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Penetrating extremity trauma is a common injury pattern seen in emergency departments (EDs) and is mainly a disease of young males. Management has evolved from mandatory surgical exploration, to mandatory angiography, to selected angiography of only high-risk patients and non-invasive studies or observation in lower risk injuries. Controversy remains in the literature regarding the optimal evaluation and management of penetrating extremity trauma.

This article covers the evaluation and management of penetrating extremity trauma. A thorough review of the relevant anatomy of the arteries and muscular compartments is presented and a plan for the initial evaluation and stabilization of these injuries is included. In addition, various investigative modalities are discussed, citing relevant literature.

Areas of controversy and agreement in the evaluation of potential arterial injuries are discussed, and the available evidence is used to develop a pathway for the physician to follow to safely and efficiently evaluate patients with penetrating extremity trauma. Continuing areas of investigation and controversy also are discussed.

— The Editor

Penetrating Extremity Trauma: The Problem of Occult Vascular Injury

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Epidemiology and Historical Perspective

The lower extremities are twice as likely to be involved in penetrating trauma as the upper extremities, probably due to their relatively larger surface areas.[1] As with most traumatic injuries, penetrating extremity trauma is mainly a disease of males, who account for 88-94% of cases.[1,2] Gunshot wounds account for approximately 60-80% of penetrating extremity injuries, while stab wounds account for 10-20%.[2,3] Shotgun wounds may account for up to 10% of penetrating extremity wounds, with glass and other missiles and projectiles accounting for the remainder.

Historically, all penetrating extremity wounds were explored in the operating room. During the Korean War, high-velocity military projectiles caused most of these wounds, and as these often involved complex vascular and orthopedic injuries, exploration on all patients was appropriate.[4,5] The civilian experience is different, involving lower velocity injuries and concomitantly less vascular injury. As a result of this difference and the large number of negative explorations, angiography supplanted routine exploration. Angiography is both sensitive and specific for vascular injury. This paradigm reduced the large number of negative explorations, along with the associated morbidity of unnecessary surgical procedures and anesthesia.

Beginning in the 1980s, the need for routine angiography has been questioned. Injuries without obvious signs of vascular injury have only a 2-12% positive angiography rate.[3,6-10] At the same time, angiography has a significant complication rate, both from the procedure and from the contrast material. Additionally, some feel angiographically minor abnormalities may not require surgical repair. Alternative, non-invasive studies are being explored to supplant angiography in patients without hard signs of injury.

Anatomic Considerations

The upper extremity is defined as extending from the deltopectoral groove to the mid-forearm, and the lower extremity is defined as extending from the inguinal ligament anteriorly and the inferior gluteal fold posteriorly to the mid-calf. More recent studies have extended the definitions of the extremities to the wrists and ankles, respectively. The upper extremity derives its blood supply from the subclavian artery, which becomes the axillary artery at the border of the first rib. Distally, the axillary artery becomes the brachial artery at the inferior aspect of the teres major muscle, which then runs along the medial aspect of the arm (in anatomic position). The brachial artery bifurcates just distal to the antecubital fossae into the radial and ulnar arteries. These continue to the wrist and hand, where a complex of arterial arcades allows for significant redundancy of blood supply to the hand and digits.[4] *(See Figures 1 and 2.)*

The lower extremity begins at the inguinal ligament anteriorly and the inferior gluteal fold posteriorly. The external iliac artery becomes the common femoral artery as it passes the inguinal ligament. This gives off the profunda femoral artery, which supplies the deep muscles of the thigh. The superficial femoral artery tracks anteromedially along the thigh, and then passes through the adductor canal, becoming the popliteal artery as it passes posterior to the femoral condyles into the popliteal fossae. At the lower border of the popliteus muscle, the polpiteal artery divides into the anterior and posterior tibial arteries, and the peroneal artery branches from the posterior tibial about three centimeters distally. The area where the popliteal bifurcates and the peroneal artery arises is referred to as the trifurcation, and these vessels supply the calf and the foot.[5] *(See Figures 3-5.)*

Major venous structures generally follow and are paired with the arteries. Because of duplications, more frequent in venous anatomy, as well as deep and superficial venous systems with multiple bridging veins, venous injuries tend to have less obvious clinical evidence of injury and probably less long-term sequellae.[11]

Compartment syndrome more commonly is associated with crush or blunt trauma, but may occur in patients with penetrating trauma. Associated bony damage, massive soft tissue trauma, and arterial injury usually are seen in patients who develop compartment syndrome in the setting of penetrating extremity trauma.The evaluation and management of compartment syndrome is beyond the scope of this review.

Knowledge of the vascular anatomy of the extremities is essential to the evaluation and management of penetrating extremity trauma. Although many arterial anatomic variants do occur, the large vessels rarely deviate significantly. Wounds proximal to anatomic definitions of the extremities, such as those in the groin or thoracic outlet, should be evaluated as torso injuries, and the recommendations described herein for evaluation of occult vascular injury should not be applied.

Initial Stabilization

Life-threatening injuries always should be dealt with first. The evaluation and stabilization of problems with the airway, breathing, or circulation should be managed in the appropriate fashion prior to attending to penetrating extremity trauma. Blood flow must be restored to an ischemic limb within six to eight hours to prevent irreversible nerve and muscle necrosis.[12]

Table. Hard Signs of Arterial Injury

• Absent distal pulses	• Active pulsatile hemorrhage
• Distal ischemia	• Large or expanding hematoma
• Bruit or thrill at injury site	• Pulsatile hematoma

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Controversy exists in the literature as to whether arterial injuries should be repaired prior or subsequent to bony stabilization. A repair prior to stabilization may be destroyed if there is unexpected movement of an unstable fracture, but a delay in reperfusion while awaiting bony stabilization may lead to irreversible ischemia.[12-14] There are no studies specifically addressing this question, and the surgeons involved will determine the sequence of repair.

Avoid placing intravenous lines in the injured extremity and leave one leg free of intravenous lines, as saphenous vein grafts often are used to repair major vascular injuries. Appropriate fluid resuscitation should proceed as usual.

Use direct pressure to provide initial hemostasis. Do not clamp blindly. If a vessel must be clamped, it should be done under direct visualization using non-crushing vascular clamps. Tourniquets should be avoided as they inhibit collateral flow and prevent venous return. Ligation of isolated distal arterial injuries (radial, ulnar, or single vessel injuries below the knee) may be performed if there is good collateral flow and if adequate visualization of the bleeding vessel is possible.[12,15]

Once hemostasis has been achieved, radiographs of the injured extremity should be obtained to look for associated fractures and foreign bodies. Tetanus immunization should be given per Centers for Disease Control and Prevention Guidelines.[16] Antibiotic prophylaxis should be reserved for wounds with significant devitalized tissue, as may be seen in close-range shotgun wounds and high-velocity military-type weapons, puncture wounds, and grossly contaminated injuries, such as those that occur with farm implements. Most gunshot wounds do not require antibiotic prophylaxis. Pain management is essential.

The Controversy in Managing Penetrating Extremity Trauma

Diagnosing obvious vascular injury in a patient with a pulseless, cold extremity is not a challenge. However, significant arterial injury may not be evident during the initial evaluation. In the setting of acute penetrating trauma, utilizing the "six Ps" of the classical approach (pain, pallor, paresthesia, paralysis, poikilothermia, and pulselessness) to evaluate ischemia caused by peripheral vascular disease is not useful. Pain may occur with or without vascular injury, and hemorrhagic shock may lead to pallor or diminished pulses. Nerve injury leading to paresthesias or paralysis can occur without concomitant vascular injury. A different paradigm is needed for the evaluation of acute vascular injury.

Clear evidence of vascular injury on physical examination is defined as "hard signs." These include: absent distal pulses; distal ischemia; bruit or thrill at injury site; large, expanding and/or pulsatile hematomas; and active pulsatile hemorrhage. *(See Table.)* "Soft signs" are suggestive but not diagnostic of vascular injury. These soft signs are defined variably and loosely in the lit-

Figure 1. Arteries of the Upper Arm

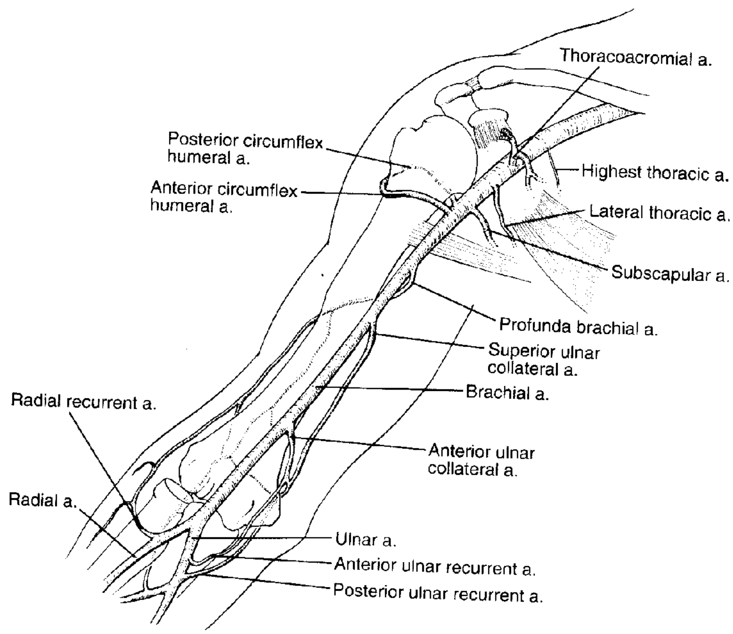

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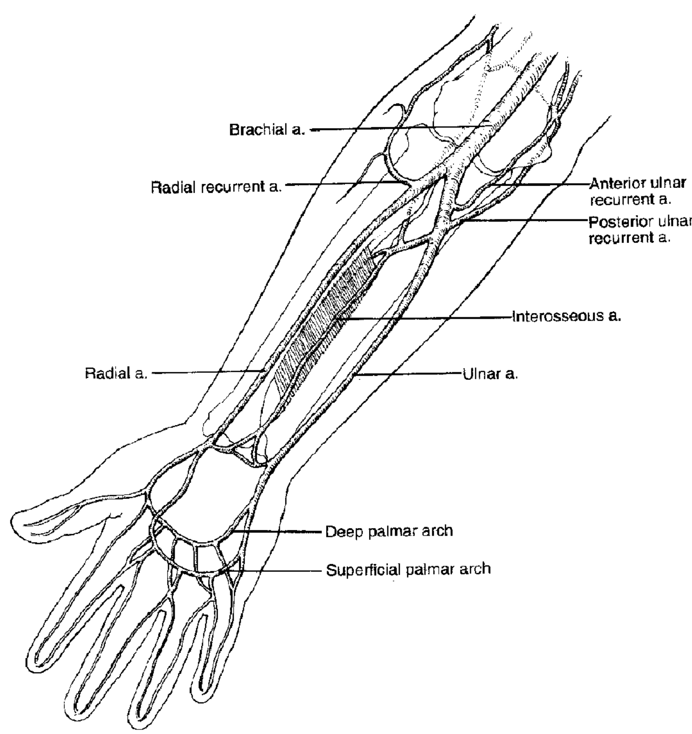
Figure 2. Arteries of the Forearm



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Figures 3-5. Arteries of the Thigh and Lower Leg

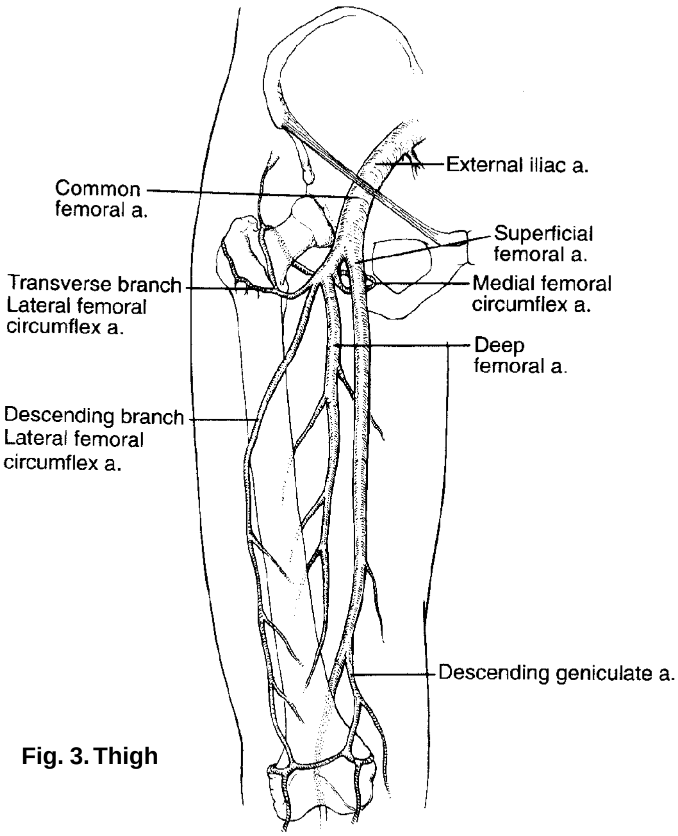


Fig. 3. Thigh

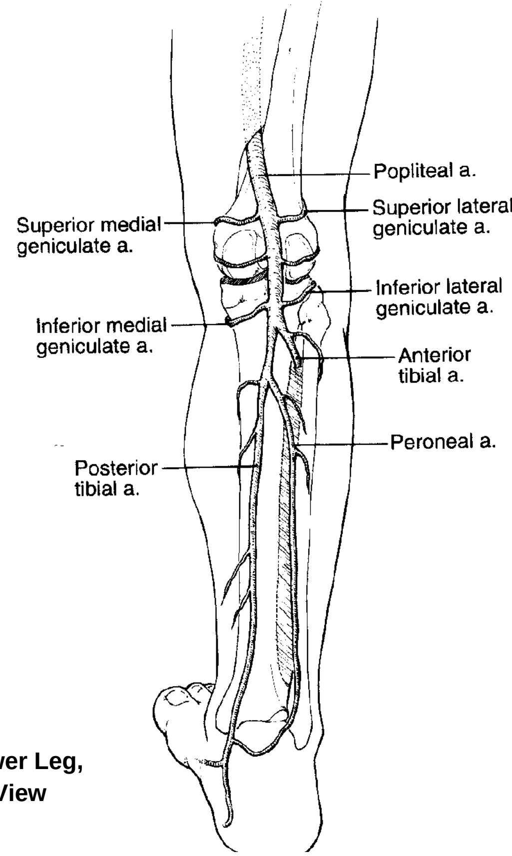


Fig. 4. Lower Leg, Posterior View

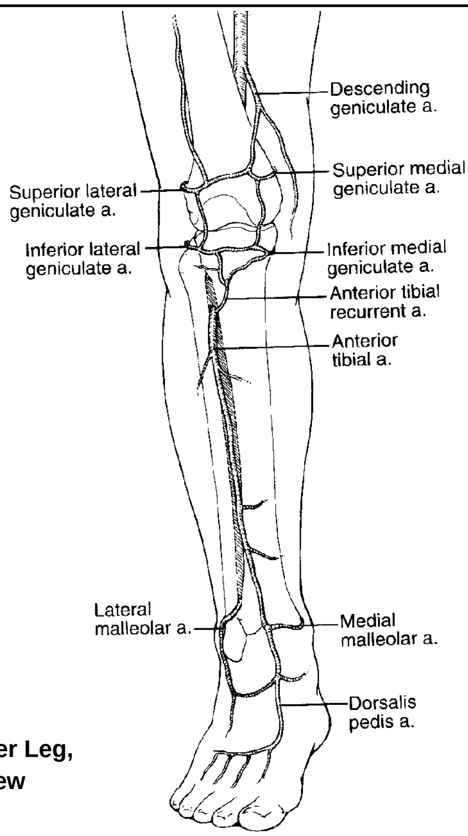


Fig. 5. Lower Leg, Anterior View

Figures 3-5 used with permission from: Blaisdell FW. Lower Extremity Vascular Injury. In: Kennedy JP, Blaisdell FW, eds. *Trauma Management IV: Extremity Trauma*. New York: Thieme Medical Publishers; 1992:60-81.

erature, but are defined here to include small or non-expanding hematomas, peripheral nerve deficit, history of pulsatile or significant hemorrhage at the time of the injury, and hypotension.[3] If a stable patient has evidence of hard signs of vascular injury and distal ischemia, the classic approach was immediate operative exploration and intervention. If hard signs were present without distal ischemia, soft signs were present, or the injury occurred in proximity to a major vessel, the classic approach required angiography. Proximity has been defined variably in the literature, and in some studies it was not defined at all. Non-proximity injuries required no further vascular evaluation.

There are several issues regarding this management scheme. Should all patients with proximity injuries be subjected to angiography? Do all injuries identified by angiography require repair? Do all patients with evidence of soft signs require angiography? Are non-invasive modalities equal to angiography in identifying significant occult vascular injury? Are different approaches needed for the evaluation of high-risk injuries such as shotgun wounds? These issues all have been explored in the literature of the last two decades, although some controversy remains.

Types of Arterial Injury

Vascular trauma can take many forms. The frequency of each type varies with mechanism of injury. A sharp, cutting-type mechanism is more likely to cause complete transection. Proximity injury caused by a temporary cavitation from a high velocity gunshot wound more often causes an arteriovenous fistula. While simple gunshot wounds frequently follow a linear path, bullets may fragment or fracture bone, and these secondary missiles also can cause injury to vascular structures.

Arterial injuries include lacerations, transections, incomplete transections, contusions with spasm or thrombosis, true aneurysms, pseudoaneurysms, arteriovenous fistula, intimal flaps, and external compression. *(See Figure 6.)* Transection, spasm, and thrombosis all may lead to absence of pulses, but their treatment may be different. All of the others can lead to diminished pulses, and there is controversy as to the best management of these injuries. Some of these injuries may be completely clinically silent on initial evaluation. There is a difference of opinion in the literature as to whether intimal flaps, which may have no physical exam findings, need any treatment.

Aneurysms are defined as true or false based on the layers of vessel involved. A true aneurysm is a stretching and thinning of all of the layers of the vessel wall, and usually is caused by cavitation effect on the vessel. Pseudoaneurysms occur when there is a defect in the outermost layer of the artery, the adventitia, through which the intima herniates and dilates. Large aneurysms can cause a disruption in the normally silent laminar flow of blood through the vessel, leading to an audible bruit and a palpable thrill. Blood flow often is slow within the sac, allowing a clot to develop. The thrombosis can extend into the vessel, causing obstruction at the site of injury, or may emboloize, causing distal ischemia. LaPlace's law describes the wall tension on a curved structure as proportional to the radius. Thus as the diameter of an aneurysm increases, the wall tension increases, allowing for further dilatation. Small aneurysms may be stable if the tensile strength of the aneurismal wall exceeds the expansile forces of the blood pressure. If large enough, the aneurysm will dilate until the wall tension exceeds the tensile strength of the vessel. The aneurysm will then rupture, a potentially catastrophic event in a major vessel.

An aneurysm also may erode into adjacent venous structures with resultant arteriovenous (AV) fistula. An AV fistula also may occur when lacerating injuries occur to adjacent vessels simultaneously. A thrill and bruit also may be noted in conjunction with this injury. High output cardiac failure can result.

Diagnostic Modalities for Arterial Injury

Physical Examination. A detailed vascular examination is paramount to the diagnosis of arterial injury secondary to penetrating trauma. Begin the examination by inspecting the injured extremity. Note the location of the injury and its proximity to major vascular and neurologic structures. Almost all arterial injuries occur within five centimeters of a penetrating entrance or exit wound, or along the track between the two. These landmarks are easier to define with gunshot wounds than with sharp penetrating trauma, in which case the path of injury often is obscure. Shotgun wounds with multiple pellets, and gunshot wounds that have secondary missiles such as comminuted bone fragments, also may not follow this rule. Inspection also should be done for swelling, expanding hematomas, and active pulsatile bleeding.

If a patient presents with a history of pulsatile or significant bleeding that has been controlled by a dressing, removal of the dressing should occur only when the examining physician is prepared to control recurrent hemorrhage. A detailed distal neurovascular examination, as described below, should occur prior to removal of any dressing.

Palpation produces the most reliable sign of vascular injury—absent pulse. There are, however, several caveats to this diagnostic clue. Up to 25% of cases with major arterial injury still have palpable pulses. Absence of pulse is a more reliable sign in the upper extremity than in the lower, as the lower extremity has extensive collateral blood supply. Spasm or underlying peripheral vascular disease can lead to a pulse deficit without true vascular injury. It is important to check the contralateral extremity to define baseline pulse status, particularly in the face of suspected underlying peripheral vascular disease. A thrill is a rare but highly specific indicator of an AV fistula. Similarly, a bruit heard on auscultation is indicative of turbulent blood flow, as may occur with an AV fistula, aneurysm, pseudoaneurysm, or partial arterial occlusion.

Physical examination findings and wound characteristics have been used to risk-stratify patients with penetrating thigh trauma. A case-control study found that hard and soft signs of injury, as well as location of the wound in the medial compartment of the thigh, are suggestive but not diagnostic of arterial injury.[17]

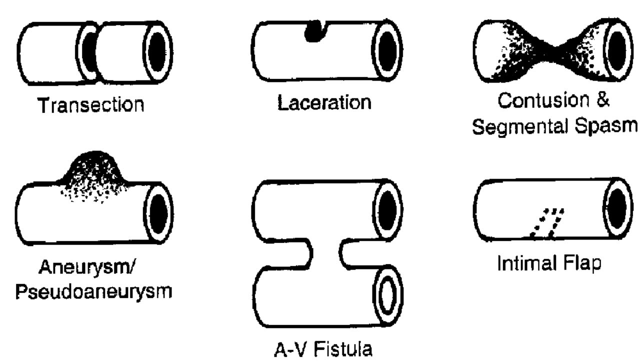
A distal neurologic examination may help identify subtle signs of neurologic injury. Peripheral nerves are sensitive to ischemia, and it may be difficult to distinguish direct nerve injury from ischemic neuropathy. Proprioception is lost early with ischemia. In the lower extremity, a foot drop secondary to peroneal nerve deficit may be an early sign of lower extremity vascular injury.

Compression tests help to identify distal vascular injuries. The classic Allen test is performed to evaluate ulnar and radial artery injuries. Both vessels are compressed tightly for 60 seconds and the fist is clenched to exsanguinate the palm. The hand is opened and one of the vessels is released; the rapidity of return of blood supply to the palm, as demonstrated by a change in color from pale to pink, is noted. The test is repeated with the other vessel. A positive test occurs when the palm stays pale. Slow refill (> 3-5 seconds) also is indicative of vascular disease or injury. A similar test can be performed on the foot. In this case, the dorsalis pedis and posterior tibial arteries are compressed, and the foot is exsanguinated by rubbing the sole and having the patient clench his or her toes.[18]

In one study of 18 forearm arterial injuries, pulses were present in nine (50%) of them. The Allen test was able to adequately distinguish between normal flow and retrograde flow in the seven patients in whom the persistent pulses were due to retrograde flow. The remaining two patients with documented forearm arterial transection but with normal pulses and Allen test were found to have large collaterals or pulses falsely transmitted through a clot at the point of transection.[18]

Doppler Pressure Index. Another bedside test to evaluate for subtle vascular injuries is the Doppler Pressure Index (DPI), also known as the Arterial Pressure Index (API). It should be considered an adjunct to the physical examination. A handheld arterial

Figure 6. Types of Arterial Injuries



Doppler device is used to measure the systolic blood pressure at a site distal to the injury on the affected extremity, and compared with the same measurement on the opposite extremity. The ratio of the blood pressures in the injured vs. uninjured extremity should approximate unity. A DPI of less than 0.9 is indicative of arterial injury.[19] A Doppler device is inexpensive, reusable, and non-invasive. As such, it is an excellent supplement to the physical examination. Serial examinations can be used to identify a developing or worsening injury. Non-hemodynamically compromising lesions will not show changes on DPI. Intimal flaps or small aneurysms may have false-negative findings. Areas with large amounts of collateral flow also may have false-negative findings on DPI. A false-positive test may occur with traumatic vasospasm. Venous injuries are missed with this and most other physical examination maneuvers.

Single-Shot Angiography. Single-shot angiography has been advocated as a rapid way to evaluate arterial injury in an extremity.[20] A physician inserts a catheter into the brachial or femoral artery proximal to the area of injury and injects contrast material. A single radiograph is taken during the injection of the dye. While this technique has the advantage of being rapid, relatively low-cost, and requiring no specialized equipment, it has several disadvantages. No studies have been done to evaluate its efficacy in demonstrating significant lesions, either by long-term follow-up or by direct comparison with standard angiography. With only one projection of the artery, small but significant injuries may be missed.

Recent studies have suggested that there is little benefit to rapidly diagnosing occult injury, and that patients with obvious evidence of arterial injury and ischemia should be explored immediately in the operating room rather than have this diagnostic test performed. This technique may be useful for patients with low risk injuries who require surgery for other injuries, as serial examination of the injured extremity will not be possible during operative intervention. The decision to perform a single-shot angiogram should be made in conjunction with the operating surgeon.

Angiography. The gold standard diagnostic test for extremity arterial injury is angiography. Prior to 1990, virtually all penetrating extremity trauma in proximity to major vessels underwent angiography.[21-23] It has a sensitivity of 98% and a specificity of 98% compared with operative findings and long-term follow-up, with a 1-2% false-negative rate.[24-27] In many centers, angiography is not rapidly available, leading to a delay of 1.5-2.4 hours in the management of patients with arterial injury. The procedure is expensive, costing between $1000 and $2000 per examination. It is an invasive procedure, with a 5% complication rate in some reports. The majority of these complications are minor, such as groin hematomas, but 0.6% are major and include significant hemorrhage, arterial laceration, and AV fistula. Children have a higher complication rate. The risk of contrast dye-related reactions also is present. The overall incidence of adverse reactions to low osmolality (nonionic) contrast materials is reported to be 1-2%. Severe reactions occur in 1-2 per 10,000, and deaths in 1 per 200,000-300,000. Digital subtraction angiography has less morbidity but essentially equivalent accuracy in the diagnosis of arterial injury. However, motion artifact and distortion from shotgun pellets or bullet fragments may decrease accuracy.[28,29]

The angiogram reliably defines the extent and location of arterial injury. Classically, angiography has been used to both characterize a known injury and to exclude a possible injury. Characterization angiography has been used in patients in whom arterial injury is highly suspect on clinical grounds, with an intention to define the location and extent of injury. This information allows the surgeon to plan the best surgical approach for exposure and repair. Exclusion angiography has been used on patients with lower suspicion of arterial injury. Those with negative findings were felt to have no arterial injury and were discharged from the ED. Intraoperative arteriography also is performed to document adequacy of repair and patency of the vessel after surgical intervention.[30]

While the cost of angiography is high, it is not prohibitively so, and if a patient can be discharged from the ED after a negative angiography it may be more cost effective than an admission for observation. No study has looked specifically at a comparison of costs and charges between routine angiography and observation.

Arterial Ultrasound. Several studies have evaluated the use of ultrasound as a potential imaging modality to supplant angiography. It allows for the visualization of direction and velocity of blood flow in a real-time setting. It requires no invasive procedures, radiation, or contrast material. No study has ever documented a negative effect of ultrasound on human beings. The machinery is portable. Serial examinations can follow small non-operative lesions over time, or patients with evolving signs or symptoms.

Arterial ultrasonography requires a moderate investment in equipment and is operator dependent. The equipment is reusable and multifunctional. A trained technician is required, and the individual reading the study relies heavily upon the real-time observations of this technician. Ultrasound studies may be limited by many technical facts. Air in the soft tissue or dressings overlying the area of interest significantly diminishes image quality. Patient discomfort with the pressure of the probe also can limit the study. While injected contrast dye follows the flow of blood, a sonographer may look only at the primary vessels and miss injuries to small, aberrant, or duplicate vessels.

Technetium-99 Nuclear Imaging. Several studies have evaluated the utility of nuclear imaging in the diagnosis of arterial trauma. While it has been shown to have good sensitivity, specificity is only about 80%. As with most imaging modalities, the experience of the interpreter impacts the accuracy of the study. A positive study still requires angiography. Limited availability of a technician, equipment, radioactive tracer, and an experienced interpreter makes this modality impractical for routine use.[31,32]

Transcutaneous Oximetry. Transcutaneous oxygen monitoring has been used in the evaluation of peripheral vascular disease and to measure response to hyperbaric oxygen therapy. The technique involves specialized oximetry probes and monitoring equipment. The probes gently warm the skin, allowing free transcutaneous diffusion of oxygen across the normally impermeable cutaneous barrier. Transcutaneous oxygen ($TCPO_2$) can be measured, and is related to the perfusion of the skin at the location of the probe. A bilateral perfusion index (BPI) can be obtained by measuring the $TCPO_2$ at a point distal to the area of suspected arterial injury and dividing it by the $TCPO_2$ obtained at the analogous site on the contralateral limb. This ratio should approach unity with normal arterial flow. Only one study has examined this modality in penetrating extremity trauma, and it reported on only 33 patients. In the study, a BPI of less than 0.9 had a sensitivity of 80% and a specificity of 91% for detecting significant arterial injury.[33]

Transcutaneous oximetry is time consuming if done properly (up to 15 minutes to equilibrate at each point) and requires specialized equipment. Given the poor performance of this modality in the one published study plus these other drawbacks, it seems unlikely to be pursued further as a diagnostic test for occult arterial injury in penetrating trauma.

Helical Computed Tomographic Angiography. One study published in 1999 by Soto and colleagues investigated the use of helical CT angiography (HCTA) for the diagnosis of arterial injury in extremity trauma.[34] CT angiography has gained popularity as an excellent study for evaluation of patients with possible pulmonary embolism, and long has been used to evaluate for both traumatic and atraumatic thoracic aortic dissections. The evaluation of peripheral arterial injury is a logical extension of this diagnostic modality, as CT is rapidly available in most trauma centers. HCTA was found to have 90% sensitivity and 100% specificity in a study of 45 consecutive patients who were referred for extremity angiography for trauma. There was a high concordance between the two study radiologists, who were blinded both to each other's interpretation and to the angiography results. Of the 45 studies, 37 were done for penetrating trauma. There were two false negatives and two non-diagnostic studies. This was an excellent initial report on which further study of helical CT angiography for penetrating extremity trauma can be based.

Fat Supression Magnetic Resonance Imaging. A small preliminary study of magnetic resonance angiography (MRA) using special extremity coils and a fat-suppression technique was published in 1992. This study by Yaquinto and colleagues looked at 11 patients and 12 injured extremities.[35] The results were perfectly consistent with conventional angiography, with three true positives and nine true negatives. Many limitations are associated with this method of diagnosis, which may explain why no further studies on this modality have been published. Special extremity coils are needed, which are not readily available in most facilities. The thigh and shoulder could not be imaged by this technique, and injuries containing ferrous pellets, such as those caused by birdshot, cannot be evaluated. The cost of studies and readings were not reported and there was no patient follow-up. MRA also has been investigated for use in the setting of peripheral arterial disease in conjunction with conventional angiography.[36] It seems unlikely that MRA will replace more conventional methods of evaluation in the near future; however, improved techniques, increased availability of magnetic resonance imaging, and use of standard rather than specialized equipment may make MRA an appropriate diagnostic tool to consider in the more distant future.

Complications of Missed Arterial Injury

One of the arguments that long has been made regarding the need for angiography in patients with proximity injury or soft signs is that missed occult injuries can progress, leading to significant, long term morbidity. There are several recognized complications of unrepaired injuries that have been reported in case series.[26] AV fistulas initially may be clinically silent, but may lead to chronic arterial or venous insufficiency in an extremity, or high output cardiac failure. Aneurysms and pseudoaneurysms can enlarge and rupture. Rupture in a major vessel can lead to significant blood loss. Enlarging aneurysms can compress adjacent structures, leading to paresthesias or paresis. Clots can develop in or near aneurysms, leading to occlusion at the site or embolization with distal ischemia. Small, intimal defects can propagate thrombi or emboli. Most series suggest that the majority of clinically occult injuries are benign and can be treated non-operatively.[37,38]

Approach to Evaluation of Arterial Injury in Penetrating Trauma

Beginning in 1988, researchers have questioned the need for angiography in all patients. In a retrospective study, Rose and Moore reviewed 169 patients who underwent angiography for penetrating extremity trauma.[24] A total of 33 major vascular injuries were found, all of which were identified by careful physical examination. In this series, no arterial injuries were identified in patients who underwent angiography for proximity only, in the absence of any signs or symptoms of vascular trauma. This small, retrospective study led to the bold conclusion that angiography is not needed for proximity-only wounds.

Another interesting retrospective study followed the next year. Stain and Yellin reviewed patients seen at Los Angeles County-University of Southern California Hospital who had sustained arteriographically demonstrated, hemodynamically stable arterial injuries. These 50 patients had a total of 61 arterial injuries, including small intimal flaps, intimal defects, pseudoaneurysms, arterial stenoses, and arteriovenous fistulas. Rather than operatively intervene, these patients were observed in the hospital for 72 hours and then monitored as outpatients. Thirty of the injuries underwent repeat arteriography at follow-up, with most demonstrating improvement or resolution. Of the 10 with persistent abnormalities, eight were treated successfully with embolization during the repeat arteriogram and the other two required operative intervention. Another 21 injuries were seen in follow-up, and no intervention or invasive evaluation was performed. These patients did well with no significant sequellae. The conclusions were that most arterial injuries without hemodynamic compromise are minor, do not require operative exploration, and are managed best by observation and serial studies.[39] This article represented a major change in the management of minor arterial injuries. While the obvious management change that resulted from this was the limitation on the surgical intervention for these injuries, it also opened the door for a change in the diagnostic approach to these injuries. If non-hemodynamically compromising arterial injuries do not require intervention, do they need to be diagnosed? A series of studies followed to try to answer this question.

In 1991, Frykberg and Dennis described a prospective protocol for patients with penetrating extremity trauma.[3] They placed patients into four categories based on their injuries and managed them accordingly. A total of 366 patients were enrolled. The 21 patients with hard signs of injury, including major or pulsatile hemorrhage; large, expanding or pulsatile hematomas; distal ischemia with diminished or absent pulse; bruit; or thrill, were taken directly to the operative theater. All had an arterial injury. The 64 patients with injury to the thoracic outlet (not considered part of the upper extremity by most other authors) or shotgun wounds were excluded from the study and underwent angiography. Patients with non-proximity wounds were discharged directly home. The remaining patients with soft signs of injury or asymptomatic proximity wounds were observed for 24 hours. Careful, serial physical examinations were documented on these patients. Two initially missed injuries were identified in this group of 286 patients, including a popliteal injury and a radial artery injury.

This large series replaced angiography almost entirely with physical examination, with very little evident morbidity. Of the 286 patients with proximity injury or soft signs, only one underwent arteriography and one developed hard signs leading to operative intervention without further study. Estimating the cost of arteriography at approximately $1000, $285,000 in arteriography charges were saved. There was no discussion of the cost of observation, so no true cost savings can be calculated.

A major criticism of the initial Frykberg and Dennis study was a lack of long-term follow-up to determine the true morbidity and missed injury rate. In 1998, they published a follow-up study.[9] One of the groups in this second study involved 287 patients with 309 asymptomatic proximity wounds that were evaluated with observation only. Four patients developed hard signs of arterial injury within one week and underwent operative repair. Although these four patients had delayed repair, they suffered no long-term sequellae. The investigators were able to contact 78 of the remaining patients or their families an average of 5.4 years later. None of these patients had evidence of delayed vascular morbidity. Although only a small percentage was captured in follow-up, this study presents good evidence that simple observation is an appropriate method of investigation for asymptomatic patients with proximity penetrating extremity trauma.

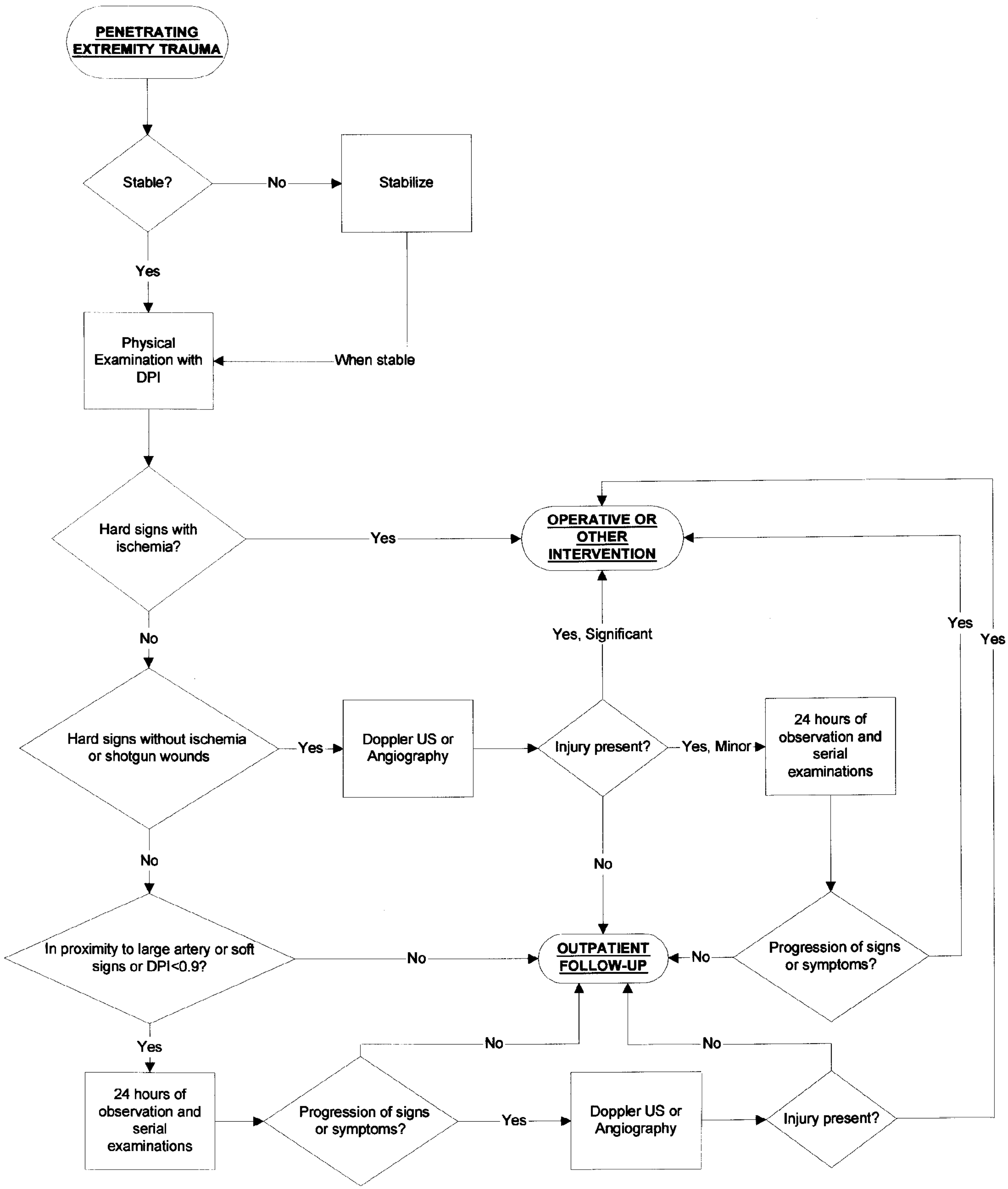
A study by Gonzalez and Falimivski in 1999 prospectively enrolled 421 patients without hard signs of injury on careful physical examination. Only four injuries were missed on initial clinical examination, and only two were considered clinically significant. As with most trauma studies, poor follow-up limited this study, but it showed a 99% sensitivity for physical examination and 24 hour observation.[2]

Evaluation of the DPI as an adjunct to the physical examination was studied by Nassoura and colleagues.[19] Over a 2.5-year period, all patients presenting with PET and no physical examination signs consistent with arterial injury were evaluated for inclusion in the study. Those with shotgun injuries or blunt trauma were excluded. All of the included patients (298 with 323 injuries) underwent physical examination, DPI, and angiography. In this group, 40 arterial injuries not found on physical exam were diagnosed with angiography. This contradicts the other studies showing excellent correlation of the physical examination with injury. An abnormal DPI, of less than 0.9, picked up 29 of these injuries. Of the 11 remaining injuries missed by physical examination and DPI, five required either operative repair or angiographic embolization. Five of the injuries were pseudoaneurysms, and three were small intimal lesions. The remaining lesions not requiring intervention included a peroneal AV fistula, and bleeding/lacerations of two small branch arteries. This study suggests a benefit from the use of DPI in addition to the physical examination. Despite the angiographically identified lesions with normal physical examination and DPI in this study, the preponderance of studies shows that physical examination with a period of observation is adequate and appropriate for proximity-only injuries.[2,3,40-42] The other studies would suggest that these lesions either would be self-limiting or would declare themselves in a short period of time during either observation or follow-up.

The utility of ultrasound for the diagnosis of occult arterial injuries initially was investigated in 1990.[43] A prospective study by Anderson using ultrasound to diagnose arterial injury in 23 patients with PET and no hard signs of injury was published in the *Journal of Trauma*. There were six injuries identified by angiography, of which five also were seen by B-mode ultrasound. The missed injury was not discussed. A follow-up study published in 1992 used color-flow Doppler ultrasound in 75 injuries without hard signs of injury.[44] There were three positive and 72 negative studies. One false positive and two false negative studies were found by comparison angiography. This indicates an excellent specificity but a low sensitivity, mainly due to the low numbers of actual injuries in this cohort.

Subsequent studies of Doppler ultrasound, with and without color flow, have shown improved accuracy. A study evaluating those with proximity injury or diminished pulses followed by angiography or exploration found 100% sensitivity and specificity in 19 patients with and 31 patients without arterial injury.[45] One study by Schwartz and associates looked at a dozen patients with small, hemodynamically insignificant, angiographically proven lesions.[46] These then were studied with color flow duplex ultrasound, and five lesions were not seen. This suggests that

Figure 7. Algorithm for the Evaluation of Arterial Injury in Penetrating Extremity Trauma



small lesions may not be seen on Doppler ultrasound. The missed injuries, however, did not require intervention. A large, prospective study involving more than 4000 patients in a seven-year period by Ordog and colleagues concluded that for clinically significant lesions, Doppler duplex is 100% accurate in patients without hard signs of injury.[1] An amazing 95% follow-up rate revealed no missed clinically significant lesions. Interestingly, this study involved only brief, focused, area-specific studies, many of which were performed by emergency physicians and surgeons in the acute trauma setting. In aggregate, the studies suggest a very high accuracy of this test, with false negatives mainly being confined to small, non-hemodynamically significant lesions.[47]

Other studies, such as CT angiography and MRA, can be considered only experimental and not ready for use in clinical practice at this time for the reasons discussed previously.

Venous Injury. Arterial injury frequently is accompanied by venous injury, as they are anatomically paired. The diagnosis and management of venous injury is not as well described in the literature. Diagnosis by Doppler duplex examination is accurate, but there is controversy as to the best management. One study suggests that both ligation and repair result in low morbidity and good outcomes, but another notes a 50% complication rate, including chronic venous insufficiency and deep venous thrombosis with pulmonary embolism.[48,49] ED management remains stabilization and achieving hemostasis.

Shotgun Wounds. Most prospective protocols have excluded shotgun wounds from approaches that would allow for non-invasive tests and observation. This is due to the extent of soft-tissue damage, unpredictability of the path of fragments, and early studies that showed high rates of associated arterial injury with shotgun wounds.[3,50] Doppler ultrasound has been used successfully for the diagnosis of occult arterial injury in patients sustaining shotgun wounds, but there are no data to support observation only. Most studies still recommend angiography for shotgun wounds.

Diagnostic Approach. Once a patient with penetrating extremity trauma has been stabilized, the next step is a good physical examination, with the use of DPI as an adjunctive measure. Those patients with hard signs of arterial injury and distal ischemia should have operative intervention at the earliest possible time. No diagnostic study is required, but some surgeons may prefer an ultrasound or angiogram to delineate the injury to plan their intervention.

Evaluation of patients with hard signs of arterial injury but no evidence of distal ischemia should be determined by the surgeon. Two approaches are equally valid: 1) Operative intervention without further diagnostic study, or 2) preoperative angiography or Doppler ultrasonography to better define the lesion prior to operative intervention. Some surgeons may prefer the latter approach to guide their interventions.

Patients with shotgun wounds should undergo a diagnostic study. Doppler ultrasound and angiography are equally appropriate choices, and the study performed will be determined by availability, expertise, and comfort level.

Patients with a DPI less than 0.9, neurologic deficit, small or non-expanding hematomas, or history of pulsatile or significant hemorrhage should be evaluated with observation. If signs or symptoms progress, either a Doppler ultrasound or an angiogram should be performed. A patient with a negative Doppler study can be discharged for outpatient follow-up. A patient with a significant injury found on Doppler should be treated appropriately. Those patients with no progression of findings after 24 hours of observation can be discharged with outpatient follow-up. This approach also applies to those with injuries in proximity to major vessels, defined as a pathway of injury within one centimeter of a major vessel.[8]

Patients with non-proximity injuries, a normal physical examination, and a normal DPI can have their injuries primarily managed. No further evaluation for arterial injury is indicated. This diagnostic algorithm is summarized in Figure 7.

Conclusions

The diagnostic algorithm described is based on the best available clinical evidence. Controversy remains as to whether Doppler ultrasonography can replace arteriography completely. Although arterial injuries may be occult, a careful physical examination using DPI as an adjunctive test will identify most injuries. For those with no arterial injury identified on physical examination but with a wound in proximity to a major vessel, serial examination over a period of observation or Doppler ultrasonography will identify hemodynamically significant injuries with a high degree of accuracy and will minimize the need for invasive and costly angiography. A careful systematic approach will help the clinician diagnose occult injuries and guide evaluation and management. Further studies are needed to determine if other diagnostic modalities, such as helical CT angiography or MRA, will replace or be adjunctive to conventional angiography and Doppler ultrasonography.

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Physician CME Questions

To earn CME credit for this issue of Trauma Reports, *please refer to the enclosed Scantron form for directions on taking the test and submitting your answers.*

1. Penetrating extremity trauma:
   A. is more common in females.
   B. is twice as likely to occur in arms compared to legs.
   C. frequently results in amputation.
   D. always requires exploration.
   E. most commonly is caused by gunshot wounds.

2. Which of the following is correct regarding the anatomy of the extremities?
   A. The arm starts at the deltopectoral groove.
   B. The arm extends to the metacarpal-phalangeal joints.
   C. The leg begins at the pelvic outlet.
   D. The leg extends to the calcaneous.

3. Initial stabilization of penetrating extremity trauma should include:
   A. blind clamping of bleeding vessels.
   B. an assessment and stabilization of airway problems prior to evaluation of an ischemic limb.
   C. application of a venous tourniquet to allow visualization of injuries.
   D. ligation of all venous bleeding.
   E. antibiotic prophylaxis for all gunshot wounds.

4. The most reliable physical examination finding for arterial injury is:
   A a bruit.
   B. a thrill.
   C. absent pulses.
   D. loss of proprioception.
   E. paralysis.

5. Which of the following modalities may prove useful in the future for the diagnosis of occult arterial injury?
   A. Helical CT angiography
   B. Transcutaneous oximetry
   C. Pulse oximetry
   D. Technetium-99 nuclear scanning
   E. Electromyography

6. Which of the following mechanisms is associated with the highest risk of arterial injury?
   A. Glass
   B. Stab
   C. Gunshot
   D. Shotgun

7. Which of the following is correct regarding occult arterial injury?
   A. The natural history of most is benign.
   B. Physical examination and Doppler pulse index (DPI) are specific but not sensitive.
   C. Transection is a common occult injury.
   D. Doppler duplex ultrasonography is sensitive but not specific.

8. What is the sequence of steps in the evaluation of a patient with a gunshot wound to the lower leg with a foot drop?
   A. Physical exam/DPI; stabilize; angiographic embolization
   B. Stabilization; physical exam/DPI; 24-hour observation; Doppler ultrasound
   C. Stabilization; angiography; observe for 24 hours if a significant injury is found
   D. Stabilize; physical examination/DPI; Doppler ultasound; intervention as indicated by ultrasound for significant injury
   E. Stabilize; physical examination/DPI; discharge if normal examination

9. In which of the following scenarios would a single-shot angiography be appropriate?
   A. A stable, asymptomatic patient with a stab wound to the thigh
   B. A patient with a pulseless right leg
   C. A patient with a pulsatile mass and evidence of ischemia
   D. A patient with a large, expanding hematoma and ischemia
   E. A patient with an epidural hematoma (which requires surgery) and a small, non-expanding hematoma and history of significant blood loss at the scene

10. The lower extremity begins at the:
    A. deep femoral artery.
    B. inguinal ligament anteriorly.
    C. top of the thigh.
    D. point where the deep femoral artery branches.
    E. area where the medial femoral circumflex artery bifurcates.

CME Objectives

Upon completing this program, the participants will be able to: quickly recognize or increase index of suspicion for specific injuries; understand the epidemiology, etiology, pathophysiology, and clinical features of the entity discussed; be educated about how to correctly perform necessary diagnostic tests; take a meaningful patient history that will reveal the most important details about the particular problem discussed; apply state-of-the-art therapeutic techniques (including the implications of pharmaceutical therapy discussed) to patients with the particular problems discussed; understand the differential diagnosis of the entity discussed; understand both likely and rare complications that may occur; understand appropriate subspecialty referral and indications for inpatient evaluation of the problem discussed; and provide patients with any necessary discharge instructions.

In Future Issues: Aeromedical Transport