4):495–506.
33. Franz RW, Skytta CK, Shah KJ, Hartman JF, Wright ML. A five-year review of management of upper-extremity arterial injuries at an urban level I trauma center. Ann Vasc Surg. 2012;26(5):655–64.
34. DuBose JJ, Rajani R, Gilani R, Arthurs ZA, Morrison JJ, Clouse WD, et al. Endovascular management of axillo-subclavian arterial injury: a review of published experience. Injury. 2012;43(11):1785–92.
35. Branco BC, Boutrous ML, DuBose JJ, Leake SS, Charlton-Ouw K, Rhee P, et al. Outcome comparison between open and endovascular management of axillosubclavian arterial injuries. J Vasc Surg. 2015. doi:10.1016/j.jvs.2015.08.117.
36. Xenos ES, Freeman M, Stevens S, Cassada D, Pacanowski J, Goldman M. Covered stents for injuries of subclavian and axillary arteries. J Vasc Surg. 2003;38(3):451–4.
37. du Toit DF, Strauss DC, Blaszczyk M, de Villiers R, Warren BL. Endovascular treatment of penetrating thoracic outlet arterial injuries. Eur J Vasc Endovasc Surg. 2000;19(5):489–95.
38. Timberlake GA, Kerstein MD. Venous injury: to repair or ligate, the dilemma revisited. Am Surg. 1995;61:139–45.
39. DuBose JJ, Savage SA, Fabian TC, Menaker J, Scalea T, Holcomb JB, et al. The American Association for the Surgery of Trauma PROspective Observational Vascular Injury Treatment (PROOVIT) registry: multicenter data on modern vascular injury diagnosis, management, and outcomes. J Trauma Acute Care Surg. 2015;78(2):215–22.
40. Fields CE, Latifi R, Ivatury RR. Brachial and forearm vessel injuries. Surg Clin N Am. 2002;82(1):105–14.
41. Sise MJ, Shackford SR. Extremity vascular trauma. In: Rich NM, Mattox KL, Hirshberg A, editors. Vascular trauma. 2nd ed. Philadelphia: Elsevier Saunders; 2004.
42. Kauvar DS, Sarfati MR, Kraiss LW. National trauma databank analysis of mortality and limb loss in isolated lower extremity vascular trauma. J Vasc Surg. 2011;53(6):1598–603.
43. Lang NW, Joestl JB, Platzer P. Characteristics and clinical outcome in patients after popliteal artery injury. J Vasc Surg. 2015;61(6):1495–500.
44. Mullenix PS, Steele SR, Andersen CA, et al. Limb salvage and outcomes among patients with traumatic popliteal vascular injury: an analysis of the National Trauma Data Bank. J Vasc Surg. 2006;44:94–100.
45. Sciarretta JD, Macedo FI, Otero CA, Figueroa JN, Pizano LR, Namias N. Management of traumatic popliteal vascular injuries in a level I trauma center: a 6-year experience. Int J Surg. 2015;18:136–41.
46. Hirshberg A, Mattox KL. Top Knife. The Art and Craft of Trauma Surgery. Shrewsbury: Tfm Publishing Ltd; 2006.
47. Wahlberg E, Olofsson P, Goldstone J. Emergency vascular surgery-practical guide. Heidelberg: Springer; 2007.
48. Stewart DK, Brown PM, Tinsley Jr EA, Hope WW, Clancy TV. Use of stent grafts in lower extremity trauma. Ann Vasc Surg. 2011;25(2):264.e9–13.

49. Wind GG, Valentine JR. Anatomic exposures in vascular surgery. 3rd ed. Philadelphia: Wolters Kluwer/Lippincott Williams & Wilkins; 2013.
50. Frykberg ER. Popliteal vascular injuries. Surg Clin N Am. 2002;82(1):67–89.
51. Bürger T, Meyer F, Tautenhahn J, Halloul Z, Fahlke J. Initial experiences with percutaneous endovascular repair of popliteal artery lesions using a new PTFE stent-graft. J Endovasc Surg. 1998;5(4):365–72.
52. Clouse WD, Rasmussen TE, Peck MA, Eliason JL, Cox MW, Bowser AN, et al. In-theater management of vascular injury: 2 years of the Balad Vascular Registry. J Am Coll Surg. 2007;204(4):625–32.
53. Woodward EB, Clouse WD, Eliason JL, Peck MA, Bowser AN, Cox MW, et al. Penetrating femoropopliteal injury during modern warfare: experience of the Balad Vascular Registry. J Vasc Surg. 2008;47(6):1259–64.
54. Williams TK, Clouse WD. Current concepts in repair of extremity venous injury. J Vasc Surg Venous Lymphat Disord. 2015. doi:10.1016/j.jvsv.2015.07.003.
55.• Perkins ZB, Yet B, Glasgow S, Cole E, Marsh W, Brohi K, et al. Meta-analysis of prognostic factors for amputation following surgical repair of lower extremity vascular trauma. Br J Surg. 2015;102(5):436–50. **A systematic review identifying prognostic factors for amputation following surgical repair of lower extremity vascular trauma**.