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AUTHORS

Matthew M. Gangidine, MD,
Emergency Medicine Resident, Department of Emergency Medicine, Boonshoft School of Medicine, Wright State University, Wright-Patterson Air Force Base, OH

Derek M. Sorensen, MD, FACEP,
Assistant Professor, Departments of Emergency Medicine and Surgery, Boonshoft School of Medicine, Wright State University, Wright-Patterson Air Force Base, OH

PEER REVIEWER

Howard A. Werman, MD, FACEP,
Professor of Clinical Emergency Medicine, Ohio State University, Columbus

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RELIAS MEDIA

Penetrating Extremity Trauma: Part I

Penetrating extremity trauma is a potentially devastating injury that must be identified and managed expeditiously. Early hemorrhage control may be life-saving. This two-part article comprehensively addresses the approach and management of penetrating extremity trauma, highlighting controversies and advances.

— Ann M. Dietrich, MD, Editor

Introduction

Penetrating extremity trauma presents both a significant challenge and a significant opportunity to the trauma care provider. These injuries can represent an important cause of morbidity and mortality in victims of penetrating trauma; yet with the proper approach, the emergency and trauma clinician will be poised to intervene in a meaningful way, and effect superior results for the patient. A methodology focused on prompt bleeding control and resuscitation, physical examination with imaging as needed, evaluation for vascular and concomitant injury, and definitive management as indicated provides the means to salvage both life and limb.

Epidemiology

Unintentional injury is now the third leading cause of death in the United States across all age groups, and it remains the number one cause of death for patients 1-44 years of age.[1] As with the parent category of trauma at large, penetrating injury of the extremities predominantly affects males (~80%) and younger people, about 30 years of age on average.[2,3] When considering the evaluation and treatment options for elderly patients with penetrating injuries, special consideration must be given to the possibility of preexisting peripheral vascular disease.[4]

Penetrating injury comprises a combined 8.3% of traumatic injuries, consisting of roughly equal portions of ballistic injuries (4.2%) and cut/pierce (stab) injuries (4.1%).[5] Injury of any type to the lower extremity is present in 40% of trauma cases, and injury to the upper extremity is present in 32%.[5] Analysis of peripheral vascular trauma in U.S. urban civilian trauma centers revealed that 75-80% of extremity injuries are due to penetrating trauma.

On the military front, with body armor to protect a great deal of the head and torso, extremity trauma is a disproportionate burden. Analyses of wounds sustained by troops in the earlier years of Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) demonstrated a 54% prevalence of extremity wounds in general, with 53% penetrating soft-tissue wounds.[6,7] Subsequent reexamination in later years of the war yielded a similar result,

EXECUTIVE SUMMARY

- Patients with penetrating extremity trauma die from hemorrhage. In the civilian setting especially, the hemorrhage predominantly occurs from named arterial vessels.
- Since stab or cut wounds lack any of the cavitation effects or potential for projectile redirection encountered with gunshot wounds, the evaluation of stab or cut wounds tends to be much clearer.
- Machete-inflicted injuries are accompanied by a 69% fracture rate and the need for neurovascular or orthopedic operative repair in 85% of cases.
- A quaternary pattern of injury typically is described for blast victims. In this classification system, secondary blast injuries consist of the penetrating injuries caused by fragments from the explosive itself or from the environment that are propelled outward by the blast. Because of the concomitant primary (direct blast pressure), tertiary (collision with environment), and quaternary (thermal effects) injuries that are present, additional management considerations are necessary.
- Certain injury characteristics portend a worse prognosis in the setting of penetrating extremity trauma. The largest risk for increased morbidity (primarily measured in the need for amputation) or mortality is the injury burden sustained: injury to vessels, injury to proximal/larger vessels, and injury to overall mass of tissue.
- A chief clinical concern is the maximum time of ischemia endured prior to significant irreversible damage (leading to some functional deficit or potential amputation). At six hours, only 10% of patients will have irreversible damage; by 12 hours, 90% will have irreversible damage. Six hours is a common goal for the upper limit of time to restoration of flow.
- The Shock Index (SI) is calculated by dividing heart rate (HR) by systolic blood pressure (SBP): SI = HR/SBP. It may aid in the detection of even well-compensated sick patients, whose vitals may not yet appear overtly concerning. A shock index greater than 0.9 or 1 has been demonstrated to correlate with increased mortality and the need for massive transfusion. An increase in SI from the field to the emergency department, especially if ≥ 0.3, portends a significant increase in mortality.
- Previously taught first-aid techniques regarding pressure points and extremity elevation are no longer recommended.
- Indications for tourniquet placement include the presence of bleeding in an extremity wound that is not easily controlled by direct pressure and/or that has the potential to be lethal. The tourniquet should be left in place until the patient is at a level of care where definitive surgical management is available. In general, less than two hours is regarded as a safe tourniquet time.

with extremity wounds comprising 52% of combat wounds.[8] In all of these instances, explosions (which typically include both blunt and penetrating components) accounted for about three-fourths of the mechanisms.[6,7,8] The characterization and treatment of extremity injury, and peripheral vascular injury in particular, have advanced historically through the crucible of wartime surgery. Treatment advances extend back to Ambrose Pare in the 1500s with the promulgation of amputation, to the Vietnam Vascular Registry of Dr. Norman Rich, to the aforementioned studies and others drawn from the Joint Theater Trauma Registry in the current Global War on Terror.[4,6-11]

Civilian estimates of the incidence of vascular trauma have closely approximated those of historical military operations up through the Vietnam era, at a rate of about 2%.[9] However, more recently in the Global War on Terror, the military has seen an increased incidence of vascular trauma up to 12%, while the civilian rate has remained roughly the same.[4,9] This may be attributable in part to an increased prevalence of explosive (rather than ballistic) mechanisms in the military environment, and possibly increased survivability (in part due to shorter transport times) for wounds that previously would have bled out on the battlefield.[9]

Etiology

When discussing penetrating extremity trauma, the focus lies with vascular trauma in particular. As Dr. David Feliciano astutely remarked, "In many ways, all life-threatening trauma other than that to the brain or heart is vascular trauma."[12] Patients with penetrating extremity trauma die from hemorrhage. In the civilian setting especially, the hemorrhage predominantly occurs from named arterial vessels. Therefore, this review will focus primarily on the evaluation and management of vascular injury, with its acute threat to life and limb. Additional consideration will be given to associated tissue trauma to skin, muscles, bones, and nerves. The approach to the penetrated extremity is one of identifying vascular injury and instituting hemorrhage control first and foremost.

Stab (knife) and ballistic (firearm) injuries are the two predominant causes of penetrating extremity trauma, and they will be the focus of this article. Blast injuries, which include both penetrating and blunt components, are present mainly in wartime injuries, but are increasingly relevant in civilian communities as well.

Stab Injuries

Stab wounds account for an estimated 30% of penetrating extremity injuries in the United States, although the percentage is higher in countries with more limited access to firearms.[13] Since stab or cut wounds lack any of the cavitation effects or potential for projectile redirection encountered with gunshot wounds, the evaluation of stab or cut wounds tends to be much clearer. The trajectory of the wounds and, therefore, any likely injured or at-risk structures can be ascertained more confidently based on the wound itself, although the depth of penetration often is more difficult to assess. The imparted kinetic energy also is lower with stab wounds than with gunshot wounds, resulting in greatly reduced surrounding tissue destruction. A London analysis of knife injuries (81% of which were assaults) revealed that 64% of these wounds occurred in the extremities.[14] The vast majority (91%) of these injuries were superficial and involved no accompanying neurovascular injury.[14]

Injury and even death due to self-inflicted wounds is another unfortunate reality. Most commonly, these wounds are incisional and are found in the upper extremities.[15] On the more severe end of this spectrum are reports of machete-inflicted injuries, which are accompanied by a 69% fracture rate and the need for neurovascular or orthopedic operative repair in 85% of cases.[16]

Ballistic Injuries

Approximately one-half of resultant peripheral vascular trauma from penetrating injuries is caused by missiles from handguns with low muzzle velocity and low kinetic energy.[13] The physics and resulting tissue destruction caused by gunshot wounds is governed primarily by the transmission of kinetic energy, which is equal to one-half of the mass of the object times its velocity squared. Thus, the speed of a projectile has a disproportionate effect on the energy it carries and imparts. Handguns are responsible for the vast majority of gunshot wounds in the United States, inflicting up to 80% of fatal injuries, and 90% of nonfatal injuries.[17] High-velocity weapons, such as hunting and assault rifles, deliver on the order of eight to five times the amount of energy as handguns, respectively.[18] Although hunting rifles impart more damage per shot than military-grade rifles, the latter are considered more deadly. Mostly this is because overall lethality is related more directly to its "rounds on target," and the fact that the increased recoil and decreased firing rate of a hunting rifle diminish the weapon's accuracy and speed.[18] For this reason, many have advocated for an assault rifle ban as a common-sense measure to decrease potential gun violence, especially in the form of mass shooting incidents.[19] In the military setting, these high-energy injuries predominate.

A bullet fired with sufficient energy not only causes damage directly, but also does so indirectly through the cavitation effect as energy is transferred through to surrounding tissue via a pressure wave.[18,20,21] The skin and muscle that primarily bear these cavitation effects in an extremity sustain less damage due to their higher tensile strength. Solid organs bearing similar injuries can be completely shattered.[18,19] As further evidence of the indirect traumatic effects of high-velocity wounds, combat wounds have shown a 12% rate of vascular injury in extremity wounds, compared to about a 2% incidence with civilian trauma. Additionally, 35% of vascular injuries in combat involve concomitant fractures.[22]

Shotgun wounds are a less common cause of peripheral vascular injury, accounting for 5% of cases.[13] Shotguns may discharge a variable number of pellets depending of the type of ammunition used, commonly ranging from eight (buckshot) up to hundreds (birdshot).[18,23] Likewise, wounding is variable. Patients sustaining injury from buckshot should be considered to have sustained multiple "regular" gunshot wounds, while patients who sustain injuries from birdshot, if it is at long-range (i.e., > 7 yards), typically will not even experience penetration of the fascia.[18] A unique but reported delayed complication of shotgun injuries is pellet emboli, in which the pellets either enter a vein and travel proximally to the heart and then lungs or enter an artery with subsequent distal occlusion.[23-25] Shotgun injuries carry the propensity to impart a greater degree of concomitant bone and soft tissue destruction compared to other penetrating injuries, especially when the shotgun is fired at closer range.

Blast Injury

Blast injuries inflict significant penetrating trauma to the extremities. A report on extremity wounds in OIF/OEF earlier in the war noted that explosive munitions accounted for 75% of the mechanisms of injury sustained by troops.[6] Blast injury is encountered most commonly in the military environment, but it is an injury pattern the civilian provider also must be prepared to manage increasingly as the result of the unfortunate but real threat of domestic terrorism, as well as other less malicious but equally destructive events, such as industrial accidents. Fireworks are another source of such injuries on the home front.[26]

Table 1. Risk Factors for Primary Amputation

Most lethal injuries were proximal wounds in the lower extremities, leading to exsanguination.

- Open fractures
- Prolonged ischemia
- Significant contamination
- Nerve transection
- Lower (vs. upper) extremity injury

A quaternary pattern of injury typically is described for blast victims.[27-29] In this classification system, secondary blast injuries consist of the penetrating injuries caused by fragments from the explosive itself or from the environment that are propelled outward by the blast. Because of the concomitant primary (direct blast pressure), tertiary (collision with environment), and quaternary (thermal effects) injuries that are present, additional management considerations are necessary. However, the management principles for the penetrating trauma aspect of these wounds is the same as for any other penetrating injury. These injuries can be particularly devastating; blast-induced vascular trauma with concomitant fracture has an overall amputation rate of 77%.[30]

Pathophysiology

Determinants of Morbidity and Mortality

Certain injury characteristics portend a worse prognosis in the setting of penetrating extremity trauma. The largest risk for increased morbidity (primarily measured in the need for amputation) or mortality is the injury burden sustained: injury to vessels, injury to proximal/larger vessels, and injury to overall mass of tissue.[31] A civilian analysis of deaths from isolated penetrating extremity trauma demonstrated that most lethal injuries were proximal wounds in the lower extremities, leading to exsanguination.[32] Additional risk factors for primary amputation include open fractures, prolonged ischemia, significant contamination, nerve transection, and lower (vs. upper) extremity injury.[22] (*See Table 1.*) Concomitant burn and venous injuries present additional challenges.[33] The amount of time from the initial injury to the restoration of flow is the most critical prognostic factor.[34] Associated hypovolemic shock exacerbates both local extremity tissue injury secondary to anoxia and leads to a higher incidence of multi-organ failure. Amputation in the upper extremity is relatively less common than in the lower extremity, likely because of the more extensive collateral circulation around the shoulder and elbow.[34]

A Word on Blunt Trauma

Although this review focuses on penetrating trauma as the primary mechanism of injury, many of the concepts translate to the management of blunt extremity trauma as well. Blunt extremity trauma typically portends a worse prognosis and higher morbidity overall when compared with a penetrating mechanism, with an amputation rate that is 2.5-10 times higher.[2,13] In large part, this is due to higher-energy mechanisms (predominantly high-speed motor vehicle crashes), with a greater degree of overall tissue damage burden. An exception to the poorer prognosis with blunt injury is in the military population subjected to high-velocity ballistic and blast injuries.

Vascular Injury Classification and Implications

Several groupings for vascular trauma have been characterized.[13,23] One useful system groups the injury patterns into occlusive and nonocclusive injuries.[23]

Occlusive injuries are more likely to be encountered in the context of penetrating trauma. The most common manifestation of occlusive injury is transection, which effectively eliminates distal flow and has the potential for exsanguinating hemorrhage, depending on surrounding tissue damage. Thrombosis may manifest acutely or in a delayed fashion up to months after the initial injury, as damaged vessel intima creates a nidus for thrombus formation. Spasm is particularly common in younger patients and may result in loss of flow as well. Vasospasm is a physiologic response to reduce hemorrhage in the setting of concomitant transection and is mediated, in part, by hemoglobin acting on exposed vessel wall.[34,35] The associated physics demonstrates the profound effect spasm can have: For a given radius of a vessel, the cross-sectional area is affected to the second power, and the flow rate is affected to the fourth power (Poiseuille's law). Therefore, a 50% reduction in vessel diameter will cause a 75% reduction in area and a 94% reduction in flow. Spasm typically is reversible. It may cause ischemia through the aforementioned flow reduction, but should only be an angiographic diagnosis and one of exclusion.

Nonocclusive injuries may or may not lead to decreased distal blood flow. When these injuries do not decrease distal blood flow, they may escape initial detection. When this is the case, any associated damage is likely to be minimal and self-limited. However, delayed complications still are possible, and identification of these occult injuries is part of what makes follow-up so important, since up to 4% of these patients eventually will require delayed intervention.[13] Conversely, up to 99% of these injuries go on to heal or remain asymptomatic.[34,36]

An intimal flap is one form of nonocclusive injury. Flow is not altered by small manifestations of this phenomenon, but this disruption may serve as a nidus for thrombus. Studies from as far back as the Korean War have demonstrated that some degree of histologic damage is present even in normal-appearing vessels (which may occur as a result of the cavitation effect with high-velocity projectiles, for example). However, subsequent work has confirmed that there is no need to treat or debride grossly normal vessel.[4,37]

Pseudoaneurysm occurs when there is complete disruption through all three layers of a vessel wall (intima, media, adventitia), and hemorrhage is contained by surrounding tissue. The artery remains patent, and blood flows freely in and out of the aneurysm (often producing an audible bruit and/or a palpable thrill on exam). The rare but distinct possibility of distal emboli coming from this pocket also exists.[15,23] Over time, the pseudoaneurysm may continue to expand under pressure, causing compression or erosion into nearby structures. By comparison, a true aneurysm involves stretching of all three layers of the vessel wall and is rare in trauma.

Dissection (propagation of a false lumen through the media of a vessel wall) is another possible injury pattern, but one that is uncommon with penetrating extremity trauma. Arteriovenous fistulae (AVF) occur when an adjacent artery and vein are injured, with an extra-anatomic passage formed between the two. Blood flows from high-pressure artery to low-pressure vein, again producing a bruit and/or thrill on exam. High-output heart failure may occur when this happens with larger proximal vessels. Distal ischemia may occur secondary to inflow insufficiency as blood follows this low-resistance "short cut" back to the central circulation without first perfusing the extremity distal to the defect. Although only a minority of such injuries go on to develop an AVF, concomitant venous injury represents a significant burden in extremity arterial trauma. Most studies put the incidence at 15% to 35%, and one wartime series focusing on the lower extremity showed a nearly 50% rate.[2,38]

Another useful classification system for penetrating vascular trauma, proposed in *Rutherford's Vascular Surgery*, categorizes wounds according to their location and the resultant feasibility of attaining hemorrhage control.[4] Tier 1 wounds are in the extremities/periphery, distal to the axillary or common femoral vessels. Such injuries are the focus of this article, and are amenable to immediate control with direct pressure and tourniquets. Tier 2 injuries occur in the axillae and groin. These "junctional" wounds are not typically amenable to the aforementioned techniques, and hemorrhage control can be quite difficult. These wounds and their management are outside the bounds of the extremity proper. Tier 3 injuries involve intracavitary wounds in the thorax, abdomen, or pelvis. (*See Table 2.*) These injuries result in "noncompressible truncal hemorrhage," and often are nearly immediately fatal unless the injury is minor and prompt surgical control is available. Heroic measures, such as resuscitative thoracotomy or resuscitation endovascular balloon occlusion of the aorta (REBOA), may provide temporization.

Table 2. A Classification System for Penetrating Vascular Trauma[4]

Wound Category	Description	Feasibility of Hemorrhage Control
Tier 1	Located in the extremities/periphery, distal to the axillary or common femoral vessels	Amenable to immediate control with direct pressure and tourniquets
Tier 2	Occur in the axillae and groin	Hemorrhage control can be difficult
Tier 3	Intracavitary wounds in the thorax, abdomen, or pelvis	Often are fatal unless injury is minor and prompt surgical control is available; heroic measures, such as resuscitative thoracotomy or resuscitation endovascular balloon occlusion of the aorta (REBOA), may provide temporization

Ischemia

Tissue damage in penetrating extremity trauma is affected through two main mechanisms: the first is direct mechanical destruction and the second is metabolically mediated cellular damage, primarily from ischemia. Direct vessel damage or subsequent increases in compartment pressures impair inflow, creating tissue ischemia due to the inadequate oxygen/nutrient supply. The extent of damage caused by this ischemia depends on the degree, distribution, and duration of obstruction. The tissue affected also matters. For example, nerve tissue has a high basal energy requirement but virtually no substrate storage, which is why sensory deficits such as paresthesias are some of the first signs of an ischemia-inducing vascular injury.[34]

Even in the setting of somewhat limited intrinsic ischemic damage, additional damage will be caused by reperfusion injury. In this phenomenon, cytotoxicity can be perpetuated rather than reversed with the restoration of flow following prolonged ischemia. A pro-inflammatory, pro-thrombotic cascade is triggered via metabolic and cellular mechanisms, leading to a "no reflow" phenomenon as increasing pressure from local edema and microthrombosis prevent any further perfusion, subsequently leading to additional irreversible ischemia.[34,39,40] This process can be slowed by cooling, but this is very rarely available and almost never done. Therefore, the ischemia a limb undergoes at ambient temperature is referred to as "warm ischemia time."

A chief clinical concern is the maximum time of ischemia endured prior to significant irreversible damage (leading to some functional deficit or potential amputation). At six hours, only 10% of patients will have irreversible damage; by 12 hours, 90% will have irreversible damage.[23] Six hours is a common goal for the upper limit of time to restoration of flow. The Mangled Extremity Severity Score (MESS), a predictor of the need for amputation, doubles the ischemia component score at six hours.[2] Other analyses have shown increased histologic and metabolic evidence of tissue injury at the three-hour mark.[34,39] Furthermore, in the setting of significant hemorrhage, the safe window for the restoration of flow has been shown to be as little as one hour.[39,40] This speaks to the importance of damage control resuscitation and early placement of temporary vascular shunts for early restoration of flow and perfusion. Importantly, even though warm ischemia time should be minimized aggressively, hemorrhage control takes precedence, and a provider should never hesitate to place or maintain a required tourniquet.

Initial/Field Evaluation and Management

Evaluation and Escalation

The initial field evaluation of penetrating extremity trauma does not need to be sophisticated. Once such an injury is identified, the focus should shift to immediate control and initiation of movement to a higher level of care. Specifically, the Centers for Disease Control's Guidelines for Field Triage of Injured Patients recommend transport to the highest level of available trauma center care for any penetrating extremity injury proximal to the elbow or knee.[41] In the initial evaluation of such injuries, the field provider should be encouraged to err on the side of over-diagnosis and over-triage. In general, the prehospital environment often can be chaotic and resource-poor. These limitations are only exacerbated in military or tactical environments, which have a higher incidence of penetrating wounds. If apparent significant hemorrhage is encountered, direct vascular injury should be assumed, and action initiated. There should be no hesitation to place a tourniquet to provide temporary but definite control, and to move on with subsequent phases of on-scene care and transportation.

A recent analysis of penetrating trauma patients in the 100 most populous metropolitan areas within the United States illustrated the importance of prompt transport and escalation of care, demonstrating decreased mortality (2.2% vs. 11.6%) in patients transported to a Level I or II trauma center via private vehicle vs. ground emergency medical services (EMS).[42] Although no one would advocate against using ambulance services, the implication that a "scoop and run" approach perhaps should be favored over a "stay and stabilize" approach in penetrating trauma is noteworthy. Other studies have demonstrated a similar benefit for swift prehospital times when it comes to penetrating trauma in particular.[43,44]

Any assessment regarding the characteristics of the initial bleeding, most importantly an estimated rate and amount, will prove useful. The goal is to provide clues to the following two key questions: Is arterial bleeding likely? How much resuscitation likely is required? Simple characteristics such as pulsatile flow or a large pool of blood are sufficient here. An initial set of vital signs can provide invaluable information. These likely are better obtained en route rather than on scene to facilitate expeditious transport time. The Shock Index (SI) is calculated by dividing heart rate (HR) by systolic blood pressure (SBP): SI = HR/SBP. It may aid in the detection of even well-compensated sick patients, whose vitals may not yet appear overtly concerning. A shock index greater than 0.9 or 1 has been demonstrated to correlate with increased mortality and the need for massive transfusion.[45-50] An increase in SI from the field to the emergency department (ED), especially if ≥ 0.3, portends a significant increase in mortality.[45]

Management: Hemorrhage Control

Patients with penetrating extremity trauma die from exsanguinating hemorrhage. Therefore, once these types of injuries are identified, the focus should be on prompt and decisive bleeding control. Most other aspects of evaluation and management are secondary, and mostly can be deferred until the hospital setting. The overall principle of hemorrhage control still will apply in the ED and operating room (OR), but the techniques employed there may begin to be more involved and more definitive. The techniques discussed in this section are primarily for use in the field and ED/trauma bay setting for initial stabilization.

Hemorrhage control should be the first, and possibly only, intervention in the field environment, especially if the provider and patient still are in a tactical or military "hot zone," in the "care under fire" phase of Tactical Combat Casualty Care (TCCC). In fact, the military edition of the Prehospital Trauma Life Support manual notes, "The tactical imperative to maintain fire superiority and move the casualty to cover dictates that *only life-threatening extremity bleeding should warrant any intervention during Care under Fire*" (emphasis original).[51] Updated models of the classic "A-B-C" (airway, breathing, circulation) approach to trauma are being emphasized now, especially in the care of patients in the tactical or military environment or for those who have sustained similar penetrating injuries in the civilian setting. The "X-A-B-C" model gives first priority to "X" for exsanguinating hemorrhage before moving on to the other interventions. Some military groups, including the Committee on TCCC (CoTCCC), use the "MARCH" acronym, which has the same effect, with different phrasing: massive hemorrhage, airway management, respiration/breathing, circulation, hypothermia/head injury.[52]

Direct Pressure

The first and most basic maneuver attempted to control bleeding should be the application of direct pressure.[53,54] The exception to this is in the care under fire scenario, when immediate escalation to tourniquet application typically is preferred. This technique can be very effective and will control bleeding adequately from most wounds that do not involve an overly significant area of soft tissue damage or direct vascular injury.

Previously taught first-aid techniques regarding pressure points and extremity elevation are no longer recommended based on their lack of effectiveness, and the more robust study of alternative, superior methods better described since the start of OIF/OEF.[55] Pressure point control of hemorrhage has been shown to lead to rebleeding within one minute because of collateral flow.[55] Therefore, pressure points and elevation should be employed only as brief bridging maneuvers while other methods of control are implemented.[55]

Hemorrhage Control Adjuncts

Wound packing can be thought of as an extension and complement to direct pressure. It is most useful when simply applied as part of the mechanism of direct pressure control.[54] Packing allows for filling of tissue defects prior to application of direct pressure, and can help provide additional hemostasis and pressure within the wound itself. Although this technique is useful for control of capillary oozing, it is insufficient for any significant vascular injury, even when combined with a bandage or pressure dressing. Such a scenario carries the additional pitfalls of potentially creating a wicking effect and continuing to draw out blood or hiding ongoing bleeding.[53,55] Therefore, a tourniquet is preferred, but packing remains a field intervention worth employing for junctional wounds that are too proximal for tourniquet application and when a specialized junctional tourniquet is not readily available. A commercial syringe device preloaded with tiny expandable sponges, known as the XSTAT, also exists for more streamlined use in this scenario, and has been shown to be a safe and effective option.[56-58]

Various hemostatic dressings also are available. They have a similar pressure benefit when packed into a wound, but with the added chemical advantage of promoting coagulation. Typically, these agents are either impregnated into gauze or come in a granular form. A few of the more common examples of commercial products across three of the most prominent mechanistic categories will be highlighted. Absorptive agents, such as QuikClot, absorb the plasma/water content of blood, thereby leaving behind a more concentrated pool of platelets and coagulation factors at the wound site.[59] Mucoadhesive (chitosan) agents, such as the HemCon bandage, ChitoGauze, and Celox, electrostatically react with blood and injured tissues to form a glue-like substance that helps to seal or tamponade the wound.[59] Procoagulant agents work to promote natural mechanisms. An example is QuikClot's Combat Gauze, which is impregnated with kaolin, an activator of the intrinsic pathway of coagulation.[59] Such adjuncts generally are effective in appropriately selected patients (i.e., not those with blatant arterial injury mandating a tourniquet), with success rates of 79-97%.[59] Combat Gauze, Celox Gauze, and ChitoGauze have demonstrated equal efficacy and are approved for use by the most recent CoTCCC device guidelines.[60,61] Combat Gauze is recommended as the CoTCCC hemostatic dressing of choice.[52]

Tourniquets

Tourniquets have been employed since antiquity, and have a controversial history, alternatively praised for their life-saving effects or vilified for concerns regarding limb-threatening complications.[62,63] Over the past almost two decades of recent military conflict in OIF and OEF, there has been a renewed interest in studying and reporting on the effectiveness and necessity of tourniquets. It did not take long for similar studies and best practices to spill over to the civilian sector as well. Many potentially survivable battle deaths are related to hemorrhage, and various reports have noted an incidence of peripheral extremity trauma, amenable to tourniquet placement, of at least 13% and up to 57% of cases.[64-67] Similarly, in a study on isolated civilian penetrating trauma, researchers also demonstrated that 57% of fatal wounds would have been amenable to tourniquet control.[32]

In a robust one-year study of approximately 500 patients from OIF, investigators demonstrated the benefits of tourniquet use in combat casualties.[68] The survival rate was 87% among patients who had a tourniquet, and only 3% of patients died from isolated limb exsanguination. In 10 patients with isolated limb exsanguination who presented during the same study period, but who were unable to have a tourniquet placed, the survival rate was 0%. Placement of a tourniquet in the prehospital environment compared to in the hospital was associated with a significant increase in survival (89% vs. 78%). Tourniquet placement prior to the onset of shock was associated with increased survival, 94% vs. 4%, compared to those who only had a tourniquet applied after the onset of shock. Most recently, a 2018 study from the Texas Tourniquet Study Group demonstrated a six-fold mortality reduction in patients with peripheral vascular injury for civilian prehospital use of tourniquets.[69] Disconcertingly, tourniquets also were underused, employed in only 18% of patients found to have peripheral vascular injuries. In a recent retrospective study from Maryland, researchers also found that if their results were applied to the U.S. population at large, an estimated nearly 500 deaths might be prevented with prompt tourniquet placement.[70] In short, tourniquets save lives, and their use should be employed aggressively as early as possible whenever applicable.

Indications for placement include the presence of bleeding in an extremity wound that is not easily controlled by direct pressure and/or that has the potential to be lethal.[23,31] (*See Table 3.*) The tourniquet should be left in place until the patient is at a level of care where definitive surgical management is available.[23,55] In general, less than two hours is regarded as a safe tourniquet time.[55,71] United States-based civilian and military trauma systems typically can transport patients from the point of injury to surgical care within this time frame.

Table 3. Indications for Tourniquet Placement

- Bleeding in an extremity wound that is not easily controlled by direct pressure
- Bleeding in an extremity wound that has the potential to be lethal

Amputation was the most feared and anticipated complication by advocates against the tourniquet, but recent work has shown no amputations attributable solely to tourniquet use.[71] The risks for major limb shortening and for transient nerve palsies have been demonstrated at 0.4% and 1.5%, respectively.[68] Fasciotomy (whether therapeutic or prophylactic) occurred in this military series at a rate of about 30%.[71] Tourniquets clearly provide mortality benefits as discussed earlier, and there is no major, permanent morbidity (i.e., limb loss).[72] Likewise, a high potential for benefit and low rate of complications has been demonstrated in the civilian environment in an urban U.S. setting.[73] In short, complications from tourniquets typically are minor and transient, and their rates are negligible. The fear of complications should not preclude the life-saving use of tourniquets.

Three commercial tourniquets were approved for use by the CoTCCC: the CAT (Combat Application Tourniquet), the SOFTT (Special Operations Forces Tactical Tourniquet), and the EMT (Emergency and Military Tourniquet). The most recent CoTCCC guidelines authorize a few additional options as of May 2019.[60] These same devices, or other similar options, are employed commonly in the civilian sector as well. Many have a location on the device to record the time of placement. Become familiar with which tourniquet devices are available in your practice environment. The facile use of these devices may be the most important life-saving intervention the trauma provider can implement in penetrating extremity trauma, and seconds can make a difference during exsanguination. The national Stop the Bleed campaign (bleedingcontrol.org) has sought to bring tourniquet training and availability to lay people as well, and has led to a growing number of trained individuals in the community. Studies have shown that the lay provider can be trained in person quickly and effectively, although skill decay thereafter remains a challenge.[74]

It should also be noted that an improperly placed tourniquet (or inadequate improvised device, like a belt), may be worse than no tourniquet at all. An insufficiently tightened tourniquet will result in adequate pressure for venous occlusion, but inadequate pressure for arterial occlusion, resulting in ongoing distal blood flow to, and subsequent loss from, the extremity.[55] Place tourniquets tightly. The last "crank" of the windlass should be difficult, and it likely will cause the patient considerable pain. Warn the patient and provide adequate analgesia. If a single tourniquet does not control bleeding adequately, place a second one adjacent and proximal to the first.

Additional Considerations

A few additional points regarding field management are worth mentioning. Any extremity instability concerning for potential fracture or dislocation should be straightened and splinted/stabilized. Traction splinting may be applicable when there is concern for a femur fracture. This will help prevent further exacerbation of injury and may reduce associated blood loss.

Whenever possible, intravenous (IV) access should be established. However, this should not delay transport and escalation of care, and should not take precedence over hemorrhage control. An increased on-scene time has been demonstrated in bleeding trauma patients with IVs placed, and placement did not result in more rapid administration of blood products.[75] Placement en route may be more appropriate, but admittedly presents technical difficulties in the transport environment. When IV access is difficult or otherwise not feasible, intraosseous (IO) access should be considered as an alternative. In the prehospital environment, first and second attempts were shown to account for 96% of successful IV placements.[76] Therefore, it is reasonable to consider moving on to an IO in the unconscious patient after two unsuccessful attempts at IV access. The EZ-IO drill gun device is a common option. Placement success rates are about 90% in both civilian and military prehospital settings.[77,78]

Intravascular volume replacement is the next step to consider. Prehospital administration of intravenous fluids (typically crystalloid) has been variably associated with an even or decreased mortality.[79-81] In patients with vascular access and concern for current or impending shock, it is appropriate to begin the rapid infusion of 1 L of crystalloid during transportation to the hospital. Studies on prehospital administration of blood products for trauma victims also have shown variable results, with possible but not definitive benefit.[82-85] The administration of prehospital transfusions is governed primarily by regional protocols. It is a reasonable intervention if available.

Emergency Department Evaluation

As with any traumatic condition, the ED evaluation of penetrating extremity trauma begins first and foremost with a thorough history and physical, which can elucidate many essential findings. Additional aspects of the ED evaluation will be subsequently discussed in Part II.

History

A general history should be obtained first. Notably, this includes information about the exact timing and mechanism of injury. The time of the injury itself should be documented as well as the time of any prehospital interventions affecting blood flow (i.e., tourniquet location and time). This critical information will determine the amount of warm ischemic time endured by the limb, which has implications for both viability and risk of later complications (such as compartment syndrome), as well as for surgical planning.

Estimated blood loss is useful. Even estimates such as "a lot" vs. "a little" can prepare the provider for the type of injury and physiology he or she may encounter.[86] Reports from reliable prehospital professionals about any features suggestive of blatant arterial injury, such as spurting/pulsatile hemorrhage or the need for tourniquet control, should be sought.[87] When feasible, query the patient regarding occupation, important hobbies, and handedness, since this may have implications in management option selection if optimization of functionality becomes a chief concern.[23,88] In patients with significant concomitant injuries or who are unconscious, beware that the distracting nature of such injuries (or incapacitation) renders early signs of vascular insufficiency, such as pain and paresthesias, unlikely to garner attention. Similarly, tourniquet application will obscure the history and exam. Thus, physical examination and any subsequently dictated further imaging evaluation become of paramount importance.

Physical Examination

General Exam. If any active, significant hemorrhage is seen upon arrival, attention to this should supersede any further evaluation or intervention. In line with an "X-A-B-C"-style primary survey, airway, breathing, and circulation may be addressed subsequently after any such exsanguinating hemorrhage. A finger in the wound or a tourniquet allows for rapid, temporary bleeding control to proceed with further evaluation.

Next, a secondary survey should be undertaken to the greatest extent feasible. Victims of penetrating injuries frequently have additional wounds in the head, neck, chest, torso, or pelvis, and all areas should be exposed completely and examined thoroughly for signs of additional injuries. For the extremities themselves, obvious deformities may be noted for high-energy penetrating mechanisms; evidence of fractures should be sought on exam. After stabilization and physical examination are concluded, plain films should be obtained of any areas with a concern for fractures or foreign bodies.

Neuromuscular function should be evaluated thoroughly. Table 4 discusses specific exam maneuvers for testing of motor and sensory function of extremity nerves (and notes associated blood

Table 4. Nerve Testing and Associations

Nerve	Associated Vessel(s)	Motor Testing	Sensory Testing
Median nerve	Brachial artery and radial artery	Wrist flexion, "OK" sign	Palmar index and middle fingers
Radial nerve	Radial artery	Wrist extension, "thumbs up"	Dorsal web space
Ulnar nerve	Ulnar artery	Finger spreading	5th digit and ulnar side of 4th digit
Femoral nerve	Femoral artery	Knee extension	Anteromedial thigh and shin
Tibial nerve	Popliteal artery, posterior tibial artery	Plantarflexion	Sole of foot
Peroneal nerve	Anterior tibial artery*	Dorsiflexion	Anterolateral shin, dorsum of foot

(*The anterior tibial artery runs with the deep branch of the peroneal nerve, which innervates the first webspace on the foot; it continues on into the dorsalis pedis artery.)

vessels as well). In a cooperative patient, evaluate motor function, being careful to distinguish deficits due to muscle/tendon injury vs. nerve injury. A precise diagnosis may be elusive, and further evaluation by orthopedics may be necessary, with potential operative exploration. Tight or firm compartments should be noted, as this may signal the onset of compartment syndrome.

Vascular status should be assessed carefully. The most critical distinction for penetrating extremity trauma is the presence or absence of peripheral vascular injury. Additional exam findings and maneuvers, as well as the subsequent imaging approach, will be discussed in Part II.

Conclusion

With a solid understanding of the injury patterns and initial field management of penetrating extremity injury, the provider is poised to initiate and continue the management of these trauma patients. The discussion will continue in Part II with an approach for a complete hospital-based evaluation and treatment of such injuries.

Disclaimer: *The views expressed herein are those of the authors alone, and do not necessarily reflect those of the Department of Defense, United States Air Force, Wright-Patterson Medical Center, or United States Air Force School of Aerospace Medicine.*

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CME/CE Questions

1. What next steps should be taken if bleeding persists after placement of a tourniquet?
   a. Remove the tourniquet and attempt to replace more tightly
   b. Remove the tourniquet and attempt alternative hemorrhage control methods
   c. Add a second tourniquet distal to the first
   d. Add a second tourniquet proximal to the first
2. What type of arterial injury involves disruption of all three layers of the vessel wall with blood in and out of the damaged area?
   a. Occlusion
   b. Intimal flap
   c. Spasm
   d. Pseudoaneurysm
3. At what time point will 10% of tourniquet patients have resultant irreversible extremity tissue damage?
   a. 1 hour
   b. 2 hours
   c. 6 hours
   d. 12 hours
4. In the tactical or military field environment, what is the proper approach to a patient with possible arterial injury?
   a. Defer treatment decision until full physical exam
   b. Apply direct pressure as temporizing measure
   c. Apply a tourniquet
   d. Delay any interventions until care under fire phase is complete

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CME/CE Objectives

Upon completing this program, the participants will be able to:

- discuss conditions that should increase suspicion for traumatic injuries;
- describe the various modalities used to identify different traumatic conditions;
- cite methods of quickly stabilizing and managing patients; and
- identify possible complications that may occur with traumatic injuries.

5. In a patient with a mild to moderate amount of slow, non-pulsatile bleeding from an extremity wound, which should be the first management method employed?
   a. Direct pressure
   b. Specialized hemostatic gauze
   c. Pressure point occlusion
   d. Tourniquet application

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