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2

Vascular Trauma: New Directions in Screening, Diagnosis and Management

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1. Introduction

Major vascular injury following trauma is uncommon, however, it can result in extremely high mortality and morbidity, particularly if diagnosis or treatment are delayed. Physical examination has historically been the mainstay of diagnosis, and open repair the mainstay of treatment for these injuries. However, as advanced imaging technologies and endovascular treatment modalities become more common, and validated in the literature the diagnosis and treatment of traumatic vascular injuries has evolved. While patients with classic "hard signs" of vascular injury such as arterial bleeding, expanding hematoma, lack of pulses, bruit, thrill, or shock should still be taken immediately to the operating theater for open exploration with, or without on table angiography if necessary; patients with soft signs of injury or concerning mechanisms now have a myriad of screening options available. Additionally, in vascular injuries that are difficult to diagnose, expose and definitively treat, such as thoracic aortic and subclavian artery injury, minimally invasive diagnostic and treatment options have significantly altered the course of care of these trauma patients. One of the most important advancements in the diagnosis of vascular injury has been the development of computed tomography (CT), specifically CT angiography (CTA). CT scanning is widely available in most hospitals in the United States, is rapid, immediately and easily performed, and does not require the presence of specially trained radiologists and technologists as in traditional angiography. CT angiography has now become the screening tool of choice for traumatic aortic injury, and is becoming more commonly utilized in the diagnosis of upper and lower extremity vascular injury. In the therapeutic realm, minimally invasive endovascular techniques such as stent graft deployment and embolization with coils, glue or gelfoam are increasingly utilized in the treatment of vascular injury. This review will discuss the use of modern imaging techniques such as CT angiography and magnetic resonance imaging (MRI) in the screening and diagnosis of thoracic aortic and upper and lower extremity vascular injuries. We will also discuss the indications for, efficacy and complications of, and outcomes in endovascular therapies for traumatic vascular injuries.

2. Diagnosis

2.1 Peripheral vascular injury

Peripheral vascular injuries, defined as injuries of, or distal to, the axillobrachial and femoropopliteal vessels, while uncommon overall, account for the majority of civilian vascular

trauma (Mattox, et al., 1989). Lower extremity injuries are more common than upper, and the majority of injuries are due to penetrating trauma, which accounts for 75-80% of cases (Dente, et al., 2008). In contrast to injuries of the thoracoabdominal vessels where injury can result in significant occult hemorrhage into the thorax, abdomen, or retroperitoneum; peripheral vascular injury generally results in bleeding or hematoma formation that is clearly visible on clinical exam. Additionally, peripheral injuries can be easily controlled in the field by direct pressure or tourniquet application. These factors combine to improve the chances of patients with peripheral vascular injury presenting to the hospital alive, and in stable condition.

Because of the peripheral and more superficial location of these vessels clinical exam is very sensitive for detection of arterial injury (Gonzalez & Falimirski, 1999; Hood, et al., 1998; Modrall, et al., 1998). The classical hard signs of vascular injury include arterial bleeding, expanding or pulsatile hematoma, lack of distal pulse, bruit, thrill, and shock without other explanation. Patients with any hard signs of injury should be taken to surgery immediately. The one exception would be in blunt trauma patients or patients with multi-level penetrating trauma such as shotgun wounds where angiography or CTA can be a helpful roadmap for surgical planning and exploration.

In stable patients lacking hard signs of vascular injury physical examination should include visual inspection, palpation for edema, compartment tension and tenderness, as well as range of motion across all joints to assess for associated fracture or dislocation. Complete neurologic examination of the affected extremity should also be performed in cooperative patients, as there is a high rate of nerve injury associated with vascular trauma, and neurologic defect should be considered a soft sign of vascular injury. Other soft signs include non-expanding non-pulsatile hematomas and history of profuse or pulsatile bleeding. A complete assessment of all peripheral pulses should be performed. If any asymmetry is noted, and in cases of obvious fracture or deformity, an ankle-brachial index (ABI) or brachial-brachial index (BBI) should be performed to rule out occult vascular injury. The blood pressure should be taken below the level of injury in the affected extremity. If the ABI/BBI is less than 0.9, or any soft signs of injury are present further imaging is mandatory as up to 35% of these patients will have a surgically significant injury (Gonzalez & Falimirski, 1999). ABI as a screening tool for diagnosis of arterial injury has a very good sensitivity ranging from 95-100% and a negative predictive value of 98% (Levy, et al., 2005; Sadjadi, et al., 2009). Unfortunately, a normal ABI may occasionally miss injuries that do not inhibit distal flow such as pseudoaneurysm, arterio-venous fistula, and intimal flap. However, the majority, 87-95%, of these lesions heal spontaneously and in follow up only 1-4% of these patients with missed injuries require intervention at 1 year, and 9% at 5-10 years (Dennis, et al., 1998; Frykberg, et al., 1991).

Patients with no hard or soft signs of injury, and with normal ABI/BBI's may be discharged if there is no other indication for admission (Figure 1). Advanced imaging or surgical exploration solely for proximity of injury is neither cost effective nor advocated in the absence of concerning ABI or physical exam findings as the likelihood of finding a surgically significant injury is very low (Hood, et al., 1998; Modrall, et al,. 1998; Weaver, et al., 1990).

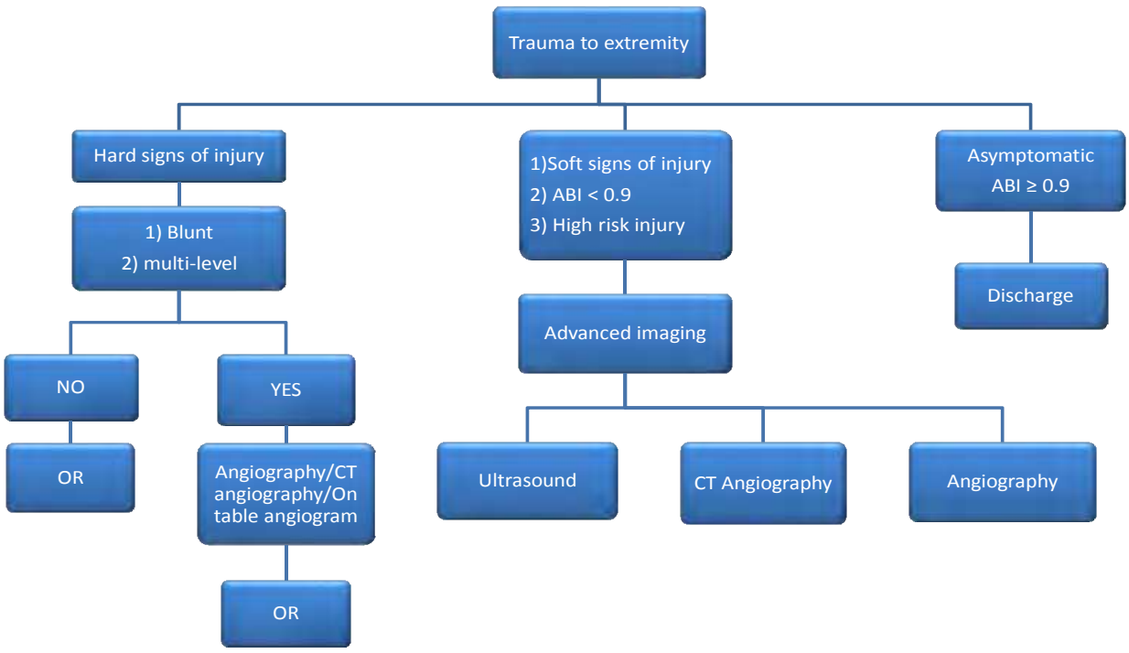


Fig. 1. Diagnostic and treatment algorithm for extremity trauma

Imaging options include MRI and MR angiography (MRA), ultrasound, angiography, and CTA. Studies of MRA in non-traumatic vascular lesions produce very accurate images of the vasculature. Among patients undergoing MRA for peripheral arterial disease sensitivity and specificity range from 92-99.5% and 64-99% respectively (Collins, et al., 2007). A single study of MRA in 12 cases of penetrating trauma revealed satisfactory studies in all patients, and successfully identified 3 injuries confirmed by angiography (Yaquinto, et al., 1992). However, MRA is not commonly utilized for diagnosis of peripheral arterial injury as it can be a lengthy and difficult to obtain exam, and may not be advisable in victims of shotgun, gunshot, or blast injuries as metallic fragments present in the patient may not be compatible with the machine. Additionally, because of the longer image acquisition time, MRA is more susceptible to motion artifact than ultrasound or CTA.

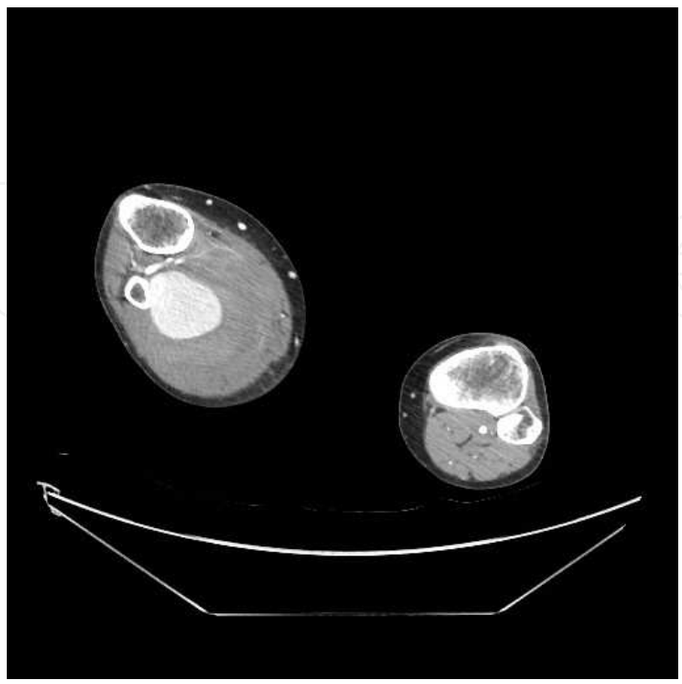
Ultrasound is an excellent option in the lower extremity below the inguinal ligament and in the upper extremity below the shoulder, however the examination can be quite limited in the presence of soft tissue injury, and is less useful for imaging proximal vessels. Ultrasound has the benefit of being portable, and imaging can be obtained quite rapidly in the emergency room, trauma bay, and operating room. It is non-invasive and does not require contrast administration or ionizing radiation. However, reported sensitivities range quite broadly from 50-100% and are highly operator dependent (Feliciano, et al., 2011). When injuries are detected specificity and accuracy are quite high ranging from 95-99% (Doody, et al., 2008; Feliciano, et al., 2011). The largest drawback for ultrasound is availability as a vascular technologist or experienced vascular surgeon with ultrasound training, are required to perform the exam.

Traditional angiography as a screening tool has a reported sensitivity and specificity of 95-100%, and 90-98% respectively (Levy, et al., 2005). Surgeon performed angiography is also quite sensitive and specific with a low complication rate of 1-4% (Itani, et al., 1992;

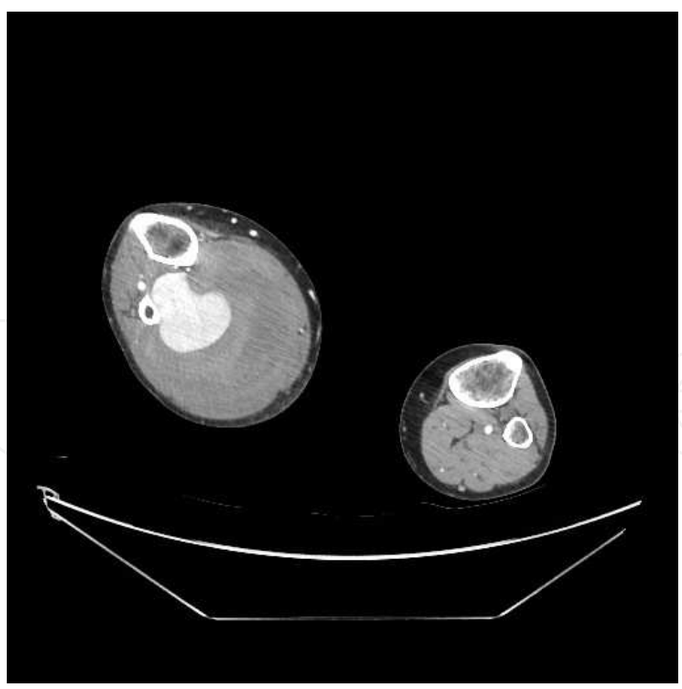
O'Gorman, et al., 1984). However, both methods are invasive, require administration of iodinated contrast, and in the case of traditional angiography may be quite lengthy and require transportation to the interventional radiology suite.

Because both ultrasound and angiography require mobilization of advanced imaging teams with specialized training and are unlikely to be immediately available in most centers after hours or on holidays/weekends, CTA has become an attractive alternative screening method. It has the benefit of speed, ease and a low rate of complications, can be performed without arterial puncture, does not require an interventional radiology team, and can be performed with significantly less contrast and radiation exposure than traditional angiography (Willmann & Wildermuth. 2005). CTA also has the benefit of giving additional information on non-vascular structures such as the bone, joint, and soft tissue. It may be of particular benefit in children as traditional angiography has an increased risk of complications among pediatric patients (Feliciano, et al., 2011). Because of these benefits CTA has now become the dominant mode of screening for peripheral vascular injury in many centers (Anderson, et al., 2008; Fleiter&Mervis. 2007; Peng, et al., 2008). Injury can present as focal narrowing, occlusion, thrombosis, pseudoaneurysm, extravasation, arteriovenous fistula, dissection, and intimal flap (Figure 2a, 2b). There is some evidence that arterial spasm may result in false positives on CTA (Figure 3), while conversely small intimal flaps may not be detected and result in false negatives (Rieger, et al., 2006; Soto, et al., 2001). Confirmatory angiography may be useful in cases of suspected spasm, vs. repeat imaging following resuscitation, while in the case of intimal flaps, the need for endovascular or open intervention is rare even in series with long term follow up (Dennis, et al., 1998). Overall CT angiography has excellent sensitivity (90-100%) and specificity (87-100%) for detecting both upper and lower extremity vascular injuries (Doody, et al., 2008; Fleiter & Mervis. 2007; Inaba, et al., 2006; Peng, et al., 2008; Rieger, et al., 2006; Seamon, et al., 2009). Accuracy appears to be particularly good when using multi-detector 16 and 64 slice scanners, and reformatting such as maximum intensity projections (MIP) and 2 and 3-dimensional reconstruction (Figure 4). Initial studies validated CTA as an excellent screening tool for proximal extremity injuries, but more recent studies have also shown good sensitivity, specificity and image quality for distal portions of extremities (Rieger, et al., 2006). One prospective study revealed a sensitivity and specificity of 100%, as compared to surgery and angiography as the gold standard, including injuries as distal as the posterior tibial trunk and radial artery. This study also found a significant cost savings with CTA over traditional angiography if it had been used as the sole screening modality (Seamon, et al., 2009). Lastly, CT is reported as being the least uncomfortable vascular exam in many series comparing it to MRA, ultrasound and traditional angiography (Collins, et al., 2007).

Limitations of CTA include the need to transport the patient to the radiology suite and exposure to contrast and ionizing radiation. Additionally, in victims of gunshot and shotgun wounds images may be compromised by metallic fragments, which occurs in 3.6-19% of cases (Anderson, et al., 2008; Soto, et al., 2001). However, metallic artifact when present did not appear to significantly limit the utility of CTA in two recent series (Anderson, et al., 2008; White, et al., 2010). Complications of CT are rare and include anaphylaxis (0.004-0.22%) and contrast infiltration (0.2-2.2%). Contrast induced nephropathy can occur in 1.2-2.6% of patients, however this can increase to 11-33% in high risk groups (Bellin, et al., 2002; Haveman, et al., 2006; Lencioni, et al., 2010; Morcos. 2005; Nguyen, et al., 2009; Pucelikova, et al., 2008; Rashid, et al., 2009; Wang, et al., 2007).



(a)



(b)

Fig. 2. a) Lower extremity pseudoaneurysm, b) pseudoaneurysm with its feeding vessel, the posterior tibial artery



Fig. 3. Lower extremity demonstrating multivessels vasospasm of the anterior tibial, peroneal and posterior tibial arteries.

2.2 Thoraco-abdominal vascular injury

Thoraco-abdominal vascular trauma is a rare entity accounting for 0.01-2% of all trauma admissions (Asensio, et al., 2000; Asensio, et al., 2002; Dente, et al., 2008; Hoyt, et al., 2001). Penetrating mechanisms are responsible for the vast majority of injuries accounting for 70-95% of patients (Asensio, et al., 2000; Asensio, et al., 2002; Hoyt, et al., 2001; Mattox, et al., 1989). Of blunt causes motor vehicle crashes are the most common followed by falls from height and pedestrians struck by vehicles (Asensio, et al., 2001b; Bertrand, et al., 2008; Mirvis & Shanmuganathan. 2007; Neschis, et al., 2008; Wintermark, et al., 2002). Unlike extremity vascular injury where bleeding, hematomas, pulsations, thrills, bruits, and in some cases the vessels themselves are easily examined clinically, outside of hypotension, there are few clinical signs of truncal vascular injury. Because of this radiographic adjuncts are of great importance in the diagnosis of truncal vascular injury. Increasingly CT scanning is being utilized for diagnosis of thoraco-abdominal vascular injury. Intravascular interventions such as covered stents have been increasingly utilized for treatment of thoracic, subclavian and iliac arterial injuries, structures which have classically been difficult to expose and treat surgically (Asensio, et al., 2001a; Boufi, et al., 2011; Carrick, et al., 2010; Castelli, et al., 2005; Cestero, et al., 2009; Demetriades, et al., 2008a; Demetriades, et al., 2008b; Starnes & Arthurs. 2006).



Fig. 4. 3-Dimensional reconstruction of SFA injury with occlusion and reconstitution of flow distal to the injury.

2.2.1 Thoracic aorta

Blunt thoracic aortic injury (TAI) is a rare but potentially lethal result of thoracic trauma. The result of acceleration-deceleration injuries, the most common mechanisms are falls and motor-vehicle crashes. Unfortunately the majority of patients with TAI do not reach the hospital alive, 80-90% die prior to hospital arrival, and TAI accounts for between 16-29% of motor-vehicle fatalities (Bertrand, et al., 2008; Mirvis, et al., 1987; Neschis, et al., 2008; O'Conor. 2004). Of patients surviving to evaluation TAI is present in approximately 0.3-2.8% of patients (Arthurs, et al., 2009; Bertrand, et al., 2008; Fitzharris, et al., 2004; Ungar, et al., 2006; Wintermark, et al., 2002). Detection of these few patients has long been a subject of debate. Chest x-ray is the primary screening exam, however, it can be normal in up to 44%

of patients with TAI, and positive findings are nonspecific (Demetriades, et al., 1998; Neschis, et al., 2008; Raptopoulos, et al., 1992; Woodring. 1990). Abnormalities associated with TAI include widened mediastinum, apical capping, left pleural effusion, loss of aorto-pulmonary window, depression of the left mainstem bronchus, deviation of the trachea or nasogastric tube to the right, and widening of the right paratracheal stripe (Woodring & Dillon. 1984). All patients with abnormalities on chest x-ray should rapidly undergo further imaging. Additionally, when the is a very high index of suspicion for TAI advanced imaging can be considered even with a normal chest x-ray. Risk factors include fall from height, high speed motor-vehicle crash particularly with a side impact, which carries a 2-fold higher risk of TAI compared to head on collision, patients with associated injuries such as traumatic brain injury, pelvic and multiple rib fractures (Bertrand, et al., 2008; Fitzharris, et al., 2004; O'Conor. 2004). Several studies also suggest a lower threshold for imaging patients ≥ 65-70 years, and in one study for patients as young as 30 years (Bertrand, et al., 2008; Fitzharris, et al., 2004; Kaiser, et al., 2011; Smith, et al., 1995).

Imaging options include traditional angiography, CTA, echocardiography, and MRI/MRA. Each of these techniques has its own set of advantages and limitations, and the choice of imaging technique will be determined not solely by sensitivity and specificity, but also by the patient's clinical condition, concomitant injuries, and institutional availability.

The historical gold standard, angiography/aortography is decreasing in popularity. While older studies of aortography, reported sensitivity nearing 100%, others utilizing modern technologies have revealed sensitivities of 38-92% (Azizzadeh, et al., 2011; Fabian, et al., 1998). The majority of missed injuries appear to be intimal tears and small intramural hematomas which are more likely to be diagnosed by echocardiography or CTA (Azizzadeh, et al., 2011; Fabian, et al., 1998; Smith, et al., 1995). Aortography has excellent specificity, ranging from 98-100% in most series and provides detailed information on the location and morphology of the aortic injury which can be used for operative planning (Fabian, et al., 1998; Mirvis, et al., 1987; O'Conor. 2004). Complications of angiography include access site thrombosis or hemorrhage with significant bleeding occurring in 3-17% of cases; compartment syndrome in 0.004% of patients; and injury to the access vessel including dissection occurring in ~0.5% of patients, pseudoaneurysm, and arteriovenous fistula complicating 0.1% of cases (Bellin, et al., 2002; Fruhwirth, et al., 1996; Meyerson, et al., 2002; Tizon-Marcos & Barbeau. 2008). Systemic complications include anaphylaxis which is rare, and contrast induced nephropathy which occurs in 3.3-14.5% of cases overall, but can increase to 15-62% in high risk populations (Haveman, et al., 2006; Morcos. 2005; Pucelikova, et al., 2008). Additionally, angiography requires specialized equipment and personnel with advanced training which may not be present in all centers, and requires the patient be transported to an angiography suite and remain there for a prolonged period of time. Because of these limitations, aortography to screen for TAI is primarily utilized in patients with other indications for angiography, such as pelvic or solid organ injury requiring angioembolization.

In contrast to angiography CT is widely available, can be performed at any time, is fast, requires a lower contrast load, and avoids arterial puncture. Because of these benefits CT is increasing in popularity. A comparison of trauma practices from the time periods 1994-1996 and 2005-2007 revealed an increase in the use of CT scan for diagnosis of TAI from 34.8% to

93.3%. In that same time period the authors also noted a decrease in use of aortography from 87% to 8.3% (Demetriades, et al., 2008b). Indications of TAI include mediastinal or intramural hematoma, pseudoaneurysm, contrast extravasation, variation in aortic contour, and intimal flap (Figure 5, 6a, 6b). More subtle changes may include aortic dilation around and narrowing distal to the injury. While early trials of CT scan were met with skepticism due to highly variable sensitivity and low specificity. Multi-detector helical scanners now have the ability to acquire more data in less time (20-35 seconds), with improved definition, and MIP and 3-dimensional reconstruction has allowed even greater anatomical accuracy. Modern series reliably report sensitivity between 95-100% (Bruckner, et al., 2006; Dyer, et al., 2000; Exadaktylos, et al., 2005; Fisher, et al., 1994; Raptopoulos, et al., 1992; Wintermark, et al., 2002). Specificity, initially a drawback ranging from 83-86% (Fabian, et al., 1998; Raptopoulos, et al., 1992), has improved with modern technology as well and now ranges between 94-99.8% (Mirvis & Shanmuganathan. 2007; Wintermark, et al., 2002; Wong, et al., 2004). These advances have come at the price of higher radiation doses due to the greater number of detectors. However, there have been a number of protocol changes that have been able to significantly reduce the amount of radiation required for scans without apparently diminishing the image quality. Particularly in multi-trauma patients who require CT imaging of multiple body parts, the use of single pass whole body protocols result in significantly decreased radiation dose, contrast dose, and scan time, as well as total time in the CT suite (Fanucci, et al., 2007; Flamm. 2007; Loupatatzis, et al., 2008; Nguyen, et al., 2009; Ptak, et al., 2003).

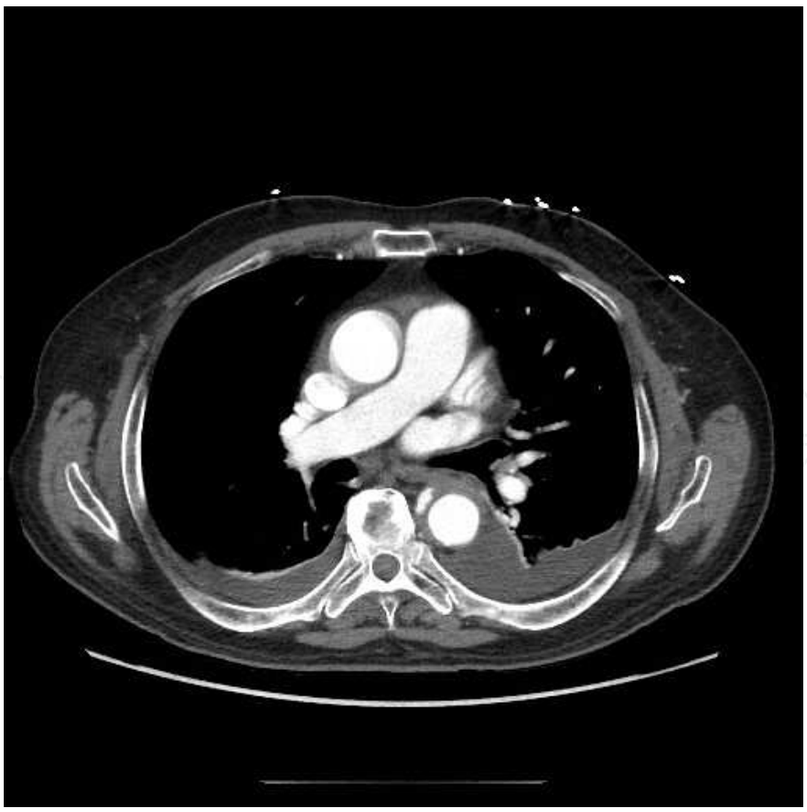


Fig. 5. Axial CT image of TAI with contrast extravasation and adjacent contained hematoma



(a)



(b)

Fig. 6. Axial CT depicting aortic dissection extending from the arch (a) to the descending thoracic aorta (b)

Given these benefits some investigators have advocated abandoning chest x-ray as a screening tool in favor of CT in all patients with blunt thoracic trauma. CT's done for this purpose will reveal injuries in 5-25% of patients with normal x-rays, but will lead to a change in management in ≤ 6% of cases (Barrios, et al., 2009; Kaiser, et al., 2011; Raptopoulos, et al., 1992). Although chest x-ray may miss up to 7-8% of TAI, use of CT as a screening tool indiscriminately is unlikely to be productive or cost effective and may result in unnecessary radiation exposure with attendant increase in cancer risk (Demetriades, et al., 1998; Kaiser, et al., 2011; Melton, et al., 2004). Careful screening with chest x-ray and directed imaging in the presence of traumatic findings or in very carefully selected victims of suspicious mechanisms in the presence of previously mentioned risk factors is likely to prevent overutilization of CT and avoid missed TAI.

In contrast to blunt trauma, in the rare victims of penetrating trauma who present in hemodynamically stable condition CT has proven to be an excellent and cost effective screening examination. Patients with transthoracic or transmediastinal gunshot wounds are at risk for vascular and aerodigestive injuries. CT scan can determine which patients require surgery, or additional more invasive imaging such as esophagoscopy, esophagography or bronchoscopy. Early studies were 100% sensitive but were non-diagnostic in up to 50% of cases, more recent studies reveal conclusive results in 82.9% of cases (Hanpeter, et al., 2000; Ibirogba, et al., 2007). Equally as important is the reduction in the need for further invasive testing, in a 2007 study CT reduced the need for angiography, ultrasound and esophagography resulting in a cost reduction of 72% (Ibirogba, et al., 2007).

Unfortunately, patients who are hemodynamically unstable or require emergent surgery cannot undergo CT scanning, in these cases echocardiography may be the ideal diagnostic modality. It is portable, can be performed rapidly, is repeatable, and does not require intravenous contrast. Echocardiography can be performed via transthoracic, transesophageal or intravascular routes. Due to the low sensitivity of transthoracic echocardiography, especially in the presence of chest wall injuries transesophageal echocardiography (TEE) is the preferred method.

Characteristics of TAI on TEE include mobile intimal flaps, intraluminal mass or thrombus, and in some cases full thickness mural tear with pseudoaneurysm or mediastinal hematoma adjacent. Larger or more severe injuries can be associated with a marked enlargement of the aortic lumen and large false aneurysms (Vignon, et al., 2005). TEE can be performed in as little as 27-30 minutes with high diagnostic accuracy (Kearney, et al., 1993; Smith, et al., 1995). Sensitivity averages 98-100% (Buckmaster, et al., 1994; Goarin, et al., 2000; Kearney, et al., 1993; Smith, et al., 1995; Vignon, et al., 2001; Vignon, et al., 2005), but like most ultrasound techniques can vary widely based on operator experience, with sensitivity as low as 60-63% being reported (Patel, et al., 2003; Saletta, et al., 1995). When directly compared to angiography TEE has comparable sensitivity for surgical lesions, but has a higher sensitivity for minor lesions such as intimal flaps (Buckmaster, et al., 1994; Goarin, et al., 2000; Kearney, et al., 1993; Smith, et al., 1995; Vignon, et al., 2005). CT scan and TEE have similar diagnostic accuracy for surgical lesions, but again TEE has improved sensitivity for minor lesions (Vignon, et al., 2001). TEE can be performed safely and successfully in most patients, the failure rate in a recent meta-analysis was 1.2%, and the majority of studies report no significant procedure related complications (Buckmaster, et al., 1994; Cinnella, et al., 2004; Goarin, et al., 2000; Kearney, et al., 1993; Smith, et al., 1995; Vignon, et al., 2005).

An alternative to TEE is intravascular ultrasound. This technique involves insertion of a moderate sized catheter with an ultrasound array over a guidewire into the aorta through the femoral artery. It has excellent diagnostic accuracy, with sensitivity in the 92-100% range, and specificity nearing 100% (Azizzadeh, et al., 2011; Patel, et al., 2003). In a study comparing IVUS, TEE and angiography among patients with blunt chest trauma, IVUS outperformed both TEE and angiography with a sensitivity of 91.7%, with only one equivocal study which was found to be an intimal flap at surgery (Patel, et al., 2003).

Drawbacks of TEE include the need for specialized equipment, esophageal intubation, and operator dependence. There are also risks of esophageal injury or perforation, and airway compromise. Additionally, the 3-5cm portion of the upper ascending aorta which is obscured by interposition of the trachea between the aorta and esophagus can be a technical "blind spot" (Smith, et al., 1995). IVUS avoids this "blind spot" phenomenom, however it has similar limitations of being very operator dependent, and requiring specialized equipment. Additionally, IVUS requires arterial puncture with the attendant risk of access site complications of hematoma, fistula, pseudoaneurysm, and dissection. The risks of such local complications may be greater for IVUS than for diagnostic angiography as the sheath size required to accommodate the ultrasound probe is larger (7-8Fr) than that typically needed for diagnostic angiography (Azizzadeh, et al., 2011; Wintermark, et al., 2002). Despite the benefits of TEE and IVUS they are used in very few cases (1-4%), and appear to be decreasing in frequency, from 11.9% to 1% (Demetriades, et al., 2008b; Melton, et al., 2004). This may reflect the lack of specialty trained personnel and resultant difficulty in obtaining TEE or IVUS particularly in off hours. It may also be a result of trauma physicians lack of familiarity in performing and interpreting the results of this diagnostic modality.

MR angiography (MRA) is typically performed both before and after administration of intravenous gadolinium. In contrast to prior time-of-flight examinations contrast enhanced MRA (CE-MRA) is able to obtain images of a higher quality more often due to decreased respiratory and cardiac artifacts (Goldman. 2003). CE-MRA is also particularly well suited to 3-dimensional reconstruction which is of great value in pre-operative or pre-stent planning. Compared to traditional angiography MRA does not require arterial puncture, and is non-invasive. In comparison to CT scanning MRA has the benefit of avoiding ionizing radiation as well as iodinated contrast. MR findings consistent with TAI are similar to those of CT angiography and include intraluminal mass, flap, or luminal irregularity, as well as pseudoaneurysm, and hematoma (Wintermark, et al., 2002). CE-MRA can be used for diagnosis with a sensitivity and specificity between 98-100% (Bruckner, et al., 2006; Chirillo, et al., 1996; Fattori, et al., 1996; Khalil, et al., 2007; Mirvis&Shanmuganathan. 2000). However, CE-MRA has the drawbacks of requiring lengthy exam times outside of a monitored critical care setting, and potentially lengthy transport times. While avoiding nephrotoxicity, gadolinium is not entirely benign, and nephrogenic systemic fibrosis can occur in up to 2-5% of patients with renal insufficiency (Li, et al., 2006; Martin, et al., 2009). Lastly, CE-MRA is not available in many centers, and in hospitals where it is available, may not be operational at night, on holidays or weekends. Because of these drawbacks it is particularly ill suited to the acute trauma work up. However it has been suggested as a logical mode of follow up in the subacute and chronic phases in cases of medical management of minor injuries, or as a follow up after surgical or endovascular repair (Fattori, et al., 1996; Mirvis & Shanmuganathan. 2000; Wintermark, et al., 2002).

2.2.2 Subclavian artery

Subclavian artery injuries are primarily due to penetrating mechanisms, but are rare, affecting less than 3% of all penetrating traumas. Injuries associated with blunt trauma are even more uncommon affecting only 0.4% of patients. These injuries are highly lethal, resulting in death in up to 42% of patients prior to, or upon presentation to the hospital (Demetriades, et al., 1999). Patients often present with hypotension, hard signs of vascular injury, or compartment syndrome and are taken emergently to the operating room. In rare instances patients present in stable condition with soft signs of injury, or are asymptomatic, in these cases CT angiography can be very helpful in detecting injuries, for preoperative planning, and in some cases determining if endovascular therapy is feasible. Two studies of endovascular therapy report utilization of CTA angiography in planning stent-graft deployment, both report successful treatment of lesions, based on CT findings, but are small, and do not describe sensitivity or specificity (Castelli, et al., 2005; Hilfiker, et al., 2000). There is little to no evidence in the literature specifically studying the use of CTA angiography in subclavian artery injuries, however, several large series of CT in proximal extremity injury including the subclavian and axillary artery have found excellent sensitivity and specificity. A study of 142 CTA angiograms, including 7 subclavian artery injuries, found a sensitivity of 95.1% and specificity of 98.7% (Soto, et al., 2001). In a study of 41 stable patients with penetrating thoracic trauma CTA angiography did not miss any injuries in 9 patients who underwent both CT and traditional angiography (LeBlang & Dolich. 2000). Traditional angiography may also be utilized and was found to be helpful in operative planning in a series of 50 patients from South Africa (Sobnach, et al., 2010), and has the added benefit of providing access for possible endovascular therapy such as embolization or stent-graft deployment. Literature on the utility of ultrasound and MRI/MRA in diagnosis of subclavian artery injury following trauma is lacking. There is evidence in the vascular literature suggesting good sensitivity and specificity of ultrasound for subclavian occlusive disease. In a study of 150 controls and 33 patients with occlusive disease ultrasound was able to correctly identify lesions in 89% of right sided, and 96%of left sided lesions, with a sensitivity of 88% and specificity of 94% compared to a gold standard of digital subtraction angiography (Yurdakul, et al., 2008). However, it is unlikely that sensitivity and specificity will be as high in trauma patients in whom intravascular volume depletion, hematoma, and subcutaneous emphysema may obscure abnormalities and increase technical difficulty. In a study of penetrating trauma patients Demetriades and colleagues found that ultrasound coupled with clinical exam had a sensitivity of 91.7% and a specificity of 100% for detecting vascular injury compared to angiography and operative findings, however, this study included only 4 subclavian injuries (Demetriades, et al., 1997).

2.2.3 Iliac artery

Though uncommon overall iliac artery and vein injuries account for 11% of vascular injuries, making them one of the most common truncal vascular structures to be injured. Iliac artery injury is quite morbid resulting in a survival of only 51% (Asensio, et al., 2003; Mattox, et al., 1989). Most commonly due to penetrating trauma, iliac artery injury in patients following blunt trauma is rare occurring in only 3.5% of all patients with severe pelvic fractures, and is associated with significant morbidity (Cestero, et al., 2009; Cushman, et al., 1997). When patients are hemodynamically stable CT has become the diagnostic tool

of choice for detection of vascular injury and need for further procedures (Vu, et al., 2010). Conversely, unstable patients have historically been triaged according to the results of pelvic plain x-rays and Focused Assessment with Sonography for Trauma (FAST). Patients with evidence of significant hemoperitoneum were taken for operative exploration while those with minimal or no peritoneal fluid and severe pelvic fracture, where retroperitoneal sources of hemorrhage are likely, were resuscitated and taken for angiography. However, this occasionally resulted in negative laparotomies due to the poor sensitivity/specificity of FAST, particularly in victims of penetrating trauma. There is currently growing support for the use of CT scanning in the triage of even unstable patients with pelvic trauma. A review of 545 patients with both pelvic and abdominal trauma revealed an increasing use of pre-operative/pre-angiographic CT for triage even among patients with blood pressures ≤ 90 mm Hg. This study revealed no increase in mortality as a result of CT scanning, nor was there a significant increase in time to angiography or laparotomy as a result of CT scanning. The authors did note a significantly decreased rate of negative laparotomy from 36% to 16%, as well as a success rate of angiographic intervention in 71-74% of patients with increased CT utilization (Fang, et al., 2011). CT reveals evidence of bleeding in up to 75% of cases, with arterial sources found in up to 57% of cases. However, the majority of arterial bleeds are due to injuries in branches of the internal iliac, injuries to the iliac arteries themselves are rare (Pinto, et al., 2010; Romano, et al., 2000). It has been noted that triple phase CT scanning (arterial, venous, and portal venous) may result in increased sensitivity and specificity for diagnosis of arterial injury as compared to the typical trauma scan utilizing just the portal venous phase (Vu, et al., 2010). However, even among studies utilizing single phase "trauma" scans, if newer generation multi-detector instruments are used sensitivity can be as high as 92.6% for detecting pelvic bleeding requiring intervention (Maturen, et al., 2007). It should also be kept in mind that triple phase scans will result in increased radiation exposure and slightly increased scan times.

3. Management

Open surgery with primary repair, vein patch, and interposition or bypass grafting has been the gold standard for management of all vascular injury. However, endovascular treatment has a number of advantages over open repair including decreased ischemia time as there is no need for cross-clamping of the vessel for repair, less incisional pain, decreased recovery time and length of stay, as well as avoidance of complications related to laparotomy or thoracotomy. Endovascular treatment options include stenting, coil, and chemical embolization. Embolization is best utilized for smaller vessels and areas with rich collateral circulation such as the pelvis, or long necked pseudoaneurysms. For larger vessels and those that should not be occluded, both bare stents and covered stent-grafts are good alternatives. In general bare stents (Figure 7) are utilized for injuries which are not full thickness such as intimal tears with or without thrombosis, and dissections. For full thickness injuries, with or without bleeding, covered stent-grafts are required. Most series favor the use of self-expanding devices such as the Wallstent, Wallgraft, and Fluency as they are more flexible and do not require balloon expansion, which may worsen arterial injuries (Brandt, et al., 2001; Piffaretti, et al., 2007; White, et al., 2006). Overall utilization of endovascular therapies for acute trauma is increasing. A study of the National Trauma Data Bank (NTDB) revealed a significant increase in the number of endovascular treatments from 1997 to 2003. This increase was particularly prominent in the years spanning 2000-2003, where endovascular

techniques increased from 2.4% to 8.1%. This study found that patients undergoing endovascular therapy were, in general, less severely injured than those undergoing open repair. However, after correcting for injury severity score and associated injuries patients undergoing endovascular repair retained a survival advantage over their open surgery counterparts (odds ratio for death 0.18; 95% confidence interval 0.04-0.84, p=0.029). Patients with torso arterial injury, especially thoracic aortic injury appeared to benefit most from endovascular repair (Reuben, et al., 2007). Despite the advantages of endovascular therapy there are a number of concerns that must be addressed before endovascular therapy can be widely advocated including long term patency, device failure, migration, leak, and deformation rates over time; as well as long term morbidity and mortality. The long term outcomes are particularly important to determine as the majority of trauma patients are young, and may survive many decades with their endovascular prosthetics. Further, the need for anticoagulation and antiplatelet agents in the peri-procedural time period, as well as their role in the maintenance of long term patency of stents and stent-grafts has yet to be defined. Lastly, the type and timing of follow up imaging for surveillance are all unknown at this time. The majority of studies of stent graft deployment use a combination of physical

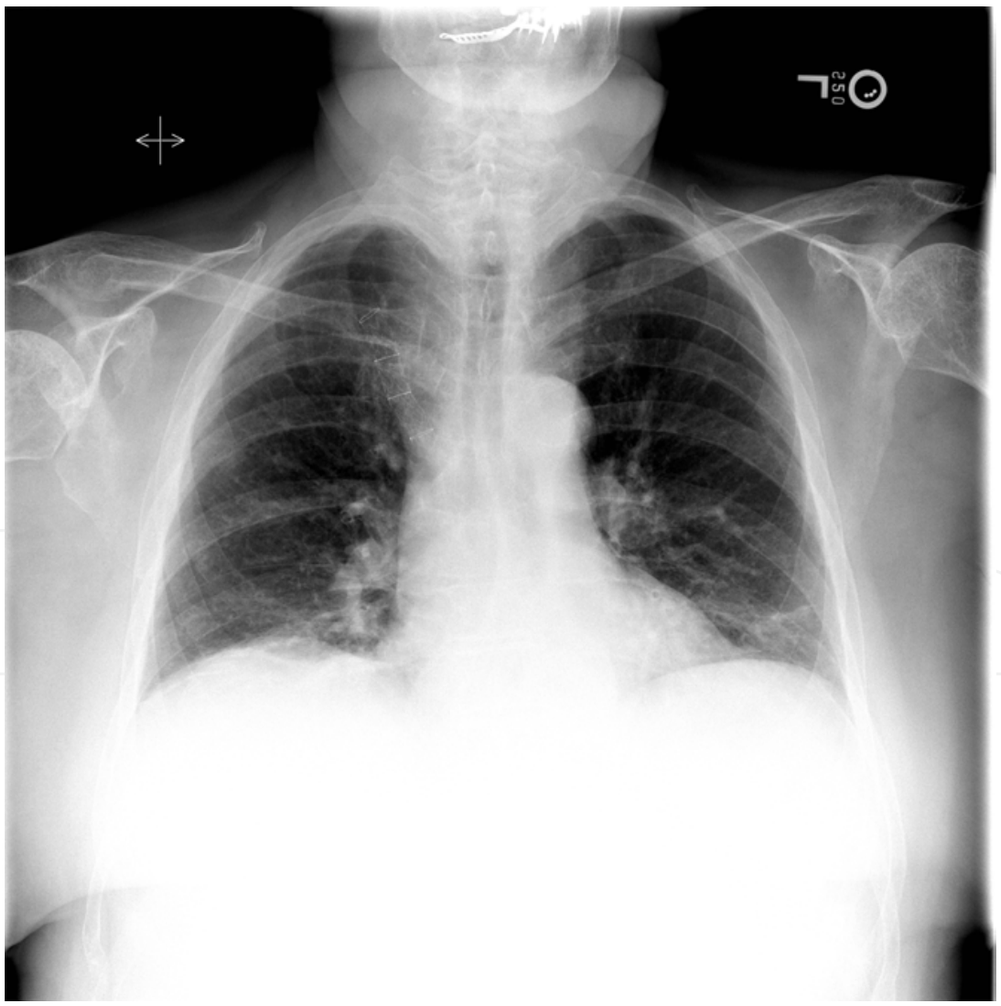


Fig. 7. Chest radiograph demonstrating bare metal stent in the right subclavian vein.

exam findings, as well as surveillance imaging for follow up. Studies use CTA, and ultrasound preferentially, no studies utilize traditional angiography as a method of surveillance, however, the optimal timing and frequency of surveillance is yet to be determined. Additionally, it is unclear if CTA will provide a significant benefit over ultrasonography in terms of sensitivity and specificity for identification of post-stent complications in locations where ultrasound is an option such as the subclavian, axillary, femoral and in certain patients iliac arteries. To surveill the arch and thoracic aorta, CT is the only non-invasive method of imaging, ultrasound requires either intravascular or transesophageal probes.

3.1 Thoracic aorta

Traditionally patients with thoracic aortic injury underwent emergent open repair, recently conservative management with blood pressure and heart rate control have allowed many patients to be temporized until open or endovascular treatment can be undertaken when the patient has been stabilized (Demetriades, et al., 2008a; Fabian, et al., 1998). Open repair is associated with significant blood loss, high mortality and morbidity, the most significant of which is paraplegia occurring in 1.6-14% of patients (Demetriades, et al., 2008a; Xenos, et al., 2008). Because of the morbidity and mortality of traditional repair, perhaps more than any other injury, the use of endovascular techniques has significantly impacted the treatment algorithm for TAI. A multicenter prospective observational study revealed significantly increased use of stent grafts for treatment of TAI (Demetriades, et al., 2008a, 2008b). There have been several retrospective case series of thoracic endovascular aortic repair (TEVAR) both with and without comparisons to open repair, however to date there have been no prospective trials. Technical success rates range from 92-100%; with complications occurring in 0-15%; leaks, when reported, range from 0-15%; and mortality ranges between 0-17.9% (Alsac, et al., 2008; Asmat, et al., 2009; Canaud, et al., 2008; Day & Buckenham. 2008; Dunham, et al., 2004; Ehrlich, et al., 2009; Garcia-Toca, et al., 2010; Moainie, et al., 2008; Oberhuber, et al., 2010; Rahimi, et al., 2010; Urgnani, et al., 2009). The leak rate may increase with time, as several studies have shown an increase in need for second intervention with follow up among TEVAR patients compared to open repair (Hershberger, et al., 2009; Lee, et al., 2011; Tang, et al., 2008). When reported the majority of leaks appear to be type I endoleaks, this is likely related to the technical difficulty in achieving a good proximal seal in the aortic arch. This difficulty is generally ascribed to the angulation of the arch, as well as the narrow aorta and difficulty with sizing stent-grafts for most young trauma patients. The majority of type I leaks are diagnosed at the time of the original procedure and treated, however, Hershberger *et al* reported 3 deaths in the literature related to failure to achieve proximal seal, highlighting the need for early detection and therapy (Hershberger, et al., 2009). Although rates of paraplegia are quoted in the literature as ranging from 0-5%, the majority of studies have no paraplegia, and three large meta-analyses found only 2 patients reported to have had paraplegia related or potentially related to TEVAR (Hershberger, et al., 2009; Tang, et al., 2008; Xenos, et al., 2008). In studies with direct comparison to open repair some studies have found no significant difference in morbidity, mortality or length of stay (Arthurs, et al., 2009; Lang, et al., 2010; Yamane, et al., 2008), while others have shown a significant decrease in mortality, blood loss, transfusion requirements, paraplegia rates, operating room times, and length of stay (Buz, et al., 2008; Moainie, et al., 2008; Rousseau, et al., 2005).

In two large meta-analyses encompassing 589 and 699 patients respectively the authors found a significant improvement in procedure related mortality and paraplegia rates among patients treated with TEVAR compared to open surgical repair. In the first meta-analysis TEVAR patients were significantly more injured, however in the second the patient demographics were roughly equivalent (Tang, et al., 2008; Xenos, et al., 2008). In a subsequent review of the literature undertaken by a panel of experts for the Society of Vascular Surgery a total of 7768 patients with TAI were identified. Compared to patients treated with medical management and open repair, patients undergoing endovascular repair had a significantly decreased mortality (46 and 19% vs. 9%). The rate of spinal cord ischemia was also decreased among TEVAR patients 9% vs. 3% (Lee, et al., 2011). Based on these findings the panel suggested that TEVAR be preferentially performed over open surgical repair or non-operative management, although based on low grade evidence (Level C).

It should be kept in mind that there have been reports of significant procedure related complications associated with TEVAR, the most common of which is iliac artery injury. Other procedure related complications include brachial artery injury and compression of the left bronchus. Additionally, when recorded the rate of stent coverage of the subclavian or carotid artery origin ranged from 50-85% (Alsac, et al., 2008; Asmat, et al., 2009; Canaud, et al., 2008; Day & Buckenham. 2008; Dunham, et al., 2004; Ehrlich, et al., 2009; Garcia-Toca, et al., 2010; Oberhuber, et al., 2010; Rahimi, et al., 2010; Urgnani, et al., 2009). Coverage of the origin of these great vessels has been associated with a risk of neurologic complication in 5.6% of patients, a rate that appears to be decreased with prophylactic re-vascularization (Hershberger, et al., 2009). Lastly long term follow up in most studies is lacking, averaging only 14-24 months (Hershberger, et al., 2009; Lee, et al., 2011; Tang, et al., 2008).

3.2 Subclavian

Because of the posterior location and intimate relationship of the subclavian artery to the brachial plexus operative exposure can be incredibly difficult, particularly in the bleeding hypotensive patient. Once localized primary repair is preferred, however tissue loss often makes this unfeasable as this vessel has very little mobility and is very friable, in these cases the vessel may be ligated or shunted. With any operative repair there is significant risk of bleeding, nerve injury, and in the case of ligation, compartment syndrome and ischemia. Operative repair is also associated with a very high mortality, up to 42% (Demetriades, et al., 1999). Because of this alternatives to open surgical repair are very attractive, and there is growing experience with covered stents for treatment of subclavian artery injuries (Figure 8, 9a, 9b, 9c). Several case series have been reported revealing mortality of 0-33%, technical success rates ranging from 67-100%, primary patency rates of 83-100%, short term complications occurring in 0-22% of patients, and long term complications ranging from 0-32% (Carrick, et al., 2010; Castelli, et al., 2005; Cohen, et al., 2008; Danetz, et al., 2005; du Toit, et al., 2008; Hilfiker, et al., 2000). Short term complications most often include access site bleeding/hematoma, infection, pseudoaneurysm and fistula. Long term complications include stent-graft stenosis, occlusion and fracture. These series are limited by relatively short term follow up and small numbers, with populations ranging from 6-57 patients, additionally the majority are limited to hemodynamically stable penetrating trauma patients, which is an uncommon presentation, and a small subset of the trauma population. A review of the literature performed by Hershberger included 23 articles describing 91

patients with subclavian artery injury treated with endovascular techniques. This review found a technical success rate of 96.7%, with a procedural complication rate of 12.1% and mortality of 3.2%. Complications included stent fracture, thrombosis, and access site pseudoaneurysm. Late complications occurred in 8.8% of patients in a mean follow up of 17 months, these included stent fracture, stenosis and occlusion (Hershberger, et al., 2009). Late stenosis and occlusions can be diagnosed with surveillance imaging or by directed investigations after patients develop symptoms. Interestingly, one study found patients with stenosis all presented with symptoms of claudication, while those with occlusion were all asymptomatic (du Toit, et al., 2008).

In most series, patients who were unstable were not considered for endovascular therapy, and in one series, the authors report one patient dying of exsanguinations in the angiography suite (Carrick, et al., 2010). Despite this, some centers with significant endovascular experience and 24 hour a day on call interventional teams have utilized stent-grafts in unstable patients with some success (Cohen, et al., 2008). Other considerations/contra-indications for endovascular repair include vessel transection, and lack of a proximal vascular fixation site. In some cases stent-graft deployment may occlude the origins of one of the subclavian artery branches, the most important of which are the vertebral and internal mammary artery. If the vertebral may be occluded it is imperative to assess if the contralateral vertebral circulation is intact, and if cerebral perfusion will be maintained after occlusion. The internal mammary may be sacrificed however, at the cost of future use for cardiac revascularization. If all of these considerations are taken into account, approximately 37% of patients presenting with subclavian artery injuries may be amenable to endovascular repair (Danetz, et al., 2005).

There is some suggestion that more flexible stents may result in better outcomes with lower rates of graft deformation or compression in comparison to stiffer devices such as the Wallgraft (du Toit, et al., 2008). This is likely to be of particular importance when treating distal lesions that may be near, or span a joint and be subject to a great deal of motion and extrinsic compression at the thoracic outlet and across the shoulder joint. While endovascular therapies most often consist of stent-graft deployment, there have been case reports of coil and thrombin embolization of pseudoaneurysms of the subclavian with good success (Lee, et al., 2010).

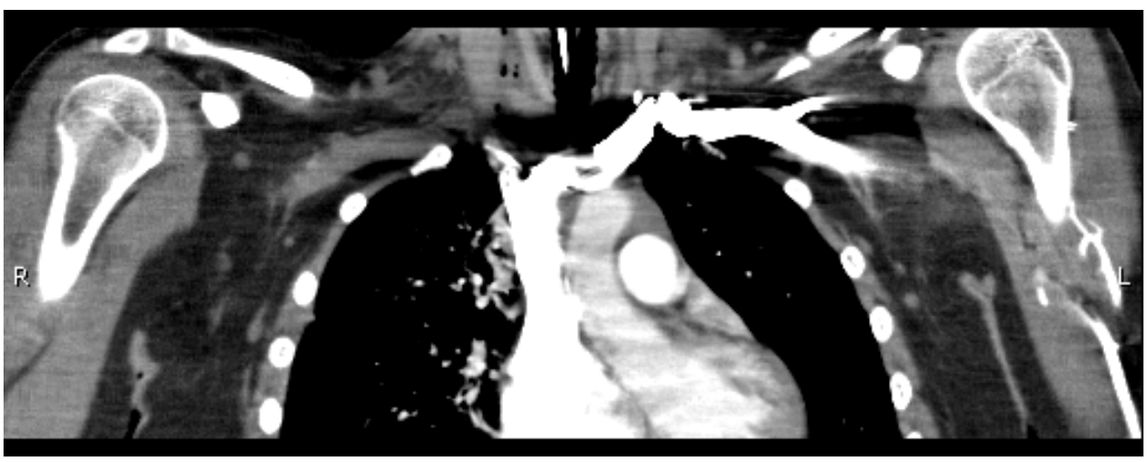
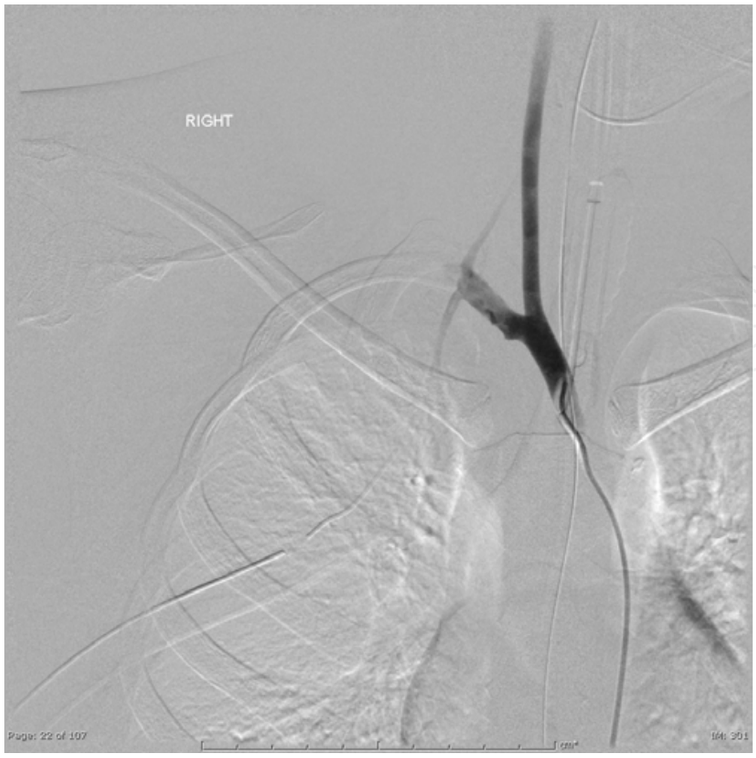
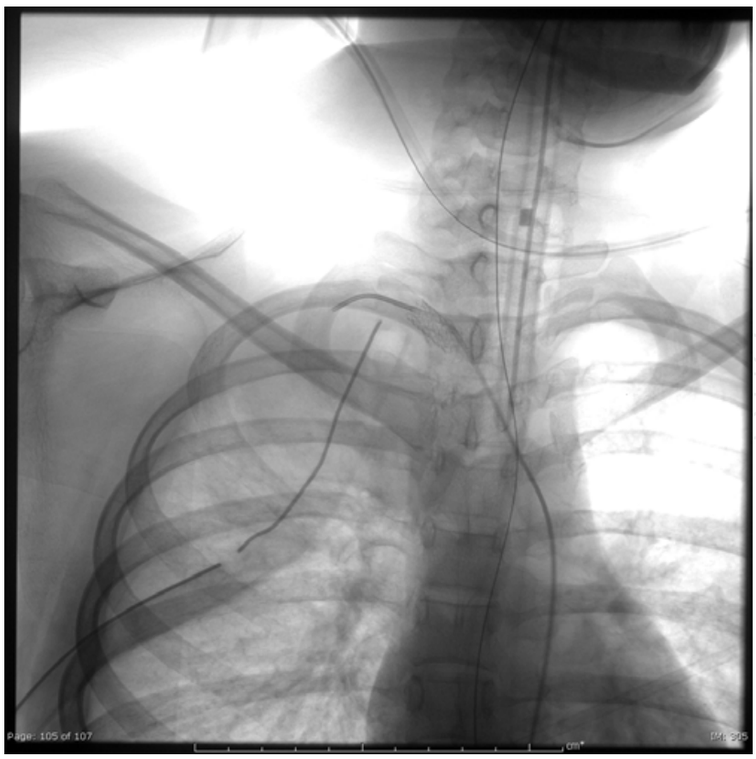


Fig. 8. Coronal CT depicting occlusion of the right subclavian artery following gunshot wound. Note the birdsbeak like tapering of the artery and surrounding subcutaneous emphysema in the neck and mediastinum.



(a)



(b)



(c)

Fig. 9. Subclavian artery injury: Angiogram depicting a) occlusion at the proximal right subclavian artery similar to the CT scan b) stent deployment across the injury without contrast c) with contrast demonstrating restoration of flow and no evidence of contrast extravasation

3.3 Iliac

Iliac arterial injury has historically been known for the difficulty of its exposure particularly in the narrow male pelvis, and its repair is rife with the potential for complications and blood loss. Advances in endovascular therapies have significantly changed the treatment approach for this rare and difficult injury. In patients who are hemodynamically stable but with severe pelvic fractures or with evidence of active extravasation on CT scan, angiography and embolization is now the treatment of choice for injuries to the internal iliac artery or its branches (Cherry, et al., 2011; Reuben, et al., 2007; Velmahos, et al., 2002). In operative cases, the use of endovascular adjuncts, pre, post, or intra-operatively has been increasing in frequency (Cherry, et al., 2011). Even among patients who present with hemodynamic instability, or ongoing transfusion requirements, angiography is increasingly viewed as an acceptable primary treatment option resulting in hemodynamic stabilization and a survival rate of 72-92% (Cherry, et al., 2011; Fang, et al., 2011; Fu, et al., 2010). Studies have also investigated the role of mobile angiography with capabilities of performing angioembolization in the emergency department with good outcomes (Morozumi, et al., 2010).

Angiographic embolization of the internal iliac artery or its branches with coils or gelfoam is common and well tolerated (Costantini, et al., 2010; Velmahos, et al., 1999). Embolization is successful in arresting hemorrhage in 80-100% of cases (Fangio, et al., 2005; Velmahos, et al., 2002). Embolization can be performed with gelfoam, which is particularly suited to highly selective embolization of branch vessels. The gelfoam can be delivered easily, and is absorbed with subsequent recanalization of the vessel in a few weeks. In larger vesssels and pseudoaneurysms, coils may be required to achieve hemostasis. Gelfoam can be used to supplement the coils as well. In cases where selective angio-emoblization is not possible, or for patients in whom the risk of hemorrhage is high, but no active bleeding is seen at angiography, bilateral internal iliac artery embolization can be performed with a gelfoam slurry. The slurry is propelled by antegrade flow and fills the majority of the hypogastric circulation. While a few case reports of ischemic complications of bilateral internal iliac artery embolization exist, major complications following therapeutic or prophylactic angioembolization are rare (Christopher J. Dente, David V. Feliciano ,2008; gracias, v. reilly, p. mckenny, m. velmahos, g ,2009; Ramirez, et al., 2004; Velmahos, et al., 2000; Velmahos, et al., 2002). Re-bleeding, or continued hemorrhage following therapeutic angioembolization is rare, occurring in about 7% of cases (Boufi, et al., 2011; Gourlay, et al., 2005). However, because of the risk of re-bleeding many trauma surgeons and interventional radiologists recommend leaving the arterial access sheath in place following the first angiogram for at least 24 hours (Christopher J. Dente, David V. Feliciano ,2008; Gracias, V. Reilly, P. Mckenny, M. Velmahos, G ,2009).



(a) (b)

Fig. 10. Aortogram depicting a) right common iliac arteriovenous fistula with immediate filling of the inferior vena cava via the fistula and b) stent graft deployed in the artery occluding flow through the fistula

Good outcomes with the placement of covered stent grafts across external and common iliac artery injuries (Figure 10) have been described, however these have been small series (Boufi, et al., 2011; Shah, et al., 2003; Starnes&Arthurs. 2006). Success rates vary from 75-100%, with complications occurring in very few patients, however, follow up was variable (Boufi, et al., 2011; Piffaretti, et al., 2007; Shah, et al., 2003). One of the larger series utilizing Wallgraft stent-grafts including 33 iliac artery injuries reports a post-procedure exclusion rate of 93.5%, a one-year exclusion rate of 91.3%, a one year primary patency rate of 76.4%, and bypass free rate of 74.3%. Complications were rare occurring in less than 10% of cases, the most common was stent-graft occlusion followed by stenosis. However, the majority of injuries treated in this study were due to iatrogenic causes, with only 13 injuries due to trauma, the majority of which were blunt (White, et al., 2006).

4. Conclusion

Vascular injury whether central or peripheral remains a challenge to the trauma surgeon. These injuries are rare and lethal, preventing even senior physicians from gaining significant experience with their management. Timely diagnosis and treatment are essential for a positive outcome, and the increasing availability and advances in imaging technology have aided in these efforts. Nowhere has this been more apparent than in the increasing utilization and accuracy of CT scanning, which is fast becoming the dominant mode of diagnosis for most vascular lesions in stable or semi-stable patients. Foreknowledge of these injuries can aid in planning incisions and operative strategy, and allows for directed therapeutic endovascular therapy in an increasing number of vascular injuries. The most common of which is the thoracic aorta. The literature to date is promising, firmly establishing that endovascular therapy is possible in an increasing number of patients, for an ever broadening range of indications. However, long term outcomes are unknown, and the optimal means, method and timing of surveillance imaging have yet to be determined.

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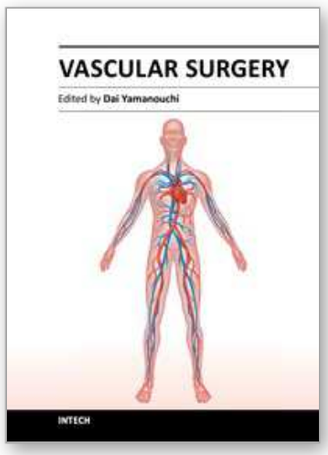
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This book aims to provide a brief overview of conventional open vascular surgery, endovascular surgery and pre- and post-operative management of vascular patients. The collections of contributions from outstanding vascular surgeons and scientists from around the world present detailed and precious information about the important topics of the current vascular surgery practice and research. I hope this book will be used worldwide by young vascular surgeons and medical students enhancing their knowledge and stimulating the advancement of this field.

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